



NOVA
NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

DEPARTMENT OF
ELECTRICAL AND COMPUTER ENGINEERING

A CONTRIBUTION TO COLLABORATIVE RENEWABLE ENERGY COMMUNITIES

KANKAM OKATAKYIE ADU-KANKAM
Master in Electronics and Information Technology

DOCTORATE IN ELECTRICAL AND COMPUTER ENGINEERING
NOVA University Lisbon
December 2023.



A CONTRIBUTION TO COLLABORATIVE RENEWABLE ENERGY COMMUNITIES

KANKAM OKATAKYIE ADU-KANKAM

Master in Electronics and Information Technology

Adviser: Luís Manuel Camarinha de Matos
Full Professor, Universidade Nova de Lisboa

Examination Committee:

Chair: João Francisco Alves Martins,
Full Professor, Universidade Nova de Lisboa

Rapporteurs: Maria Leonilde Rocha Varela,
Associate Professor with Habilitation, Universidade do Minho
Patrícia Alexandra Pires Macedo,
Associate Professor, Instituto Politécnico de Setúbal

Adviser: Luís Manuel Camarinha de Matos,
Full Professor, Universidade Nova de Lisboa

Members: António João Pina da Costa Feliciano Abreu,
Coordinator Professor with Habilitation, Instituto Superior de Engenharia de Lisboa

João Francisco Alves Martins,
Full Professor, Universidade Nova de Lisboa

Filipa Alexandra Moreira Ferrada,
Assistant Professor, Universidade Nova de Lisboa

A Contribution to Collaborative Renewable Energy Communities.

Copyright © Kankam Okatakyie Adu-Kankam, NOVA School of Science and Technology, NOVA University Lisbon.

The NOVA School of Science and Technology and the NOVA University Lisbon have the right, perpetual and without geographical boundaries, to file and publish this dissertation through printed copies reproduced on paper or on digital form, or by any other means known or that may be invented, and to disseminate through scientific repositories and admit its copying and distribution for non-commercial, educational or research purposes, as long as credit is given to the author and editor.

To God first, my wife Gloria, the kids: Kaithlyn & Kaiden, and all my loved ones.

Acknowledgments

I would like to extend my sincere appreciation and profound gratitude to my supervisor, in the person of **Prof. Luis Camarinha-Matos**, for his unfailing assistance and encouragement throughout this PhD journey. Although the journey has been long, his patience, motivation, encouragement, and especially pressure at the right moments were crucial towards the completion of this work. I also thank him for sharing with me his valuable knowledge and experience, and for his rigorous comments, brilliant suggestions, contemporary ideas, and rich contributions. He has been a tremendous coach and a mentor to me. Under his leadership, my personal growth and development as a scientific researcher have been exponential.

My appreciation also goes out to FCT-NOVA, the Centre for Technology and Systems (CTS), UNINOVA, and the Department of Electrical and Computer Engineering for providing me with a comfortable office space, learning resources, and access to scientific seminars and conferences that have helped to shape my thinking and knowledge as a young researcher.

My profound appreciation goes to my family (siblings, wife, daughter and son), co-workers, colleagues in my research group (Filipa Ferrada, Ines Oliveira and Paula Graça) and friends for their support during the development of my thesis and my life in general.

*“The Earth is 4.6 billion years old. Let’s scale that down to 46 years.
We’ve been here for 4 hours.
Our industrial revolution began 1 minute ago.
In that time, we’ve destroyed more than 50% of the world’s rain forests.
(Greenpeace)*

*This isn’t sustainable.
Let us make a difference. We believe sustainability isn’t just a trend. It should not be a job left to the
next generation. We see it as our mission. Now and in the future.
(SunContract)*

Abstract

The notions of Collaborative Energy Ecosystem (CEE) and Cognitive Household Digital Twins (CHDTs) are proposed as two complementary and prospective concepts that could contribute to the efficient organization and management of emerging Renewable Energy Communities (RECs). The CEE concept was derived from the merger of principles and concepts from the disciplines of Collaborative Networks and Virtual Power Plants and is proposed as a representation of a REC, where members approach energy conservation (generation and consumption) from a collaborative point of view. The notion of CHDTs is also proposed as a digital twin representation of the constituent households of a CEE. It is further suggested that CHDTs could have the form of software agents within the cyber space and could be designed to possess some autonomous and cognitive capabilities which could enable them to play complimentary roles as decision-making agents within the corresponding physical households. The decisions of these agents are expected to promote collaborative behaviours that could increase the survivability and sustainability of the CEE. In this thesis, we use software simulation to demonstrate the feasibility of the CEE and CHDT concepts. We further show that through the cognitive capabilities of CHDTs, behaviours such as collaborative generation and consumption of energy could be achieved. Other behaviours, such as mutual influence and the ability to adopt some form of social innovation, are also shown. We adopted the Design Science Research Method by developing a software model (an artifact) of the CEE and its constituent CHDTs using a multi-paradigm simulation technique that involves the integration of System Dynamics, Agent-Based, and Discrete Event simulation techniques on a single platform. The thesis's outcome suggests that these concepts could be useful for managing the sustainability of CEEs or RECs.

Keywords: Collaborative Networks, Digital twins, Cognitive agents, Cognitive intelligence, Sustainable energy consumption, Renewable Energy communities.

Resumo

As noções de Ecosistema Colaborativo de Energia (CEE) e Gémeos Digitais Cognitivos de Habitações (CHDTs) são propostas como dois conceitos complementares e prospectivos que podem contribuir para a organização e gestão eficientes de Comunidades emergentes de Energia Renovável (RECs). O conceito CEE é derivado da fusão de princípios e conceitos das disciplinas de Redes Colaborativas e Plantas Virtuais de Energia e é proposto como uma representação de uma REC, onde os membros abordam a conservação de energia (geração e consumo) de um ponto de vista colaborativo. A noção de CHDT também é proposta como uma representação Gémeo Digital dos domicílios constituintes de um CEE. É ainda sugerido que os CHDTs podem ter a forma de agentes de software dentro do espaço cibernético e podem ser projetados para possuir algumas capacidades autónomas e cognitivas que os capacitariam a desempenhar papéis complementares como agentes de tomada de decisão dentro dos domicílios físicos correspondentes. Espera-se que as decisões desses agentes promovam comportamentos colaborativos que possam aumentar a capacidade de sobrevivência e sustentabilidade do CEE. Nesta tese usamos simulação por software para demonstrar a viabilidade dos conceitos CEE e CHDT. Mostramos ainda que, por meio das capacidades cognitivas dos CHDTs, comportamentos como geração e consumo colaborativos de energia podem ser alcançados. Outros comportamentos como a influência mútua e a capacidade de adotar alguma forma de inovação social também são mostrados. Adotamos o "Design Science Research Method" desenvolvendo um modelo de software (um artefato) do CEE usando uma técnica de simulação multiparadigma que envolve a integração de técnicas de simulação de "System Dynamics", "Agent-Based" e "Discrete Event" numa mesma plataforma. O resultado da tese sugere que estes conceitos podem ser úteis para a gestão da sustentabilidade de CEEs ou RECs.

Palavras chave: Redes Colaborativas, Gémeos Digitais, Agentes Cognitivos, Inteligência Cognitiva, Consumo de Energia Sustentável, Comunidades de Energia Renovável.

Content

ACKNOWLEDGMENTS.....	IX
ABSTRACT	XIII
RESUMO.....	XIV
CONTENT	XV
LIST OF TABLES	XXII
1 INTRODUCTION	1
1.1 BACKGROUND.....	1
1.2 PROBLEM INTRODUCTION.....	3
1.3 RESEARCH QUESTION AND HYPOTHESIS.....	6
1.4 RESEARCH METHOD.....	7
1.5 APPROACH AND CONTRIBUTIONS	9
1.6 ALIGNMENT WITH THE SUSTAINABLE DEVELOPMENT GOALS	10
1.7 DESCRIPTION OF THE THESIS STRUCTURE.....	11
2 LITERATURE REVIEW	13
2.1 BRIEF OVERVIEW OF COLLABORATIVE NETWORKS	13
2.2 THE NOTION OF RENEWABLE ENERGY COMMUNITIES (RECs).....	19
2.3 REVIEW METHODOLOGY.....	20
2.4 PART-1: AREAS OF CONVERGENCE BETWEEN VIRTUAL POWER PLANTS AND COLLABORATIVE NETWORKS	22
2.4.1 Introduction.....	22
2.4.2 Article Search, Identification, Screening and Selection Processes.....	23
2.4.3 Focus Areas	24
2.4.3.1 VPP Operation and Control	24
2.4.3.1.1 VPP Aggregation or Clustering	25
2.4.3.1.2 VPP Organization or Architecture.....	28
2.4.3.1.3 VPP Operation and Support Technologies.....	30
2.4.3.1.4 VPP Market Participation.....	32
2.4.3.2 VPP Security	34
2.4.4 Concluding Remarks	36
2.5 PART-2: A REVIEW ON RENEWABLE ENERGY COMMUNITIES	38
2.5.1 Introduction.....	38
2.5.2 A Brief/Panoramic Analysis of Renewable Energy Communities.....	38
2.5.2.1 Article Search, Identification, Screening and Selection Processes.....	38
2.5.2.2 Focus Areas.....	39
2.5.2.2.1 Technology	39
2.5.2.2.2 Energy Management.....	40
2.5.2.2.3 Architecture, Design and Planning of RECs	41
2.5.2.2.4 Policy	42
2.5.3 A Review of the Areas of Convergence Between Renewable Energy Communities and Collaborative Networks.....	42
2.5.3.1 Cases Search, Identification, Screening and Selection Processes.....	43
2.5.3.2 Overview of the Selected Cases.....	44
2.5.3.3 Summary and Cases Comparison	46
2.5.3.4 Focus Areas.....	47
2.5.3.4.1 Collaborative Relationships.....	48
2.5.3.4.2 Technological Enablers and Trends.....	54

2.6	HOW DO RECs COMPARE TO VPPs.....	60
2.7	OTHER RELEVANT CHARACTERISTICS OF RECs AND VPPs IN TERMS OF THEIR GENERAL ORGANIZATION.....	62
2.8	SUMMARY AND CONCLUSION OF FINDINGS	63
2.9	GENERAL REMARKS ABOUT RECs AS OBSERVED IN THE REVIEW.....	64
2.10	SUMMARY OF RESEARCH GAPS	65
3	THE COLLABORATIVE ENERGY ECOSYSTEM MODELLING FRAMEWORK...69	
3.1	BACKGROUND AND CONCEPTION OF THE CEE NOTION	69
3.2	A HIGH-LEVEL ARCHITECTURAL FRAMEWORK OF THE CEE.....	70
3.3	THE SCOPE OF THE THESIS	72
3.3.1	Collaborative Facets and Behaviours Considered Under the Scope of this Work 74	
3.3.2	Energy Flexibility and Flexible Contribution.....	76
3.4	THE CEE MODELLING FRAMEWORK	76
3.4.1	The CEE Collaborative/Cyber Layer	76
3.4.1.1	The CEE VO layer.....	76
3.4.1.2	The CEE VBE layer	76
3.4.1.2.1	The CEE VBE Manager.....	77
3.4.1.2.2	The Cognitive Household Digital Twins (CHDTs).....	83
3.4.2	The Physical Layer	95
4	THE CEE SIMULATION MODELLING	97
4.1	THE MODELLING METHODOLOGY.....	97
4.1.1	System Dynamics	98
4.1.2	Agent-based Systems.....	98
4.1.3	Discrete Event Modelling.....	99
4.2	SCENARIOS FOR THE MODELLING OF COLLABORATIVE BEHAVIOURS IN THE CEE.....	99
4.2.1	Scenarios for Modelling the Broker Role of the CEE Manager.....	99
4.2.2	Scenario for Modelling the CEE	100
4.2.3	Scenario for Modelling VO Formations	100
4.2.4	Scenario for Modelling the Various Households and their Embedded Appliances 100	
4.2.4.1	Scenario for modelling the various households.....	100
4.2.4.2	Scenario for modelling the various household appliances.....	101
4.2.5	Scenario for Modelling Mutual Influence.....	103
4.3	MODELLING COLLABORATIVE ROLES/ BEHAVIOURS OF THE CEE MANAGER.....	104
4.4	MODELLING COLLABORATIVE ROLES/ BEHAVIOURS OF CHDTs.....	109
4.4.1	The Integrated Model of the CHDT.....	109
4.4.2	Modelling the Sharing of Common Resources	115
4.5	LIMITATION OF THE SIMULATION MODEL.....	119
5	VALIDATION	121
5.1	VALIDATION THROUGH SIMULATION OUTCOMES.....	121
5.1.1	Scenario 1: Exploring the Relationship Between Delegation, Acceptance or Decline to an Invitation, and VO Formation	122
5.1.2	Scenario 2: Exploring the Notions of Value System and Delegated Autonomy 124	
5.1.3	Scenario 3: How Value Systems Affect Sustainable Energy Consumption in the Ecosystem	128
5.1.4	Scenario 4: Exploring Mutual Influence and Collective Decision Making of CHDTs.....	132
5.1.4.1	Scenarios 4A: Modelling Collective Decision-making by CHDTs	132
5.1.4.2	Scenario 4B: Using “mutual influence” to influence the decisions of CHDTs towards sustainable energy consumption.....	135
5.1.5	Scenario 5: Exploring Resources Sharing.....	137

5.1.5.1	Scenario 5A: Enabling and Disabling Resource Sharing	137
5.1.5.2	Scenario 5B: Demonstrating Level 1 and Level 2 Resource Sharing	141
5.2	VALIDATION BY POTENTIAL USERS AND INTEREST GROUPS	143
5.2.1	The Potential User Group.....	143
5.2.2	The Professional Interest Group 1.....	144
5.2.3	The professional Interest Group 2.....	145
5.2.4	The Validation Processes.....	146
5.2.4.1	The Unified Theory of Acceptance and use of Technology Model.....	147
5.2.4.2	Measuring the Validation Constructs and Dimensions.....	149
5.3	VALIDATION BY THE RESEARCH COMMUNITY.....	151
5.4	LIMITATIONS OF THE VALIDATION PROCESS.....	157
5.5	LIMITATIONS OF THE CEE AND CHDT MODELS	157
5.6	ADDRESSING ETHICAL CONCERNS RELATING TO THE CEE CONCEPT	158
5.7	ADDRESSING SOME POTENTIAL CONFLICTS IN RECS	158
6	CONCLUSIONS AND FUTURE WORK	167
6.1	OVERVIEW OF THE WORK	167
6.2	NOVEL CONTRIBUTIONS	168
6.3	FUTURE WORK.....	170
6.3.1	Real World Implementations:.....	170
6.3.2	Exploration of Other Collaborative Behaviours	170
	BIBLIOGRAPHY	173
	APPENDIX 1	193
	APPENDIX 2	197
	APPENDIX 3	198

List of Figures

Figure 1.1 – The DSR steps.....	7
Figure 2.1 – Collaborative Network Taxonomy	14
Figure 2.2 – CEE as a VBE, forming VOs 1, 2 and 3 to take advantage of grid opportunity 1, 2 and 3	19
Figure 2.3 – The flow of the systematic literature review process.....	21
Figure 2.4 – A REC is focused on common goals, citizen driven, voluntary participation, community centred and energy democracy.....	63
Figure 2.5 – A VPP is focused on aggregation, automation, energy management system scheduling and dispatch of energy and finally optimization of the system.....	63
Figure 3.1 – The three concepts that are integrated to form the Collaborative Energy Ecosystem.....	70
Figure 3.2 – A high level view of the Collaborative Energy Ecosystem.....	72
Figure 3.3 – The scope of the study.....	74
Figure 3.4 – External coordination between the CEE VBE manager and external entities.....	78
Figure 3.5 – The CEE manager coordination with CHDTs in the ecosystem.....	78
Figure 3.6 – Opportunity seeking process of the CEE manager.....	81
Figure 3.7 – Formulation of goals 1 and 2 and sending invitation for goals 1 and 2.....	82
Figure 3.8 – The VO formation and planning process.....	83
Figure 3.9 – The logical structure of the CHDT.....	84
Figure 3.10 – Examples of value systems in the context of the CEE.....	86
Figure 3.11 – A simple interface to illustrate how “deferrable loads” can be delegated in the CEE.....	87
Figure 3.12 – How IoT sensors/actuators are connected between appliances and their CHDTs.....	88
Figure 3.13 A BPMN representation of the decision-making process of a CHDT.....	89
Figure 3.14 – Process of information exchange towards the formation of a coalition - joining a VO.....	92
Figure 3.15 – The process of resource sharing.....	94
Figure 3.16 – The process of sharing a common resource.....	95
Figure 4.1 – Example of stock and flow diagram representing generation and storage.....	102
Figure 4. 1 – Example of a stock and flow diagram of consumption.....	102
Figure 4. 2 – Illustration of the integrated model of the CEE Manager.....	105
Figure 4.4 – All three preconditions for community Goals-1 and 2 are satisfied. Both community goals are formulated and pursued concurrently	106
Figure 4.5 – All three preconditions for community Goal 2 are satisfied. Only two preconditions for community goal 1 are satisfied. Goal 2 will be formulated but Goal 1 will not.	106
Figure 4.6 – Goal formulation component illustrating the formation of Goals 1 & 2.....	107
Figure 4.7 – A discrete event component that is used to broadcast invitations of goals 1 & 2 to the community.	107
Figure 4.8 – VO formation, dissolution, and statistical analysis component	109
Figure 4.9 – The integrated model of the CHDT	110
Figure 4.10 – A replica of the community goal that is replicated inside CHDT number 36	1100
Figure 4.11 – Example of no prevailing value system. Both value systems are dormant for CHDT 61	111
Figure 4.12 – Example of one active/prevaling value system (VSG1) for CHDT 87	111
Figure 4.13 – Example of two active/prevaling value system (VSG1 and VSG2) for CHDT 30.....	112
Figure 4.14 – A delegated CHDT (CHDT 90).....	112
Figure 4.15 – The decision component shows the “decline” of Goals-1 and 2 based on un-delegation for CHDT number 61	113
Figure 4. 16 – The decision component shows the “decline” of Goal 1 based on non-compatibility and acceptance of Goal 2 for CHDT number 62	113

Figure 4. 17—The decision component shows the acceptance of Goals 1 and 2 for CHDT number 91	114
Figure 4.18 —Implementing delegated autonomy.	115
Figure 4.19 — A model of the four embedded PV systems with the integrated local energy storage system	116
Figure 4.20—Codes that facilitate the sharing of surplus energy from the photovoltaic source with the community storage.....	117
Figure 4.21 —The community storage System	117
Figure 4.22 —Codes for sharing excess energy from the community (Charging the community storage)	118
Figure 4.23—Codes for sharing energy from community storage with the community (Discharging community storage)	119
Figure 5.1—Relationship Between Delegation, Acceptance/Decline to an Invitation, and VO Formation.....	123
Figure 5.2 —Case 1: A VO formed with 100% of CHDTs in the population with 100% full delegated autonomy.....	125
Figure 5.3—Case 2: A VO formed with 10% of CHDTs in the population, with 10% full delegated autonomy.....	126
Figure 5.4 —Case 3: A VO formed with 90% of the population, with 90% full delegated autonomy.	126
Figure 5.5 —Case 4: High population of delegated CHDTs (90%), Low population of undelegated CHDTs (10%), partial delegation, double appliances	127
Figure 5.6 —Case 5: High population of delegated CHDTs (90%) Low population of undelegated CHDTs (10%), Partial delegation, single appliance	127
Figure 5.7 —Case 1a: results for 10% prosumers, 90% consumers. 10% of the total population having full delegated autonomy.	129
Figure 5.8 —Case 1b: results for 10% prosumers, 90% consumers, with 90% of the total population having the full delegated autonomy.	130
Figure 5.9—Case 1c: results for 10% prosumers and 90% consumers, with 100% of the total population having DDL autonomy.....	130
Figure 5.10—Case 1d: results for 10% prosumers and 90% consumers with no DDL authority	131
Figure 5.11—Case 2a: results for a population of 10% Consumers, 90% prosumers, and 90% of the population with delegated autonomy	131
Figure 5.12—Case 2b: results for a population of 10% Consumers, 90% prosumers, 10% of the population with delegated autonomy.....	132
Figure 5.13 —Influences received by CHDT 1.	133
Figure 5.14 —Influences received by CHDT 2	134
Figure 5.15—Behaviour of CHDT number 3. Initially influenced negatively, but the influence changed to become positive influence and the CHDT was able to make a decision.	134
Figure 5.16 — Behaviour of CHDT number 4. Initially influenced negatively, but the influence changed to become positive influence, however, the CHDT was unable to make a decision.....	134
Figure 5.17 — Behaviour of CHDT number 5. Initially influenced negatively, but the influence changed to become positive influence, however, the CHDT was unable to make a decision.....	135
Figure 5.18— Behaviour of CHDT number 6. This CHDT was initially influenced positively, and maintained the positive influence until it was able to make a decision.....	135
Figure 5.19 —Case-1a. 90% positive influencers and 10% negative influencers.....	136
Figure 5.20—Case-1b. 10% positive influencers and 90% negative influencers.....	136
Figure 5.21—Case-2a. A high population of positive influencers (90%) despite a high consumer population (80%).	137
Figure 5.22—Case-2b. A high population of negative influencers (90%) despite a high prosumer population (80%)	137

Figure 5.23—Case 1a: results for 90% of prosumers and 10% of consumers with “sharing disabled.”	139
Figure 5.24—Case 1b: results for 90% prosumers and 10% consumers with “sharing enabled.”	139
Figure 5.25—Case 2a: results for 50% consumers 50% prosumers with “sharing disabled.”	140
Figure 5.26—Case 2b: results for 50% consumers 50% prosumers with “sharing enabled.”	140
Figure 5.27—Case 3a: results for 10% of prosumers and 90% of consumers “sharing disabled.”	140
Figure 5.28—Results for 10% of prosumers and 90% of consumers with “sharing enabled.”	141
Figure 5.29—Potential user group validating event.	144
Figure 5.30—Professional interest group 1	145
Figure 5.31—Professional user group 2	146
Figure 5.32—The Unified Theory of Acceptance and Use of Technology (UTAUT) model. Adopted from (Venkatesh et al., 2003).	148
Figure 5.33—Performance expectancy.	150
Figure 5.34—Effort expectancy.	150
Figure 5.35—Social influence.	150
Figure 5.36—Facilitating conditions.	150
Figure 5.37—Use intension.	151
Figure 5.38—Goal alignment.	151
Figure 5.39—Delegation.	151
Figure 5.40—Collaboration.	151
Figure 6.1 — The main contributions of this work.	169

List of Tables

<i>Table 2. 1—Terms used in the articles search and selection process.....</i>	<i>23</i>
<i>Table 2. 2. Technological enablers and areas of application within the VPP concepts.....</i>	<i>31</i>
<i>Table 2. 3 VPP participation in the energy market.....</i>	<i>33</i>
<i>Table 2. 4 A combination of keywords that were used to search for the articles.....</i>	<i>38</i>
<i>Table 2. 5—Keywords that were used to search for cases</i>	<i>43</i>
<i>Table 2. 6—A summary of the selected cases for the study.....</i>	<i>44</i>
<i>Table 2. 7—A summary and case comparison</i>	<i>47</i>
<i>Table 2.8—Analysis of cases to identify the features of Collaboration or Cooperation (RQ-1).....</i>	<i>49</i>
<i>Table 2.9—Summary of technological enablers for energy ecosystems</i>	<i>58</i>
<i>Table 2.10—The outcome of PT2 Sub research question 7.....</i>	<i>61</i>
<i>Table 5.1—Scenario for exploring the relationship between delegation, acceptance of an invitation, and VO formation.....</i>	<i>123</i>
<i>Table 5.2—Results of scenario 1, acceptance to initiation for goals 1 and 2, and VO formation.....</i>	<i>123</i>
<i>Table 5.3—Results of scenario 1, decline of invitation to goals 1 and 2.....</i>	<i>124</i>
<i>Table 5.4—Scenarios for testing delegated autonomy, degree of delegation, and VO size.....</i>	<i>124</i>
<i>Table 5.5—Energy consumption priority list for prosumers and consumers.....</i>	<i>128</i>
<i>Table 5.6—Delegation of deferrable loads.....</i>	<i>129</i>
<i>Table 5.7—Two cases with varying population sizes are used to test collective decision-making.....</i>	<i>133</i>
<i>Table 5.8—Different ratios of prosumer and consumer population with corresponding delegated autonomy.....</i>	<i>138</i>
<i>Table 5.9—Results of scenario 4b demonstrating level 1 and 2 sharing.....</i>	<i>142</i>
<i>Table 5.10— Definition of the various constructs and their related dimensions.....</i>	<i>146</i>
<i>Table 5.11—Conclusion drawn from the data which was collected from the respondent.....</i>	<i>149</i>
<i>Table 5.12— List of publications related to CEE.....</i>	<i>152</i>
<i>Table 5.13—Publications and their related contributions to the thesis.....</i>	<i>153</i>

Acronyms

APR	Appliance Power Rating
CEE	Collaborative Energy Ecosystem
CHDT	Cognitive Household Digital Twin
CI	Cognitive Intelligence
CN	Collaborative Network
CPS	Cyber-Physical System
DA	Delegated Autonomy
DER	Distributed Energy Resource
DoU	Duration of Use
DSR	Design Science Research
DT	Digital Twin
EE	Effort Expectancy
FC	Facilitating Conditions
FoU	Frequency of Use
GA	Goal Alignment
IDT	Intelligent Digital Twin
GhG	Green House Gases
RE	Renewable Energy
REC	Renewable Energy Community
SDG	Sustainable Development Goal
PE	Performance Expectancy
PT	Physical Twin
PV	Photovoltaic
UI	Use Intention
VBE	Virtual Breeding Environment
VO	Virtual Organization
VPP	Virtual Power Plant
VS	Value System

INTRODUCTION

This section provides background information about the topic of the thesis and further outlines the major trends that motivated this work. The research questions that guided the research work and the related hypotheses are introduced. The adopted research method is also presented in the section. The aimed contribution of the thesis as well as a detailed workplan are presented. The alignment of this work with the sustainable development goals of the United Nations is also highlighted at the end of the section.

1.1 Background

Electrical energy is crucial nowadays, and without it, contemporary societies cannot function adequately. This claim stems from the fact that critical sectors of modern society, which include industries, housing, communication, transportation infrastructure, education, health, and the financial sectors, depend largely on electrical energy. However, unlike past societies, the modern society has heavily been dependent on fossil fuels energy sources. As stated in “our world in data” (Ritchie et al., 2020), fossil fuels have been the fundamental driver or enabler of the technological, social, economic and developmental progress of the current Industrial Revolution. In (Rapier, 2020), Forbes claims that fossil fuels still account for 84% of global energy use, although this conventional energy source is known for its limited availability (Martins et al., 2019) and adverse impact on the environment (Guo et al., 2022), human health (Kotcher et al., 2019), and economic activities (Neves & Marques, 2021). Moreover, the literature suggests that severe exploitation of the Earth's resources to satisfy society's growing demands for energy is troubling (United Nations, 2023), and has contributed to the ongoing climate change catastrophe (Intergovernmental Panel on climate change, 2023), which poses a ruinous risk to the sustainability of the planet (Lee et al., 2021). Due to the many environmental concerns that are associated with fossil fuels, the need for safer, greener and more sustainable energy sources is imminent (IRENA, 2021).

Currently, researchers and policymakers have realized the potential benefits of transitioning from fossil fuel sources to renewable sources (Nathaniel et al., 2020). This is because, unlike fossil fuels, renewable energy is known to be inexhaustible (Nyasapoh et al., 2022) and can replenish itself in a relatively short period, thus helping to overcome the finite-supply problem associated with fossil fuels. In addition, renewable energy sources are cleaner, self-replenishing, environmentally friendly, and less harmful to human existence on planet Earth.

Regarding the transition from fossil fuels to renewable sources, the word economic forum in (Astarloa et al., 2017) asserted that the future of energy would be cleaner, mobile, intelligent, and smarter as it would be dominated by renewable sources. Evidence of this claim is becoming visible in the form of novel and widespread renewable energy-related technologies and services that are currently emerging at the peripheries of the power grid. The expectation is that these advances could be the technological drivers or enablers of the transition agenda, which aims to transform the current power grid towards a "digitized," "decentralized," "decarbonized," "democratized" and "smart" power network (Harrison et al., 2018). The projections of the ongoing energy transition initiatives are also affirmed by other researchers, such as (Danish & Senjyu, 2023), (Camarinha-Matos, 2016), and (Farhangi, 2010), regarding the future of energy. Some of the advances pointed out in the literature include (a) widespread integration of distributed generation (Nadeem et al., 2023), (b) peer-to-peer energy trading (Das et al., 2023), (c) renewable energy communities (Adu-Kankam & Camarinha-Matos, 2022), and many more. Besides these ones, several cutting-edge, innovative, and complementary technologies, such as (i) artificial intelligence, (ii) cloud computing, (iii) the internet of things, (iv) cyber-physical systems, (v) blockchain, and (vi) digital twins are also emerging within the energy domain. The integration of these diverse, innovative and complementary technologies into the renewable energy landscape is paving the way for new types of organizations, relationships, partnerships, business models, and services that are beginning to show within the energy space (Adu-Kankam & Camarinha-Matos, 2018), (Camarinha-Matos et al., 2017), (Camarinha-Matos, 2016). Other aspects of the transition, as mentioned by Gartner in (Harrison et al., 2018), involve new roles that are played by autonomous actors, such as asset owners, system operators, and other economic entities, who have also evolved to become active participants and key players in the transition.

Among the plethora of approaches that have been suggested to help increase the penetration of renewable energy sources in support of the transition is the notion of Renewable Energy Communities (RECs) or energy exchange/sharing ecosystems. A summary of these ecosystems is presented in a survey conducted by (Adu-Kankam & Camarinha-Matos, 2018). These ecosystems are gradually becoming an integral part of the grid system due to their potential benefits (Karunathilake et al., 2019). According to the European Parliament and the Council of the European Union (The European Union, 2018) a REC is constituted of a group of citizens and stakeholders who are motivated by a common objective or goal, such as creating and sharing renewable energy locally, cost-effective green energy management, the control of energy waste, helping to increased citizen participation in renewable energy projects (Algarvio, 2021), decongest the power grid, decrease the contribution of greenhouse gas emissions (Barbiroglio, 2022), and address energy injustice by empowering citizens and communities in the ongoing transition.

According to the European Parliament and the Council of the European Union (European Parliament, 2018), REC membership is supposed to be open and voluntary. RECs are supposed to be autonomous and governed by their owners or stakeholders. One key attribute of RECs is that members can produce their own energy, which can be used locally, stored, sold, or shared with others in the community. According to the European Commission

(European Commission, 2021), in 2021 at least 2 million people in the European Union were involved in more than 7700 RECs. By this time, these RECs have contributed nearly 7% of the Union's installed capacity, with an estimated total renewable capacity of no less than 6.3 GW. In terms of financial investment, some 2.6 billion euros have been invested in RECs until 2021. Similarly, in the United Kingdom, there have been over 5000 RECs until 2015 (Gov.uk, 2015). In terms of financial investment, a total of 105 million pounds has been invested so far. This investment is comprised of 10 million pounds as the rural community energy fund, 15 million as the urban community energy fund, and 80 million as the green deal community scheme. As a result, it was expected that RECs involving local communities in the UK could supply enough electricity for 1 million homes.

This notwithstanding the number, types, composition, and characteristics of members who are found to participate in these REC ecosystems have changed in recent years. Membership to these RECs is currently found to be constituted of several, diverse, autonomous and heterogeneous entities that can participate in the exchange of energy-related goods and services either "for-profit" or "non-profit" within this energy landscape. Usually, these members are driven by a common interest or some objective that is compatible or common to all the involved members. Membership to these RECs may constitute (a) prosumer and consumer households, (b) research and academic institutions, (c) public authorities, (d) financial institutions, (e) distribution service operators, (f) social entrepreneurs, (g) various energy service providers, etc. According to (Platt et al., 2014), when all of these autonomous and heterogeneous entities work together in the context of a community, they could help uncover new ways to generate value, such as earning revenue that could help participants mitigate the rising cost of energy in these ecosystems, as well as promote investment in renewable energy. Hence, this idea of "communalization," or developing communities around energy infrastructure, could be a useful approach to facilitating the transition agenda in several ways. These may include: encouraging flexible participation and empowerment of citizens and communities in the ongoing transition (Interreg Europe, 2022), delivering energy justice (Hanke et al., 2021), enabling efficient use of energy, increasing the penetration of renewable sources (Pontes Luz & Amaro e Silva, 2021), decongesting the power grid (Algarvio, 2021), decentralizing energy generation, and enhancing the reliability and resilience of the power grid.

1.2 Problem Introduction

The current power grid, particularly the grid infrastructure in regions such as the United States or the European Union, is over a century old because it was built during the first industrial revolution (Lo & Ansari, 2012). As a result of aging, there is a growing concern about its sustainability, resilience, and reliability, due to the dominance of legacy systems (Lo & Ansari, 2012). Therefore, a major upgrade to the grid is needed to reliably incorporate new technologies as well as governance structures such as digitalization and intelligence into the grid system (Bose & Overbye, 2021).

Furthermore, the introduction of Renewable Energy Communities (RECs) into the grid ecosystem is one of the many pathways that have been suggested by experts as a sustainable

approach. RECs have the potential to increase the penetration of renewable sources in the power grid, help reduce the heavy dependence on fossil fuels sources and increase citizens participation in renewable energy projects. However, it is suggested that by forming communities around the energy infrastructure (communalization of energy), it may be possible to introduce another layer of complexity to the grid infrastructure which is already in distress. The reasons are that first, each REC is likely to have a different set of objectives, different kinds of energy resources, different resource ownership, different governance system, and different geographic location. Second, each constituent actor may be autonomous and may therefore have the right to take autonomous decisions. Besides their autonomy, the involved actors may also have heterogeneous characteristics that could make them also behave differently. These issues suggest that organizing and managing RECs could be problematic, and therefore, a flexible and yet effective approach is urgently needed to manage the diversity of community attributes.

Nonetheless, a community can be said to be a social unit or socio-cultural system (Axon, 2020) that share some characteristics, such as common interests (Louisiana Community Network, 2004), common norms (UNICEF, 2021), common belief systems (Usó-Doménech & Nescolarde-Selva, 2016), common value systems (Nowack & Schoderer, 2020), shared resources (Harbo et al., 2016), common identity as well as shared risks, among other things (Cobigo et al., 2016). These community attributes play a very essential role in the community's dynamics such as its membership fluidity and degree of cohesion (Nowack & Schoderer, 2020). Membership fluidity refers to the turnover of members in a given time (Park & Shin, 2015) and level of cohesion is a measure of the social relationships within a community. These are key attributes or determinants that affect the stability and survivability of a community. However, a measure of the degree of commitment and contribution of each actor to these community attributes could vary from one member to another. This is because the involved members may have different levels of interest, diverse needs, varying preferences, different priorities, different levels of expectations, and a different spectrum of objectives to either contribute to or receive from the community. These community dynamics further emphasize the claim that a "one size fits all" kind of approach may fall short in managing these complexities. Therefore, it is foreseen that the communization of energy could further exacerbate or aggravate the complexity of an already stressed energy ecosystem due to the diversity and dynamic nature of the elements that characterise a community's stability.

Additionally, one key aspect of RECs as described by the Union (The European Union, 2018) is that they are supposed to enhance citizens' "participation" in renewable energy endeavours. Participation in this context can take several forms. For example, participation in decision-making or participation in pro-sustainable energy consumption and/or generation activities. The limitation is that most works in this area focus on the development of systems that are mostly in line with home automation, which provides limited room for users to flexibly make input based on their preferences, which oftentimes are dynamic. These systems are often invasive, inflexible, and imposing. Hence, the literature reports that they usually have a slow rate of diffusion (Gross et al., 2020). Therefore, they could potentially limit user participation instead of enhancing it, particularly in the current situation where

each member is different and has different needs, preferences, priorities, and expectations. In the case of RECs, users would like to participate in all endeavours in a flexible way without having to compromise their needs. The need for a solution that enhances the flexible participation of members in RECs is therefore imminent.

Given that:

1. The current power grid is dominated by legacy systems;
2. The need for grid transformation, requiring digitalization and intelligence;
3. The stochastic attributes of the grid due to the increasing integration of renewable energy sources;
4. The communization of energy, resulting in the diversity of members with different measures of interest and commitment to community goals;
5. The need for a solution or approach that enhances flexible participation from each member of the REC.

It can be argued that such a problem cannot be addressed using knowledge and concepts from a single discipline. This is because the problem is multifaceted and has several dimensions, namely the social dimension, the management dimension, the behavioural dimension, and the technological dimension. Therefore, it can be averred that a novel approach that is also multifaceted in nature and incorporates a multi-disciplinary and interdisciplinary dimension may be a plausible approach to consider, as far as the effective organization, stability, survivability, and resilience of these emerging energy ecosystems are concerned.

On these grounds, contributions are sought from different scientific domains to help address different aspects of the problem in a common environment. In this regard, this thesis proposes a solution that borrows and merges knowledge, concepts, and mechanisms from four key knowledge areas. These are (a) the domain of collaborative networks to address aspects of flexible contribution, diversity, and sustainable participation of members; (b) the domain of virtual power plants to address the organizational aspect of the community and energy aggregation aspect; (c) the domain of renewable energy communities to address the environmental suitability aspects; and finally (d) the domain of digital twin technology to address the intelligent and digitalization aspects.

In the context of this work, the primary actors of the considered RECs are mainly limited to prosumer and consumer households. This is because according to (Aversa et al., 2016) buildings utilize nearly 40% of global energy, 25% of global water, 40% of global resources, and contribute nearly 72% of global greenhouse gas (GHG) emissions (Hertwich & Peters, 2009). From the perspective of the European Commission, buildings are responsible for approximately 40% of the EU's energy consumption and 36% of CO₂ emissions in Europe (European Commission, 2019). Consequently, buildings have been declared the single largest energy consumer in Europe. These empirical data reveal the significant role that buildings play towards global emissions, resource utilization, and energy demand. Other studies have also reiterated that due to population and economic growth (Pasten & Santamarina, 2012), urbanization and industrialization (Rehman et al., 2022), and technological advances (Jin et al., 2018), energy demand in contemporary societies has increased substantially. This

increase results from the need to meet the energy needs of people who live in these households.

Again, until recently, the integration of Photovoltaic (PV) sources from households into the traditional grid system was negligible (Alam et al., 2020). However, several changing factors such as declining prices of solar panels (Feldman et al., 2021), favourable public opinion towards the energy transition (Thomas et al., 2022), coupled with sound governmental policies (Dobracev et al., 2021), are changing the narrative. For instance, currently in Europe, the number of households with installed PV systems is rising steadily (IRENA, 2019). Concurrently, battery storage technology is also maturing rapidly (Figgenger et al., 2021). This opens the opportunity for individual dwellings as well as communities to incorporate energy storage into their PV systems. A Community Energy Storage System (Gähns & Knoefel, 2020) is an energy storage technology that enables energy sharing between members of a community.

In a nutshell, the Paris Agreement (United Nations, 2016) and other initiatives (Delbeke & Vis, 2019) have acknowledged the magnitude of the sustainability problem, particularly the role of households, and have shown that there is the urgent need to adopt pragmatic measures towards the mitigation of the problem by all stakeholders, most importantly, by the households, which are a major cause of the problem.

1.3 Research Question and Hypothesis

Considering the enumerated challenges that currently confront the power grid, the following research question and hypotheses are therefore adopted for this research:

Research Question

How can the application of collaborative networks principles and mechanisms enhance the response of renewable energy communities (RECs)?

In this context, we focus on response to demand and supply dynamics using collaborative energy consumption behaviours, and response to challenges in stakeholders' satisfaction and flexible participation in RECs.

Hypothesis

The performance of RECs can be enhanced if collaborative network principles and mechanisms are integrated into its organization and operations, using the necessary soft modelling characteristics, to structure and operate RECs, thereby being capable of providing a more agile and flexible response to demand and supply dynamics, while ensuring

compliance to governance and organizational principles, and also improving stakeholders' satisfaction and flexible participation in RECs.

1.4 Research Method

The methodological approach taken in this work follows the Design Science Research (DSR) method illustrated in Figure 1.1. According to (Johannesson & Perjons, 2014), DSR is described as *“the scientific study and creation of artifacts as they are developed and used by people with the goal of solving practical problems of general interest.”* These authors also suggest that empirical research usually describes, explains, and predicts the world. For instance, Newton’s laws expound on the motion of planets, the trajectories of missiles, and help explain the tides. Similarly, meteorology predicts rainfall, storms, and other weather phenomena. However, Johannesson and Perjons claimed that DSR is not limited to just describing, explaining, and predicting. Rather, it seeks to change the world or improve it through the creation of new worlds in the form of artifacts that can help researchers fulfil the identified needs, overcome the problems, and grasp new opportunities. Thus, DSR not only creates novel artifacts but also knowledge about the artifacts, their uses, and their environments.

In an effort to solve engineering problems, the use of DSR becomes a relevant approach, because, according to (Vaishnavi & Kuechler, 2007), DSR is considered suitable for solving ICT-related problems like the one being addressed in this thesis. The reason is that human-computer information-producing and processing systems are, by their nature, complex and grounded in multiple disciplines. Hence, exploring with the DSR method excels in the outcome (Peffer et al., 2007). By adopting DSR, a prototype model of the real world can be created and used to experiment with or study the real world, as such systems are difficult or sometimes impracticable to conduct experiments on due to the cost, complexity, disruptions, and time involved.

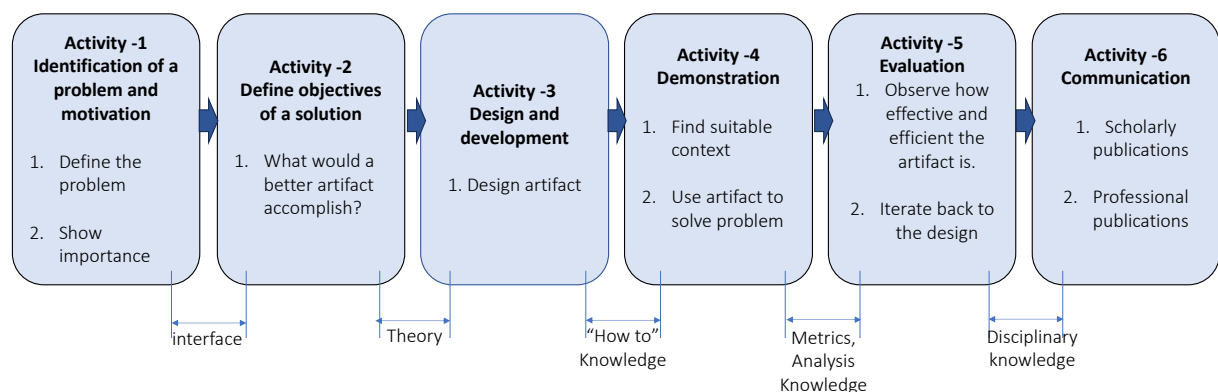


Figure 1 1—The DSR steps adopted from (Peffer et al., 2007)

In relation to this thesis, the following stages of the DSR are adopted:

1. **Problem identification stage (activity 1)** – This step involves the identification of the research problem(s) and justifying the value of a potential solution(s). As discussed in

Sections 1.2 and 1.3, this work faces some main challenges, such as the complexity of the subject matter and the unstructured, inconsistent, and incoherent information sources in the literature concerning the various aspects of RECs. Therefore, this step contributes to identifying: (a) the main stakeholders, organizations, and characteristics of RECs; (b) the behavioural attributes of RECs; (c) the operational and management behaviours/processes that can be enhanced through collaborations; and (d) the appropriate collaborative principles and mechanisms from the domain of CNs that can be applied to RECs to enhance flexible operation, management, and behavioural processes. These steps are shown in Chapters 1 and 2 of the thesis.

2. **Definition of the objectives for a solution (activity 2)** - The goals of a solution may be deduced once the problem has been identified and a description of what is doable and conceivable has also been provided. As discussed in the approach and contribution section, this work attempts to highlight the significance of supporting the implementation, operation, and management of RECs using collaborative techniques. For a better understanding and synthesis of the existing research, debates, and ideas around this body of knowledge, we conducted a literature review on two key knowledge areas that are central to this work. The review involved (a) identifying points of convergence between the domain of collaborative networks and virtual power plants and (b) identifying points of convergence between the domain of collaborative networks and renewable energy communities. These reviews helped us provide a foundation of general and specialized knowledge on the topic. These steps are reflected in Chapter 2.
3. **Design and development (activity 3)** - During the design and development phases, an artifact is created. In the context of this work, the created artifact is a model of a REC that can be used to solve the problems that have already been identified. To help address the identified problems and the related research questions, we propose two complementary concepts, namely the collaborative energy ecosystem (CEE) and cognitive household digital twins (CHDTs). These concepts are discussed in detail in Chapter 3. The framework for the proposed concepts emanated from the background knowledge and experiences in combination with some relevant solutions reported in the literature and summarized in Chapter 2.
4. **Demonstration and Evaluation (activities 4 and 5)** - During the demonstration and evaluation phases, DSR suggests that the artifact is utilized and tested to assist in the resolution of one or more facets of the problem. This may entail using the artifact in an experiment, simulation, case study, proof, or any other activity that is relevant. In the context of this work, the artifact is first demonstrated using different simulation scenarios and cases. Furthermore, the artifact is evaluated through a validation process that allowed experts from different domains (focus group) particularly from the area of energy to assess the model and subsequently offer their opinions concerning the acceptability, capability, and effectiveness of the artifact. These activities and results are presented in Chapters 4 and 5.
5. **Communication (activity 6)**- Finally, the inputs and outputs of this work are shared with others through some publications. The outcome of the work is shared within three different research communities. These included (a) the collaborative networks

community, (b) the energy community, and (c) the community of cyber-physical systems. Details of the published papers are presented in Chapter 5.

1.5 Approach and Contributions

This thesis is approached from a collaboration point of view. The notion of collaboration is suggested as one of the community values by which resources such as energy are flexibly managed. Collaboration is a process by which entities share information, resources, and responsibilities to jointly plan, implement, and evaluate a program of activities aimed at achieving some specific goals. It can be viewed as a process of shared creation, in which a group of entities improve each other's capabilities. It implies sharing risks, resources, responsibilities, and rewards, which can also give an outside observer the image of a collective identity if desired by the group. Collaboration involves the mutual engagement of participants in solving a problem together, which implies mutual trust and therefore requires time, effort, and dedication.

Furthermore, we propose the complementary notions of Collaborative Energy Ecosystem (CEE) and Cognitive Household Digital Twins (CHDTs). The CEE idea results from merging collaborative concepts, principles, and mechanisms from the domain of Collaborative Networks (CNs) and the area of Virtual Power Plants (VPP). This synergy results in the representation of the REC in a virtual form, having its members adopt collaborative principles and mechanisms in its operations to ensure flexible and sustainable energy consumption/ exchanges, while also exhibiting characteristics of a VPP, such as having the capability to reduce dependence on the grid during peak periods or aggregate surplus energy from the community and export or sell it to the grid when needed.

Digital twin concepts are adopted in the virtualization of the physical community and the involved households. As such, the digital twin of the involved households is called "Cognitive Household Digital Twins (CHDTs)." CHDTs are designed to interact with each other within the CEE environment. They are suggested to be endowed with cognitive intelligence, thereby having the capability to make rational and autonomous decisions based on some input received from their physical household. These inputs may correspond to the value system of the physical household. Based on that input, they can make some basic, autonomous, and rational energy use decisions on behalf of the household owner. In the context of CNs the proposed CEE and CHDTs can be organized to function like a virtual organization breeding environment (VBE) where members are always ready in preparedness for an opportunity to collaborate and achieve some common goals.

We also introduce the notion of a household's "value system" to help address the aspect of flexible participation in community goals or opportunities. The values system of a household is used to represent the values of the that household in terms of levels of interest, needs, preferences, priorities, expectations, and objectives. A household's contribution to community goals will predominantly be based on its value system. The value system is thus the basis to enable households to flexibly contribute to community goals without having to compromise their needs, expectations, or quality of service.

Additionally, we introduce the notions of “delegation” and “delegated autonomy.” Delegation, in this sense, represents the permissions that a household owner can give to its CHDT. When a CHDT is delegated, it means it has the permission of the household owner to participate in community endeavours or goals on his/her behalf. In this case, the CHDT can make some basic and rational decisions on behalf of the household. On the contrary, an undelegated CHDT is not permitted to participate in community endeavours and cannot make decisions for the household. The level of permission granted to a CHDT is determined by its “delegated autonomy:” Delegated autonomy is the specific instruction that is given to a CHDT by the physical household (owner) regarding the degree of delegation and thus, how and when its value system should be implemented or carried out. Under the concept of delegated autonomy, and for illustration purposes, we consider three appliances whose use can be deferred to a later time without affecting the quality of service the appliance provides to the user. The considered appliances include (a) washing machine, (b) dishwasher, and (c) tumble dryer. The concepts of delegation, delegated autonomy, and value systems are discussed in detail in Chapter 3.

1.6 Alignment with the Sustainable Development Goals

In September of 2015, countries across the world came together to embrace a series of goals called the Sustainable Development Goals (United Nations, 2022). As a result of their acceptance, environmental degradation, sustainability, climate change, and water security are now receiving significant attention on a global scale. These goals aim to eliminate poverty, safeguard the environment, and promote prosperity and a more sustainable future for all.

Due to the relevance of the SDGs, it is important to mention that the principal objective of this study is aligned with the 7th goal of the SDG. Despite the fact that energy is the engine of civilization, access to sufficient and affordable sources is not yet distributed equitably around the globe (Cuenca et al., 2023). Its presence is tied to economic and social development and as a result, poorer nations have the weakest energy services, resulting in hunger, poor living conditions, and limited access to education and employment.

According to the European Union, energy poverty is defined as a condition commonly understood as the inability of a household to secure socially and materially-necessitated levels of energy in the home (Committee on Industry Research and Energy (ITRE), 2017). Another quote by the EU is “household's lack of access to essential energy services that underpin a decent standard of living and health, including adequate warmth, cooling, lighting, and energy to power appliances, in the relevant national context, existing social policy and other relevant policies” (Widuto, 2022). In a general sense, Energy poverty is any circumstances that results in the lack of appropriate, cheap, dependable, quality, safe, and environmentally responsible energy services to promote growth.

Again, the current rise in energy prices have been a major factor affecting the lives of many people worldwide. They have also threatened the efforts to address climate change, which is a critical global challenge. In 2022, the situation in Europe became worse due to the disruption of natural gas supplies from Russia. Due to the Russia-Ukraine conflict, the price

of energy in the EU reached record levels in 2022 (European Council of the European Union, 2023). This energy crunch has affected not only the European population but also small business owners, farmers, and big corporations (energy companies) who require a lot of energy to get up and running. Payment of electricity bills has been a burden for most households in Europe (Bloomberg, 2022). In response to the energy crisis, many countries have started implementing voluntary measures to reduce their power consumption. The European Union also discussed the possibility of implementing measures such as caps on the prices of electricity and mandatory limits on power usage.

It is in line with these escalating energy crises that this research becomes relevant to the contemporary context. This work has the potential to contribute to addressing this crisis by providing capacity and flexibility for households and the general citizenry to engage and participate in renewable energy programs without having to compromise their expected quality of service. The concepts described in this thesis could also be adopted by city councils, emergency response teams, the police service, policy makers and other governmental agencies that seek to protect and contribute to the welfare of communities and the citizenry. This is also in line with SDG 11 (United Nations Development Programme, 2016) which concerns sustainable cities and communities. This SDG ensures that cities and human settlements are inclusive, safe, resilient, and sustainable.

1.7 Description of the Thesis Structure

This thesis is organized into six chapters and three supporting annexes. In the succeeding paragraphs, a brief abstract of each chapter is presented to give an overview of this work. The structure of the thesis involves:

Chapter 1: Introduction: This chapter introduces the research theme and provides the background for the thesis. The chapter involves a description of the problem and its justification. The problem description section is followed by the research questions and their accompanying hypotheses. The chapter proceeds to discuss the research method, the research contribution, the scope of the study, and finally concludes by aligning the aimed objectives of this research work with the United Nations Sustainable Development Goals.

Chapter 2: Background Literature Review: This section is organised in two main parts. The first part discusses the background concepts of the thesis which involves a brief description of the domains of collaborative networks, virtual power plants and digital twin technology. The second part is dedicated to the literature review of the thesis. The second part is also subdivided in two sections. The first section is comprised of a review of areas of convergence between virtual power plants and collaborative networks. The second section begins with a brief review of the scientific concepts underlying the notion of RECs. It is followed by a study of thirty-four emerging online renewable energy communities. Both sections conclude with a brief summary of the outcomes of the reviews.

Chapter 3: The CEE Modelling Framework. This chapter presents the architectural framework of the proposed CEE and CHDT concepts. First, the concepts and knowledge that support the CEE and CHDT notions are introduced. Then, the simulation modelling approach used in the development of both components, namely the CEE and CHDTs architectures, is presented.

Chapter 4: The CEE Simulation Modelling: This chapter presents a simulation implementation that demonstrates how the artifact/prototype models of the CEE environment is presented. Furthermore, the mechanisms through which CHDTs can engage in collaborative endeavours that result in sustainable energy consumption within the CEE environment is also shown. The chapter describes the roles of the CEE manager, and the various collaborative behaviours of CHDTs in collaborative endeavours. The notion of Virtual Organizations formation is also described in this section. The adopted simulation method is also disused.

Chapter 5: Validation: The chapter discusses the validation of the artifact/prototype and its underlying concepts. The validation process is disused in three sections. These include: (a) validation of the model through simulation outcomes for some selected scenarios, (b) validation by potential users and professional interest groups, and finally, (c) validation by the research community.

Chapter 6: Conclusion and Future Work: This chapter presents the concluding remarks on the original contributions of this research and discusses a number of outstanding issues that have been identified as research opportunities for future works.

LITERATURE REVIEW

In this section, a literature review covering two key knowledge areas is presented: (a) the domain of virtual power plants (VPP) and (b) renewable energy communities. The rationale for conducting a review in these two knowledge areas stems from the fact that the concept of collaborative energy ecosystem is a derivative of the synergy of principles and concepts from these two knowledge areas. Therefore, the review seeks to investigate the presence of CN principles and mechanisms in current developments in these areas. The first part of the review attempts to find areas of convergence between the collaborative networks discipline and the virtual power plant concepts. In this case, certain key CN attributes such as CN principles, CN organizational forms, and the kinds of technological enablers that support cooperative or collaborative mechanisms in the VPP domain are investigated. The second part covers the domain of renewable energy communities. Similar to the first part, this section investigates the presence of some CN attributes such as cooperative or collaborative relationships between members of the selected ecosystems, technological enablers and trends, and finally, how the characteristics of these communities compare to those of virtual power plants. This part of the review is preceded by a brief review of the scientific concepts, models and trends in the domain of RECs. In all the reviews conducted, the methodology adopted is the systematic literature review. This methodology is explained briefly in the succeeding paragraphs. Since collaborative networks play a key role in this work, the chapter starts with a brief overview of this area.

2.1 Brief Overview of Collaborative Networks

The literature in the domain of collaborative networks (CN) shows that its knowledge base has expanded significantly during the last 20 years (Camarinha-Matos & Afsarmanesh, 2021a). The rapid growth in this scientific domain has arisen from the numerous challenges that today's society is facing as it pursues the "digital transformation" agenda, which is expected to transition our current society to a digitalized society, namely, Society 5.0 (Camarinha-Matos et al., 2022). This agenda pursues the introduction of intelligence into all facets of technology, as well as promoting the hyperconnectivity of millions of organizations, people, and things. Additionally, the blurring of physical and virtual spaces in the context of cyber-physical systems and IoT is likely to lead to future scenarios where billions and billions

of networked actors, smart devices, intelligent systems, and ecosystems can coexist and cooperate with each other. For such a synergy to be effective, advantageous, and reliable, the participating parties must learn to work together (collaborate) in a trustful manner that brings benefits to all the involved parties. The scientific area of CN focuses on developing concepts, mechanisms, and models that can facilitate understanding and support these challenges in a collaborative environment. According to (Camarinha-Matos et al., 2009), collaboration is known to bring benefits to the involved parties, which forms the basis and motivation to pursue collaboration in a digitalized and hyperconnected society.

As claimed by (Camarinha-Matos et al., 2009), collaboration is a process by which a set of entities strengthen their mutual capabilities. The process entails the participants' mutual cooperation in jointly addressing a problem using a collective approach. Collaboration also helps to improve an organization's ability to compete with other similar organizations or groupings. Additionally, it can improve the ability of the involved entities to survive turbulent times. At their current level of development, models, mechanisms, and tools from the CN area have been proposed as promising enablers, and have subsequently been used to address challenges in various domains such as the smart grid (Camarinha-Matos, 2016), industry 4.0 (Camarinha-Matos, et al., 2017), energy 4.0 (Mourtzis et al., 2021), society 5.0 (Camarinha-Matos et al., 2022), digital twin technology (Calvo-Bascones et al., 2022), artificial intelligence (Schleiger et al., 2023), the internet of things (Adu-Kankam & Camarinha-Matos, 2022a), cyber-physical systems (Nazarenko & Camarinha-Matos, 2020), (Adu-Kankam & Camarinha-Matos, 2022b), etc. Although there are several types of CNs, some key types that are relevant to this study are discussed in the subsequent paragraphs.

Types of Collaborative Networks: Generally, there are several types of CNs. A taxonomy of CN types is shown in Figure 2.1. Some selected ones that are relevant to this thesis are briefly described in the subsequent paragraphs.

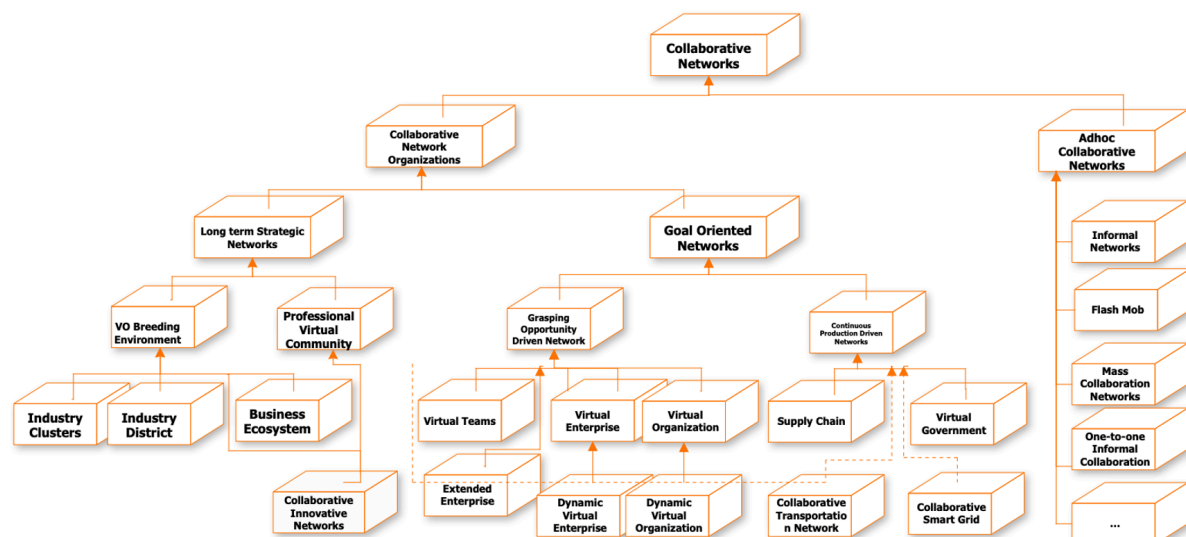


Figure 2 1—Collaborative Network Taxonomy. Adapted from (Camarinha-Matos & Afsarmanesh, 2021b)

According to (Camarinha-Matos, 2009) and (Camarinha-Matos, Afsarmanesh, 2021), a Collaborative network is defined as:

“Constituted by a variety of entities (e.g., organizations and people) that are largely autonomous, geographically distributed, and heterogeneous in terms of their: operating environment, culture, social capital, and goals. Nevertheless, these entities collaborate to better achieve common or compatible goals, and whose interactions are supported by computer networks.”

This definition presupposes that a number of pre-existing enterprises or organizations that share common goals, culture, social capital, etc. can merge virtually to form a virtual organization (VO) that acts as a single virtual entity (Camarinha-Matos & Afsarmanesh, 2005). CNs have seen significant progress in terms of conceptual frameworks, models, tools, and infrastructures for collaboration. Technically, there are two main classes of CNs. These are:

1. **Ad-hoc collaboration:** It is a spontaneous form of collaboration without a precise structure or predefined organization.
2. **A collaborative networked organization:** It is a CN involving some kind of organization that has control over the activities of its constituents. The organizational structure helps identify roles for each participant using some forms of governance rules. Collaborative networked organizations can be further divided into two subcategories:
 - a. **Long-term strategic network:** A strategic alliance established with the purpose of having its members prepared for participation in collaboration opportunities, and in fact, not only collaboration but cooperation is practiced among its members. Under long-term strategic networks, these are some of the main subcategories:
 - i. **A Virtual organizations Breeding Environment (VBE):** A VBE can be perceived as a business ecosystem where members have some form of binding agreement to work together. It is a concept that represents a long-term association (sometimes known as a cluster) of organizations and their supporting institutions that have both the ability and the desire to cooperate through the establishment of a long-term "base cooperation agreement" and the adoption of a common or interoperable infrastructure. When one member, usually the community manager acting as a broker, identifies a business opportunity, some members of the VBE whose interests are in line with that opportunity can come together to form a coalition, i.e., a virtual enterprise or a virtual organization, to respond to that opportunity. A VBE can be seen as a long-term association of entities that are ready to cooperate anytime an opportunity comes, in order to meet their agreed needs. In such a business arrangement, it is vital for members to be prepared and willing to join in the collaboration process since there may be critical situations where the window of opportunity is limited and calls for a prompt reaction, particularly when the timeframe for a joint reaction is constrained. "Being ready" entails building a foundation of mutual trust between the participants, compatible operating methods, and

collaboration agreements. This strategy can be used to ensure preparedness and speed up the development of collaborative networks. In a similar manner, the grid is a very sensitive infrastructure that requires a quick response time in order to avoid catastrophic failures like a system collapse. In this context, RECs can be organized as a kind of VBE where the participating households form an agreement to cooperate and jointly pursue some common or compatible goals relating to the sustainable generation and consumption of energy. In this sense, the proposed CEE can be organized in the form of VBE so that the involved members can be better equipped and prepared to take advantage of any energy-related opportunities that may arise. Examples of such opportunities include:

- Grid management services like demand response,
- Selling energy to the grid, and
- Disaster management services.

Roles of Actors involved in a VBE: These roles are being introduced here to serve as a reference since some of the roles discussed here are adopted by some actors in the CEE.

- **VBE manager/administrator role:** This role is performed by the organization responsible for the VBE's operation and evolution, promotion of cooperation among VBE members, filling skills or competency gaps in the VBE by searching for and recruiting or inviting new organizations into the VBE, and daily management of the VBE's general processes, including the assignment or reassignment of rights to different actors in the VBE based on their responsibilities, conflict resolution, and preparation of a shared bag of assets.
 - **VBE Opportunity broker role:** This position is played by a VBE member, which may be an organization or a person representing the VBE. By selling VBE capabilities and assets and negotiating with clients, brokers find and gain new partnership prospects. There is also the potential for an external firm to do this brokerage role as a service to the VBE. In the proposed energy ecosystem, the CEE manager is responsible for this role.
 - **VO planner:** This role is played by a VBE actor whenever a new opportunity for collaboration arises. The planner is responsible for identifying the required capabilities and competencies, selecting a suitable group of partners (VBE members and even outsiders if the VBE lacks the relevant competencies and/or capacities), and structuring the new VO. In many instances, the same actor plays both the roles of opportunity broker and VO planner. In the proposed ecosystem, the CEE manager is responsible for this role.
- ii. **Professional virtual community:** A long-term alliance of professional individuals that provides an environment to facilitate the agile and

fluid formation of virtual teams, similar to what VBE aims to provide in the case of virtual organizations.

- iii. **Business Ecosystem:** is a class of collaborative network that falls under the sub-class of long-term strategic networks, more specifically a type of VBE. It is defined in (Camarinha-Matos & Afsarmanesh, 2008) (Graça & Camarinha-Matos, 2021) as “a long-term strategic collaborative network similar to a cluster or industry district.” A business ecosystem draws inspiration from the mechanisms of biological ecosystems. This type of ecosystem fosters collaboration among diverse entities and promotes synergistic relationships among different sectors to drive economic growth and development. Through the lens of CN, the organization of a REC can be viewed as a form of business ecosystem. The REC may involve several stakeholders within a specific geographical region. The analysis of the REC as a business ecosystem helps identify opportunities for economic growth and the establishment of sustainable energy practices within the community.
- b. **Goal-oriented network:** A CN in which intense collaboration is practiced among its partners towards a common goal or a set of compatible goals. Under goal-oriented networks, two main subclasses can be seen:
 - i. **Grasping opportunity-driven network:** A CN driven by the aim of addressing a single collaboration opportunity and which is dissolved after the goal is accomplished. Some examples of this type of network include:
 - **Virtual enterprises:** These are temporary alliances of enterprises that come together to achieve a specific goal and are typically formed within the context of a VBE. The collaboration preparedness characteristics acquired by VBE members facilitate the rapid formation of a virtual enterprise when a new business opportunity is identified.
 - **Virtual teams:** These are similar to a virtual enterprise but are formed by humans, not organizations. A virtual team is a temporary group of professionals that work together towards a common goal, such as realizing a consulting job, a joint project, etc., and that use computer networks as their main interaction environment.
 - **Virtual organizations (VO):** According to (Camarinha-Matos & Afsarmanesh, 2021b) a VO is sub-class of grasping opportunity driven network that is established quickly in response to a short-term business opportunity. This VO can be dissolved when the short-term objective or goal has been achieved. In the context of the CEE, the formation of VOs is proposed to occur in a dynamic manner. This means that the creation of a VO becomes necessary only when a viable business opportunity arises. These

opportunities may have varying lifecycles and response times, necessitating an agile and adaptable approach. The capability of CEE members to dynamically form VOs to pursue opportunities and have them dissolve when the opportunity is achieved is key to the CEE concept.

A VO is a temporary organization that can be formed out of a VBE to take advantage of a business opportunity. VOs are a class of collaborative networks that have received a lot of attention and raised expectations across a range of application areas (Adu-Kankam & Camarinha-Matos, 2018). One way to stay adaptable and survive market volatility is to be able to swiftly form VOs in response to business opportunities and have them tailored to the needs of each particular opportunity. This notion is not just useful in the business world but also in non-business settings such as incident management and disaster management processes, where multiple entities need to work together in a swift, decisive, and efficient manner. Agility is best exemplified by the notion of groups of organizations quickly transforming into a collaborative form focused on a mission or objective.

A VO can be formed in the context of a CEE in order to strategically take advantage of business opportunities like selling renewable energy to the grid or utilizing the strength of collective actions by aggregating resources found in the CEE, like deferrable loads, and using them to swiftly respond to demands on the grid. In Figure 2.2, we illustrate a scenario of three VOs, namely VO1, VO2, and VO3, which are formed from a CEE to take advantage of grid opportunities 1, 2, and 3.

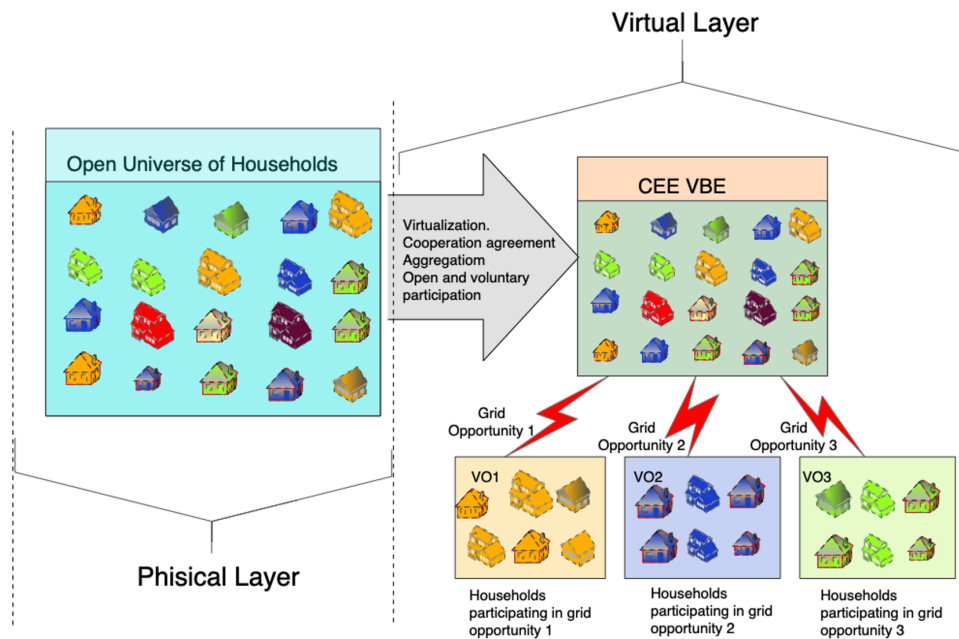


Figure 2 2— CEE as a VBE, forming VOs 1, 2 and 3 to take advantage of grid opportunity 1, 2 and 3.

- **Extended enterprises:** A concept typically applied to an organizational form in which a dominant enterprise “extends” its boundaries to all or some of its suppliers. An extended enterprise can be seen as a particular case of a virtual enterprise.
- ii. **Continuous production driven network:** A CN driven by or oriented to continuous production or service provision activities. One example is a supply chain.

2.2 The notion of Renewable Energy Communities (RECs)

A REC is a collective entity that is autonomous, operates in line with the applicable national laws, is based on open and voluntary participation, and is effectively governed by shareholders or members who participate in these communities. The establishment and operation of RECs are supported by legal frameworks such as the European Union Directive 2018/2001 (The European Union, 2018). This directive mandates member states of the European Union to ensure that final customers, especially household customers, are allowed to participate in a REC while upholding their rights and obligations as final customers and without being subjected to unjustified or discriminatory conditions or procedures that would prevent their participation, provided that their participation does not constitute their primary commercial or profit motive.

RECs can contribute to the alleviation of fossil fuel dominance in the current grid in several ways. For example, they can contribute to energy justice by promoting more equitable access to renewable energy resources and reducing the disproportionate impacts of energy production and consumption on marginalized communities (Sovacool et al., 2017). One of the main avenues for RECs to promote energy justice is to make renewable energy more accessible and affordable to more people. By pooling resources and sharing the costs and

benefits of renewable energy systems, communities can make it possible for more people to access clean and sustainable energy sources. RECs can also help to address the unequal impacts of energy production and consumption on marginalized communities and genders. For example, many low-income and minority communities are disproportionately impacted by pollution and other negative effects of fossil fuel energy production (Donaghy & Jiang, 2021). By supporting the transition to renewable energy sources, communities can reduce these impacts and create a more just and sustainable energy system. In addition, renewable energy communities can promote energy democracy by giving people a greater say in how their energy is produced and consumed. By working together, community members can create a more participatory and democratic energy system that benefits everyone, not just a few powerful stakeholders but also to include marginalized genders such as women. Overall, renewable energy communities can play an important role in promoting energy justice by making renewable energy more accessible, reducing the negative impacts of energy production and consumption on marginalized communities, and promoting greater democratic participation in the energy system. Renewable energy communities can contribute to increasing citizens' participation in renewable energy as well.

2.3 Review Methodology

For the analysis of the state of the art, we followed the systematic literature review (SLR) method. The motivation for adopting this approach is that it helps to provide a balanced and objective summary of the state-of-the-art in a specific knowledge area by collecting, identifying, and critically analysing the available literature on the subject matter from sources such as articles, conference proceedings, books, and dissertations using a systematic procedure. In fact, SLR is widely used (Carrera-Rivera et al., 2022) because it provides a rigorous and systematic method of literature review, assisting in the generation of robust and empirically derived answers to the focused research questions (Mallett et al., 2012). Instead of summarizing a collection of publications, the method suggests formulating some research questions which are used to guide the entire review process (Chigbu et al., 2023). In this section, a brief description of the various steps that are taken to identify and select materials for the review process is provided. Two separate reviews are conducted. The first review involves the analysis of 86 published articles from the area of virtual power plants. The second review involves (a) A brief/panoramic review of renewable energy communities and (b) an analysis of 34 cases from the area of renewable energy communities. The inclusion and exclusion criteria that is used for the selection of both the articles and cases for the review are also presented. Figure 2.3 illustrates the various steps that are followed in the selection of the articles/cases. The articles/cases that are considered in the review are published between the years 2010 and 2023, inclusive. The various stages used in the selection processes are as follows:

1. **Article/case search and identification:** The first stage of the review process involves searching for articles/cases that are deemed relevant to the subject matter, in this case, the proposed research question(s). At this stage, the articles/cases are identified based on their titles only. The search is conducted from known databases of academic

literature. The databases consulted included Scopus, Web of Science, IEEE Xplore, Google Scholar, Google Search, JSTOR, and Science Direct. Additional information is also gleaned from other sources, such as books and YouTube. Articles/cases are selected from the search using the selection criteria described below, which consisted of a set of keywords that is used in several different combinations. For instance, the keywords that are used to identify renewable energy cases in the second review are shown in Table 2.1.

2. **Article/case selection:** At this stage, the articles/cases that are identified in the previous stage are collected into a folder for further review. At this stage, the articles are reviewed based on the abstract only. For the cases, they are reviewed based on the case introduction.
3. **Article/case screening:** At this stage, the articles/cases are reviewed thoroughly using the defined inclusion and exclusion criteria. Articles/cases that passed the inclusion criteria are retained for further analysis, and the others are excluded.
 - **Inclusion criteria:** Each one of the reviews had a different inclusion criterion. These criteria are discussed in subsequent paragraphs.
 - **Exclusion criteria:** Each one of the reviews had a different exclusion criterion. These criteria are discussed in subsequent paragraphs.
4. **Articles/cases eligibility stage:** Eligible articles/cases are those that passed (a) the search and identification stage, (b) the articles/cases selection stage, and (c) the articles/cases screening stage. These are the articles/cases that are finally included in the review. Ineligible articles/cases are those that did not meet the eligible criteria mentioned above.

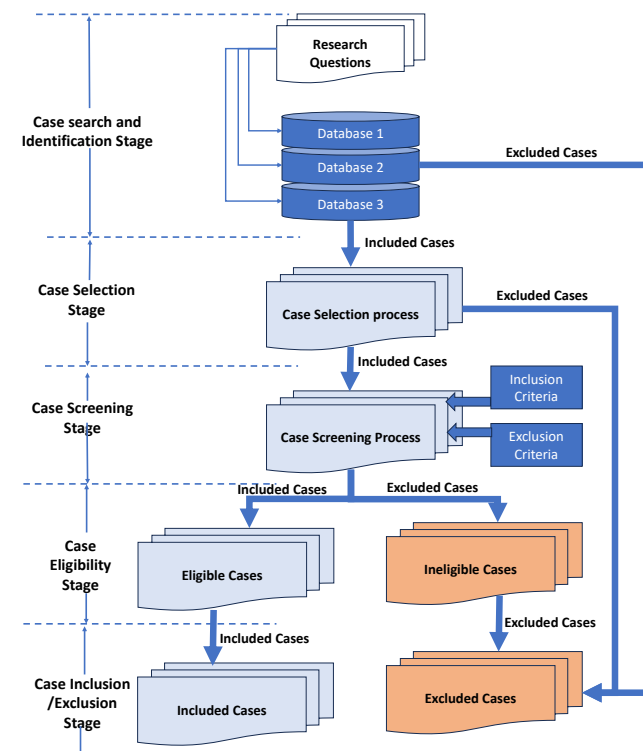


Figure 2 3 — The flow of the systematic literature review process

2.4 Part-1: Areas of Convergence Between Virtual Power Plants and Collaborative Networks

2.4.1 Introduction

The energy transition and ongoing digitalization in the energy sector have played a significant role in the current evolution of electric power systems (Cao et al., 2023). This trend is characterized by the increasing penetration of distributed energy resources (DERs) in the power grid (MIT Technology Review insights, 2022). Due to the immense potential of these energy resources, the use of the virtual power plant (VPP) concept is gaining ground as one of the plausible ways to harness their potential. Through the process of aggregation, these distributed resources can be integrated into the power grid. According to the literature, the concept of VPP is relatively new (Mao et al., 2020), therefore, publications in this area are still dispersed in terms of content, context, and organization (Zhang, 2022). Furthermore, a unified definition for the concept is currently unavailable (Rouzbahani et al., 2021).

Some selected definitions from the literature include (Saboori et al., 2011), who defines a VPP as a collection of distributed generating units, variable loads, and storage systems that have been combined to function as a single power plant. The generators can run on fossil fuels or clean energy. An energy management system, the brain of a VPP, controls the power flows coming from the generators, controllable loads, and storages. Due to the two-way nature of the communication, the VPP is able to send signals to control the DERs as well as receive information about each unit's present status. In (Nikonowicz & Milewski, 2012) and (El Bakari et al., 2009) a VPP is said to be a modularly constructed entity based on software communication technologies that effectively organizes, manages, and merges decentralized generation, storage, and consumption through an intelligent energy management system. Combining the different views, (Adu-Kankam & Camarinha-Matos, 2018) suggest that a VPP is a virtual entity involving multiple stakeholders and comprising decentralized multi-site heterogeneous technologies, formed by aggregating dispatchable and non-dispatchable distributed energy sources and energy storage systems, including electric vehicles and controllable loads. It is supported by information and communication technology to form the equivalent of a single virtual power plant with the capacity to manage and coordinate its operations, ensuring power and information flow among its stakeholders, in order to minimize generation costs, maximize profits, and enhance participation in demand response programs as well as trade within the electricity market.

Among the plethora of existing definitions, some common themes that run through suggest that a VPP can be considered as an aggregation of DER units, using software technology to establish the equivalent of a single power plant that has the capability to serve similar purposes as traditional power plants. The VPP concept enables the control of the aggregated units and helps manage the electrical energy flow between these units in order to obtain some economic or commercial value at the end.

The rationale for this part of the literature review is to attempt to establish a correlation between the two disciplines, i.e., the domains of CNs and VPPs. To help identify current synergy and a better synthesis of these areas, three guiding questions are used to help define the scope of the review, namely:

PT1-RQ1: Which collaborative principles are currently being applied in the domain of VPPs?

[Collaborative Network principles].

PT1-RQ2: Which collaborative organisations are emerging in the domain of VPPs?

[Organizational forms].

PT1-RQ3: Which technological enablers support collaboration in VPPs?

[Technological enablers].

2.4.2 Article Search, Identification, Screening and Selection Processes

This section describes the various stages through which the articles for this part of the review are selected.

1. **Article search and identification stage:** At this stage of the review, the following search terms/words are used to search and select prospective articles. In the Table 2.1, each keyword from column 1 is used in combination with the keywords from subsequent columns such as columns 2, column 3, and column 4 to search for prospective articles.

Table 2.1—Terms used in the articles search and selection process

Column-1	Column-2	Column-3	Columns-4
Keywords describing the VPP	Keywords describing the type of virtual entity	Keywords describing the type of interaction	Keywords describing the type of ecosystem
Virtual Cyber Cyber-physical Aggregated Microgrid	Power Player Distributed Multi-agent Energy Resources Microgrid Renewable Producers	Sharing Collaboration Cooperation Coordination Network Partnership Joint Co-evolution Coalition Clusters Balancing groups	Plant Ecosystem Platform Portal Energy market Electricity market Balancing markets Carbon market Day ahead market

Results from the search revealed some interesting trends. All articles obtained from the search showed that the term ‘collaboration or collaborative’ was relatively uncommon in this area. However, terms like Virtual, Players, Producers, Multi-agent, Micro-grids, Aggregation, Aggregators, Energy Market, and DERs are used quite frequent in most articles found. The search conducted with these search terms yielded a total of 205 articles.

2. **Article selection stage:** At this stage 149 articles are selected, and 56 articles are rejected. The selection of articles at this stage is based on their titles only. The rejected articles are due to duplication and out of scope titles.
3. **Article screening stage:** At this stage 55 articles are screened out and 94 articles are retained for further scrutiny.
 - a. **The inclusion criteria:** The following are the inclusion criteria for a paper to be included in the survey: (a) The article must be published between the years 2010 and 2023, inclusive. The reason for selecting this time window (13 years) is to help gather sufficient evidence regarding the evolutionary trend of these concepts over time; (b) The article must discuss any form of collaborative, cooperative, collective, or aggregation mechanism or relationship within the energy domain; (c) These cooperative or collaborative relationships must be a result of the aggregation of DERs, demand response programs, energy storage systems, combined heat and power, controllable loads or a combination of any of them; (d) The aggregation must result in the equivalent of single virtual entity; and (e) The aggregated unit must have the capability to provide some commercial value.
 - b. **Exclusion criteria:** All articles that failed to meet the inclusion criteria are automatically excluded.

Using the inclusion and exclusion criteria, the selected/screened articles are narrowed down from 94 to 86. The first part of review is therefore conducted using these 86 cases.

2.4.3 Focus Areas

According to (Next Kraftwerke, 2021) the term "Virtual Power Plant" (VPP) refers to a network of flexible power consumers, storage devices, and decentralized, medium-scale power generating units. VPPs are capable of a wide variety of functions, depending on the specific market scenario. Generally speaking, the goal is to connect distributed energy resources, such as wind farms, solar parks, and Combined Heat and Electricity (CHP) units, in order to monitor, forecast, optimize, and exchange their power. By varying the power generation and consumption of controllable units, fluctuations in the production of renewable energy can be balanced (Yu et al., 2022). The VPP does, however, contribute to more than just grid stabilization. Additionally, it sets up the conditions necessary for the market integration of renewable energy sources. Most of the time, small plants cannot offer their flexibility on the power exchanges or balance services. They either do not satisfy the minimum bid size of the marketplaces or their generation profile exhibits too much variation. A VPP can provide the same service and redundancy by combining the power of numerous units and can then trade on the same markets as big central power plants or commercial clients. From this background, the review discusses 2 key areas: (a) VPP operation and control, and (b) VPP security.

2.4.3.1 VPP Operation and Control

The increasing integration of DERs in the grid has created operational and control challenges that require coordinated techniques for efficient management (Roozbehani et al., 2022). In this regard, the following areas are discussed:

2.4.3.1.1 VPP Aggregation or Clustering

VPP aggregation is the process of bringing diverse DERs together to create a composite unit whose capability is equivalent to that of a conventional power plant. Currently, there are several techniques that are used in the aggregation process. The objective of this section of the review is to ascertain if collaborative network principles and techniques are adopted in the aggregation of DERs.

To avoid further grid volatility, (Wang et al., 2022) claimed that it is crucial for VPPs to engage in power grid balance adjustments by offering stable available capacity. By relying on just one or a few types of adjustable resource clusters, it may be difficult to meet this need. As a result, to address the output fluctuation, a dynamic aggregate response model based on the “state priority queue” is proposed. The approach by (Wang et al., 2022) suggests a dynamic aggregation technique that divides a cluster of electric vehicles and electrical loads (thermostatically controlled loads) in the VPP into subclusters based on each unit's characteristics (operational state). This helps to create a “response priority queue” within the subcluster of the VPP in accordance with a “response capability indicator” of the various resources. When a resource cannot participate in the response due to some special reasons, the VPP can set up new response resources from the various clusters of the VPP based on their status in the priority queue to participate in the grid balancing activity. This technique appears similar to invitations to participate in coalition formation in the context of CNs. Again, in (Bao et al., 2021) a multi-objective VPP member selection model is presented. The two key optimization objectives mentioned include the maximization of VPP economic benefits and the voltage deviation of the distribution network. Based on these optimization goals, a VPP member is selected. This member selection process is similar to CN partner search and selection process as well as the alignment of member competencies. In (Dethlefs et al., 2015) an aggregation method which uses a common active registry system is proposed. The registry system provides a common platform for the exchange of “energy services and information.” This system has two key actors. The first actor is the resource provider, who manages the DER resources and provides an energy service to the second actor, who is the aggregator. The roles of these actors are as follows: (a) the registry system allows a resource provider to register and de-register its DER(s) resources; (b) The resource provider has the ability to add, modify, and remove energy services offered in the registry system. The role of the aggregator, on the other hand, is that it can search the database for accessible energy services. The aggregator establishes the search and filter criteria for the search use case. The aggregator will subsequently receive a result list detailing all eligible DERs. Furthermore, the aggregator can reserve an energy service by determining whether all requirements, such as availability, the aggregator's right to reserve, etc., are satisfied. The DER is then informed that the aggregator is permitted to control it within the parameters of the energy service. This approach appears similar to the grasping opportunity kind of collaboration in CNs. This

method enables aggregators to dynamically adjust the composition of their VPPs to meet the specific needs of the market (a facet of agility) and to quickly reconfigure the VPP in the face of a challenge.

Another interesting aggregation technique is proposed by (Botsis et al., 2015) and (Rinaldi et al., 2016). These authors proposed a virtual DER cluster (VDC). This cluster is composed of several DERs that are united in the form of coalitions. Each member of the coalition can participate in the market as a single entity. Furthermore, each cluster may have a goal. To achieve these goals, an efficient clustering algorithm is proposed. The clustering algorithm is based on a minimum and maximum optimization policy. The algorithm helps to dynamically derive the cluster that best satisfies the coalition's goals. Several VDCs can be connected to a web-based platform through a gateway, which leads to a virtual DER clustering aggregator (VDCA). The VDCA serves as an intermediary for the VDCs to work together. The utilities (market operators) and VDCA help facilitate energy trade among different VDCs. The VDCA builds a directory of DERs from which dynamic VDCs can easily be formed. Cluster formation or aggregation is dynamic, thus on an hourly interval or day ahead since energy demand and supply are also dynamic processes. The dynamic aggregation processes described are similar to the dynamic formation of virtual organizations in the context of a virtual organizations breeding environment. Again, a similar aggregation technique is discussed in (Cai et al., 2022), (Huang, 2015), and (Bahloul et al., 2022). In these examples, the focus is placed on "smart grid social networks." Their motivation is based on shared geographical location and shared values such as sustainability, social cohesion, or energy sharing. Members engage each other through a "smart grid social network" portal to achieve these compatible goals. This type of organization is also similar to that of a VBE in the context of a CN, where members agree to work together based on some common interests and agreed-upon governing principles.

In (Biswas et al., 2014) a VPP aggregation is as an optimal combinatorial auction problem. In their model, a VPP planner acts as market broker which collaborates with multiple DER supplier agents and consumers by aggregating the energy produced by those DERs and making it available to consumers through the grid in real time. Similar to this case, (Siebert et al., 2013) proposed a flexibility aggregation system comprising an "aggregator solution" entity which interacts with several prosumers and systems. The proposed approach was deployed in the "Reflexe pilot project." In this project, meter and sensor information as well as forecast of expected load, production, and flexibility from participating DERs are sent to the "Aggregator Solution." The "Aggregator Solution" entity processes these data which are available in its database to determine the status of power supply, demand and flexibility available in the system. This knowledge is used to build proposals for market bids based on traders defined energy specifications which they make available in the "Aggregator Solution." From the perspective of CNs the "aggregator solution" acts like a market broker who seeks business opportunities in the market and works with its members (prosumers) to take advantage of each opportunity.

Typically, the types of energy resources that are often aggregated to form a VPP in the literature involve: (a) battery storage systems (Krishna & Hemamalini, 2022), (b) electric vehicles (Ravikumar et al., 2022), (c) wind turbines (Baeyens et al., 2011), and (d) solar

photovoltaic systems (Bannavikarn & Hoonchareon, 2021). One area that is gradually gaining attention in the literature is the aggregation of energy resources in smart homes or smart buildings into a VPP. In this regard, several examples can be seen. For instance, in (Behi et al., 2021), 67 dwellings with assorted DERs are aggregated into a VPP. Another example is discussed in (Zhang, 2022) where the aggregation of air-conditioner loads are used to control a VPP. In another example, a building VPP architecture that aggregates building-side energy resources is presented in (Luo et al., 2022), and finally a smart buildings VPP which can participate jointly in the energy and regulation markets is also addressed in (Zhu et al., 2022).

Discussion: In terms of CN forms, this part of the review has shown evidence that suggests the use of certain CN principles and organizational forms that are similar to some traditional CN forms. Some novel organizational forms are also seen. Although the current organizational forms bear some semblance to traditional CN organizational forms, they appear not to be fully matured methods to be adopted for efficient DER aggregation. It can therefore be inferred that there is opportunity for improvement and that more efficient aggregation methods could be sought. Adopting a more efficient and mature approach from the domain CNs could be helpful in this sense. Based on the set of cases discussed, the following traditional CN organization forms, roles and principles are found, although not necessarily in an explicit way:

1. **Virtual Organizations Breeding Environment:** Cases such as (Dethlefs et al., 2015) and (Botsis et al., 2015) resemble VBEs as per their characteristics, formation, and mode of operation. However, upon critical scrutiny, it is observed that these systems do not incorporate mechanisms that can facilitate the aggregation process in a way that makes it similar to VO creation as in CNs. It is however relevant to mention that the key essence of a VBE is to improve the preparedness of its members for efficient VO creation. Preparedness includes defining core competences, harmonizing procedures, creating and sharing common knowledge, managing performance, reliability, trustworthiness, and general competencies, which are critical components to consider in such dynamic VBEs. The cases identified in this review still do not incorporate mechanisms to ensure preparedness. Therefore, these limitations will adversely impact the sustainability and agility of the VPP. Thus, although these cases bear some semblance to VBEs, it is noteworthy to mention that the full concept of VBEs and their support functionalities are not yet endogenous in this area.
2. **VBE broker role:** The role of a broker in a CN is primarily to seek business opportunities (Camarinha-Matos & Afsarmanesh, 2021a), (Camarinha-Matos & Afsarmanesh, 2008). A broker may function as part of a VBE or may function outside of a VBE. When a broker finds an opportunity, other players, such as the VO planner, the VO coordinator, etc., take over and facilitate the formation of the VO and the alignment of the VO's competences and assets with the opportunity. Some of the core functions of these players include negotiation, partner search and selection, VO creation, operation, and dissolution. Other functions include the alignment of the VO competences to the opportunity (Camarinha-Matos et al., 2005).

3. However, in the cases that are considered in this survey, e.g., (Botsis et al., 2015) and (Rinaldi et al., 2016), the proposed systems incorporate some of these functions into a single system. For instance, in (Rinaldi et al., 2016) all the participating DERs register in the “Aggregator Solution” to form a kind of VBE. The functions of this VBE (aggregator solution) include:
 - a. “Aggregator Solution” processes received information from DERs, and weather forecast to determine availability of flexibility - *Identification of opportunity*.
 - b. “Aggregator Solution” searches its database and aggregates flexibilities- *partner search or selection and VO creation*.
 - c. “Aggregator Solution” prepares market bid proposals for the market - *Negotiation*.
 - d. Trader accepts the bid proposals and subsequently energy is dispatched to trader - *VO alignment with opportunity and operation*.

Although the proposed systems in (Botsis et al., 2015) and (Rinaldi et al., 2016) have good potential for such dynamic environments, they do not possess the mechanisms that can assess members’ competences, address trust issues, identify value systems, or assess members’ performance. For these reasons, it can be inferred that the reviewed cases do not have the full functionalities to support the proposed concepts adequately as compared to similar roles that are played by corresponding entities in the context of CNs.

- *Grasping Opportunity Networks*: In most of the cases considered, the ultimate objective for aggregation was inclined towards grasping a particular market opportunity. The opportunity may usually include participation in the energy market (Ullah, 2022) or to provide some ancillary services to the grid (Wang et al., 2022). To grasp these opportunities, different methods are used to aggregate capacities of DERs to pursue these opportunities. The cases considered above satisfy these criteria and can therefore be considered as *Grasping opportunity networks*.

On the other hand, certain other organizational forms were also observed which did not conform to the traditional CN organizational forms. These can be considered as emerging organizational forms because they are new and composed mostly of a hybrid between two of the known traditional forms. For instance, a hybrid mix of VBE and Goal Oriented Network was found in cases such as (Siebert et al., 2013), (Biswas et al., 2014), (Botsis et al., 2015), (Dethlefs et al., 2015), and (Zhao et al., 2022).

2.4.3.1.2 VPP Organization or Architecture

This section addresses articles that make contributions to the organization of VPPs. Generally, VPPs are organized into three main categories (Nikonowicz & Milewski, 2012). These categorizations are as follows:

1. **A centralized controlled architecture**: In this arrangement, the VPP is responsible for all control logic, and the DER is kept separate from all market and production

planning knowledge. The benefit of this design is that it provides the VPP with a straightforward method of utilizing DERs to satisfy market demand.

2. **A hierarchically distributed controlled architecture:** This type of VPP establishes a hierarchical model by outlining VPPs at various levels. While assigning some decisions to a higher level VPP, a local VPP supervises and organizes a small number of DERs. Individual VPP responsibilities and communication may be made easier by this design.
3. **Fully distributed controlled architecture:** Each DER functions as an autonomous, intelligent agent that engages with and responds to the market and power system volatility. This idea is promising as it provides the DERs with some flexibility in terms of their contribution to the power system.

Besides these three general categories, it is again found that VPPs are often constructed of several interdependent components. These components could be in a modular form (IANOS, 2020), in a layered structure (Jiang et al., 2021), or in a hierarchical order (Rädle et al., 2021). Some VPPs are scalable (Bianchi et al., 2021), and others are not. However, the components of VPPs are usually integrated into a composite unit, a platform, or a software system. A common attribute that runs through all the different architectural frameworks is that there is some synergy or coordination between the various components, that enables them to talk to one another or work together in a cooperative manner. For instance, reviewing the work of (Song et al., 2021), a “VPP with centralized control platform” architecture is presented. The system is comprised of (a) business architecture, (b) technical framework, and (c) application architecture. These three blocks of the architecture provide a multi-source big data platform that enables multiple data sources to be integrated into a unified data management platform for the VPP. The big data sources include data from: (a) systems data such as scheduling, automation, distribution network automation, power management, smart meters, geographic information systems, etc., (b) Equipment data, including energy terminal acquisition equipment data, gas network data, thermal networks, including energy storage, microgas turbines, air source heat pumps, solar thermal, biomass energy, electric vehicle charging piles, and other sources, (c) macroeconomic policies such as environmental and climate data, (d) data from energy terminal acquisition equipment. In this example, all three components are integrated, and they talk to each other.

In another example, (Ma et al., 2020) present the architecture of the transaction management system of a VPP that is based on blockchain technology. In this example, the blockchain is used to manage all the power transactions of the VPP. The architecture is comprised of distributed energy source nodes, VPP aggregators, and smart meters. The case of a double-layered architecture is also proposed in (Wang et al., 2021). In this case, the upper layer is a commercial VPP that participates in energy market transactions, while the lower layer is a technical VPP. Similarly, in (El Bakari & Kling, 2011) and (El Bakari & Kling, 2012), a VPP architecture that is claimed to be hierarchical, modular, and scalable at the same time is presented. The architecture consists of three layers. The first one is the local layer that constitutes the local VPPs (LVPPs), which is intended to coordinate the DERs that are located within a local community and small neighbourhood level. The second is the regional layer of the architecture, which is an aggregation of LVPPs from the local level to form a regional

VPP (RVPP) that also cooperates at the district level. The third layer is an aggregation of RVPPs to form a large-scale VPP framework that serves the transmission system operator. This enables a power system architecture that integrates a high number of DERs that can be managed at all three levels in a hierarchical order, helping to maintain system stability and increase the reliability of the power supply. Again, (Rinaldi et al., 2016) proposed a four-layer hierarchical architecture for a distributed monitoring system. The architecture includes: (a) Bottom layer which constitutes a network of distributed generation, distributed storage, and all devices installed in the local grid; (b) The middle level of the architecture is composed of a central power plant controller, which coordinates, and aggregates data provided by distributed generation and distributed storage systems at the bottom layer of the architecture; (c) The third layer is made up of a VPP monitor that is responsible for the virtualization of the plants under its control. The final layer, (d) which is the distributed monitoring system is the topmost layer of the framework. Jointly, they form a single (virtual) plant with a hierarchical relationship between the various layers. This enables bottom-up and top-down relationships to be established at all levels of the system.

In terms of organization and architectural framework, VPPs are found to be organized in a similar manner as is the case for collaborative network systems. They are made up of a variety of discrete entities that are geographically dispersed, however, they are integrated to form a complex system. The components "talk" to each other in order to achieve some common objectives. Furthermore, these interactions are supported by computer networks. Nevertheless, it can be inferred that the use of CN principles in this area is very negligible and still emerging.

2.4.3.1.3 VPP Operation and Support Technologies

In this aspect of the work, we review the various technological enablers that are found to help the advancement of the VPP notion. As shown in Table 2.2, the following technological domains were identified as the key technological enablers in this area: (a) information and communication technology (ICT) such as artificial intelligence, cyber-physical systems, agent-based technology, blockchain technology, electrical vehicle technology, and distributed generation technology. The key areas where these technological enablers are mostly applied include (a) VPP forecasting, (b) VPP optimization, (c) VPP transactions, (d) VPP dispatch and scheduling, (e) VPP aggregation and clustering, (f) VPP management and control, (g) VPP security, and (h) VPP market/bidding. It is also observed that the idea of system-of-systems technology is extensively used to enable seamless systems integration. This also helps to achieve decentralized and hierarchical control of energy resources.

Table 2.2. Technological enablers and areas of application within the VPP concepts

Technological Enablers	Reference	Areas of application								
		VPP Forecasting	VPP Optimization	VPP Transaction	VPP Dispatch/ Scheduling	VPP Aggregation/ Clustering	VPP Management /Control	VPP Security	VPP Market/Bidding	VPP Architecture
Artificial Intelligence	(Sierla et al., 2022)	Yes	Yes	-	-	-	-	-	-	-
	(AI and the Tech behind the Virtual Power Plant, 2021)	Yes	Yes	-	-	-	Yes	-	-	-
	(Karitpower, 2023)	Yes	Yes	-	-	-	Yes	-	-	-
Agent-based Technology	(Sosnina et al., 2022)	-	Yes	-	-	-	Yes	-	-	-
	(Que et al., 2021)	-	Yes	-	-	-	Yes	-	-	-
	(Wang et al., 2022)	-	Yes	-	-	-	Yes	Yes	-	-
	(Zhang et al., 2020)	-	-	-	Yes	-	Yes	-	-	-
Blockchain Technology	(Huang et al., 2020)	-	-	-	-	-	-	-	-	-
	(Wang, Zhang, Jia, et al., 2021)	-	-	-	-	-	Yes	-	-	-
	(Wang et al., 2022)	-	-	Yes	-	-	Yes	-	-	-
	(Ma et al., 2020)	-	-	Yes	-	-	-	-	-	-
	(Mnatsakanyan et al., 2022)	-	-	-	-	-	-	-	-	-
Electric Vehicles Integration	(Ravikumar et al., 2022)	-	Yes	-	-	Yes	-	-	-	-
	(Ahmadian et al., 2023)	Yes	Yes	-	-	-	Yes	-	-	-
	(Li et al., 2022)	-	Yes	-	Yes	-	Yes	-	-	-
	(Nair & Shereef, 2022)	-	-	-	Yes	Yes	Yes	-	-	-
Distributed Generation	Solar PVs: (Bannavikarn & Hoonchareon, 2021)	-	Yes	-	-	-	-	-	Yes	-
	Hybrid systems: (Laoharajanaphand & Ongsakul, 2021)	-	Yes	-	Yes	-	-	-	Yes	-
Information/Communication Technology	5G Technology: (Jazaeri, 2021)	-	-	-	Yes	-	Yes	Yes	-	-
	Network Slicing: Tian & Qiu, 2022)	-	-	-	Yes	-	Yes	Yes	-	-
Cyber-physical Systems	(Gao et al., 2021)	-	-	-	-	-	-	Yes	-	-
	(Gan et al., 2021)	-	-	-	Yes	-	Yes	Yes	-	-
	(Venkatachary et al., 2021)	-	-	-	-	-	-	Yes	-	Yes
	(Tian et al., 2020)	-	-	-	-	Yes	Yes	-	Yes	Yes

Discussion: In terms of technological enablers, it is found that ICT is a dominant technology that is used to support the VPP concepts. Regarding the use of ICT, it is observed that similar aspects of this technology are also applied in the domain of CNs. For instance, in (Ferrada & Camarinha-Matos, 2019), agent-based technology is used to simulate emotions in a CN. Similarly, in (Nazarenko & Camarinha-Matos, 2021), a collaborative cyber-physical system design is presented. Furthermore, blockchain technology is suggested in (Adamopoulos et al., 2019) as the basis for developing a “blockchain CN framework,” while (Unhelkar & Arntzen, 2020) present an intelligent CN enterprise system.

Besides the concurrent use of similar technologies in both domains, other aspects of ICT, particularly in the area of communication are also found. For example, some communication protocols and standards such as IEEE 802.11ac, Long Term Evolution (LTE), TCP-IP, are also found. These protocols and standards enable inter-device communication and cooperation. They also enhance communication between the cyber and physical components of the VPP. It is, however, envisaged that these standards and protocols could be similar to CN communication systems as they might also be comprised of cyber-physical components that need to communicate with each other.

It is observed from the review that at the current stage of development, there are several technologies that are integrated into several systems that talk to each other using several

communication technologies, protocols, and standards. However, cooperation between these systems is not based on collaborative network principles. It can, however, be inferred from the review that, currently, the technological environment and support systems for the VPP concept are mature enough to support the integration of CN principles and mechanisms into the VPP domain. This can facilitate effective collaboration, communication, and cooperation among the plethora of technological systems found within the VPP domain.

2.4.3.1.4 *VPP Market Participation*

The primary objective of a VPP is to aggregate small-scale distributed generation into an aggregated unit to enable it to participate in the energy market (Bannavikarn & Hoonchareon, 2021). According to the (European Parliament & Council of the European Union, 2019), the electricity market is a marketplace for the trading of electricity, including over-the-counter markets and electricity exchanges, capacity, balancing, and ancillary services in all timeframes, including forward, day-ahead, and intraday markets. There are other short-term trades, generally in the form of financial or obligation swaps. Bids and offers that use supply and demand principles to set prices. The literature in this area also covers other aspects of electricity trading, such as tariffs, remunerations, and negotiations. Table 2.3 shows how different resources are aggregated into a VPP and which market these VPPs participate in. The table also shows which cooperative or collective mechanism these VPPs adopt in order to participate in the energy market. These findings however, are not necessarily generic, as they may also depend on the legislation or legal framework existing in the geographical region/country within which the VPP is operated.

Table 2.3 VPP participation in the energy market.

References	Type of Resources that are Aggregated to Participate in the Market	Type of market			Market Strategy		Cooperative/ collaborate mechanism
		Electricity Market	Peak Regulation Market	Carbon Market	Bidding	Auction/negotiation	
(Liang et al., 2022)	1. Electric vehicles 2. Energy storage	-	-	-	Yes	-	A cooperative control strategy
(Fan et al., 2022)	1. Flexible demand-side resources	Yes	Yes	-	Yes	-	cooperation among internal members
(Zhu et al., 2022)	1. Flexible loads 2. Renewable energy	Yes	Yes	-	Yes	-	Real-time cooperation scheme
(Zishou et al., 2022)	1. Demand response 2. Gas-fired unit 3. Energy storage	-	Yes	-	-	-	Cooperation between controllable loads and transferable loads
(Ruhai et al., 2022)	1. Wind turbine 2. Photovoltaics 3. Energy storage 4. schedulable loads	Yes	-	-	Yes	-	Cooperation between upper and lower layers of the model
(De & Badar, 2022)	1. Photo-voltaic 2. Wind turbine, 3. Micro-turbine 4. Controllable load	Yes	-	Yes	Yes	-	Adopts four different optimization techniques
(Zhang & Zhao, 2021)	1. wind power, 2. photovoltaic 3. energy storage 4. controllable load 5. dispatchable loads	Yes	-	Yes	Yes	-	A two-stage bidding strategy
(Chen. et al., 2018)	1. 1-MW PV plant 2. 4-MW Wind farm	Yes	Yes	Yes	Yes	-	A cooperative game
(Seven et al., 2022)	1. Inter VPP peer to peer trading	Yes	-	-	Yes	-	The Avalanche open-source platform
(Ullah et al., 2022)	1. Demand Response 2. Energy Storage System	Yes	-	-	Yes	-	Seeing the social welfare of participation entities
(Capodiecì & Cabri, 2013).	1. Generation companies 2. Prosumers	Yes	-	-	-	Yes	Self-organization, self-repairing, and self-adaptation.
(Faria et al., 2016)	1. Distributed generation units, 3. DR consumers	Yes	-	-	-	-	Clustering algorithm

Discussion: It is observed that some CN principles are visible within the VPP market participation domain. First, all the cases that were reviewed showed evidence of a kind of VBE that is formed through the aggregation of several distributed resources to enable the formation of the VPP and subsequent participation in the energy market. For instance, in the case of (Ruhai et al., 2022), resources such as (a) wind turbines, (b) photovoltaic systems, (c) energy storage systems, and (d) schedulable load are aggregated into a VPP, a form of a VBE that uses a cooperative mechanism to enable it to trade in the energy market. In (Capodiecì & Cabri, 2013), a dynamic VO formation process using dynamic aggregation as well as the application of eNotary concepts are seen. The notion of an eNotary is extensively used to manage transactions and contracts in the domain of CNs, however, it is not necessarily a collaboration principle (but rather a support mechanism). The role of VO administrator is also visible in this case.

In (Seven et al., 2022), the Avalanche open-source platform that is used to deploy a decentralized application and business wide blockchain solution is introduced. The platform uses a protocol which is a “repeated sub-sampled voting” mechanism that employs a novel consensus approach in order to provide robust safety guarantees, quick finality, and high

throughput in energy trading transactions without sacrificing decentralization. First, a validator who is a member of the blockchain polls a small, ad-hoc set of validators together to determine if a transaction should be permitted. The questioned validator will respond that the transaction should be refused if it thinks the transaction is invalid, has already rejected it, or prefers a different competing transaction. Otherwise, if a sufficiently large portion agree that the transaction should be authorized, the validator accepts it. This valuation technique requires the cooperation of all the involved validators to either approve or decline a transaction. In (Ullah et al., 2022), a market trading system for a VPP that integrates a demand response program and an energy storage system to enable it to trade in the day-ahead energy market is presented. This study aimed to maximize social welfare, thus, maximizing consumer benefits, while at the same time minimizing the energy expenditures of a VPP in the electricity market. The aspect of social welfare suggests that the benefits, interests, capabilities, and priorities of each consumer's participation in the demand response program are given the needed consideration. This is a sign of cooperation or a collaborative mechanism. Other works in the literature that discuss the social welfare of VPP participants include (Singh et al., 2022).

Remuneration forms a critical component of the energy market, as market participants are motivated by market proceeds in the form of incentives. In (Faria et al., 2016), a method in which VPPs can dynamically form clusters through the dynamic aggregation and scheduling of DERs to enable VPPs to offer optimum remuneration packages to both customers and producers is discussed. The same authors also proposed a clustering approach for a fairer tariff group organization that considers the resource type and the importance of each participating resource in each specific scenario (Faria et al., 2016). Again, these aspects are not necessarily generic, as they may depend on the legislation or legal framework existing in the geographical region/country within which the VPP operates.

Energy resources considered in both cases are distributed generation units and demand response programs. Other cases of VPP collaboration in the energy market include: strategic bidding for VPPs (Rahimiyan & Baringo, 2016), remuneration and tariffs (Ribeiro et al., 2012), and the development of an intelligent VPP remuneration system using machine learning and data mining techniques (Ribeiro et al., 2013).

Other concepts relating to technology were also found to be used in the VPP market domain. Some of these concepts included: electronic notary, agent-based concepts, dynamic strategy concepts, resilient systems, cluster formation techniques, and dynamic systems, etc.

2.4.3.2 *VPP Security*

In this section, VPP security is given a wider coverage to also include articles outside of the strict scope of VPPs. This is because issues concerning VPP security cannot be treated in isolation from the main grid, therefore, a more realistic view can be obtained by analysing security from the perspective of the entire smart grid. VPP networks are supported extensively by ICT infrastructures (Oest et al., 2021), which are deployed to enable wide area monitoring, protection, and control of the grid (Behi et al., 2021). With this kind of integration, the traditional power system is gradually evolving into a cyber-physical system that is comprised of both physical and cyber components (Jha et al., 2021). The co-evolution of both components of the grid makes it vulnerable to both natural and man-made

disruptions (Alonso et al., 2021). For instance, Pike Research (Gohn & Wheelock, 2010) predicts that security will become a major smart grid concern hence, huge investments would be required to address worldwide smart grid cyber-security in the future.

As one attempt to address these concerns, a modular and hierarchical layered architecture for the smart grid is suggested in (Enose, 2014). The components of this modular architectures are described by their functional roles. Each layer implements local security measures at the layer level and at the same time engages in a cross-layer cooperation to ensure good security. This layered security approach is claimed to repel attacks but also help to better contain cyber intrusions. Another layered based security architecture is proposed in (Farag et al., 2014). In this work, a three-layer framework, called CyNetPhy is simulated at the laboratory. CyNetPhy is constituted of a cyber-security layer, a behaviour estimation layer, and a physical security layer, all engaging in cooperative mechanisms towards an enhanced cross-layered grid security and against pervasive and persistent attacks. Each layer in the CyNetPhy framework represents a broad hierarchical model encapsulating interrelated sub-layers. These individual defence layers cooperate with each other to enable prompt detection of cyber related attacks. Currently there are many open security issues in this area which need further attention of the research community. These include but not limited to: SCADA specific man-in-the-middle attacks using “address resolution protocol” (Rosa et al., 2017), spoofing (Baldini, 2022), the smart meter denial of service attacks (Ortega-Fernandez & Liberati, 2023), smart meter-based false data injection attacks (Lukumba & Simon, 2023), micro-grid based jamming attacks (Jamil et al., 2021), and electric vehicle-based man in the middle attacks (Ahmad et al., 2018), etc.

In another related work, a security-aware distribution system architecture for smart-grid applications is proposed and simulated in (Hittini et al., 2016). In this example, a four-layered cloud-based security architecture is proposed, including: (a) the control centre cloud layer; (b) the primary substation cloud layer; (c) the secondary substation; and (d) the control centre cloud. This architecture is hierarchical, thereby supporting better scalability and effective cooperation to ensure system security in the distribution network. In (Sedjelmaci & Senouci, 2016), the authors proposed an intrusion detection system (IDS) deployed to detect intruders who may impair the proper operation of the grid. Three categories of IDS agents are suggested to monitor the behaviour of appliances, namely: (a) at smart meters to monitor the behaviour of appliances; (b) at the collector level to monitor the meter data delivered by smart meters; (c) in the control centre to monitor the behaviours of collectors and verify the intrusion decision. These software agents rely on rule-based detection techniques to collectively monitor the behaviour of a target node and analyse it.

With the current trends in terms of natural disasters, globalization, climate change, economic crisis, demographic shifts, fast technological evolution, terrorism and cyber-attacks, and rise of nationalism, the need to incorporate resilience into the power grid has become eminent. Towards this objective, an attack-resilient cooperative control strategy is simulated in (Liu et al., 2016). In this approach, an observation network of DERs within the power system can monitor the behaviours of all its neighbours, and collectively decide to isolate DERs suspected to be under attack. The remaining DERs can cooperate with each other to accomplish the security objective of the power system provided that the

communication network remains intact. (Qi et al., 2016) engage in analytical discussions on the potential of cyber-security challenges associated with DER integration into the power grid and proposes a holistic attack resilient framework to protect the integrated DER and the critical power grid infrastructure from malicious cyber-attacks. The proposed cyber-security framework consists of a cyber-threat modelling, resilience analysis, attack prevention, detection, and a collective response, at the cyber, physical, and utility layers of the power system. In another related work, (Aydeger et al., 2016), simulated a software defined network (SDN) for smart grid communication infrastructure at the distribution network connecting substations. SDN technology provides good flexibility to large-scale networks in terms of control, management, security, and maintenance. In this model, each substation is integrated with an SDN gateway switch. Comparing SDN and TCP, the authors concluded that for TCP, there is a higher delay to restart transmissions due to the need for re-establishment of the TCP connection without having to lose any packets.

A survey conducted by (Egbue et al., 2016), concludes that micro-grids have high potential to increase the reliability and resilience of the smart grid during a blackout or cyber-attack. This is because the decentralized nature of micro-grids can provide direct cyber-security benefits if structured properly. Decentralization reduces the number of vulnerable nodes in the network and provide alternate routes for avoiding redundant or attacked nodal components. Furthermore, micro-grids have the ability to incorporate the concept of “mutual suspicion” which enables peers to protect themselves and their neighbours by recognizing compromised communication channels and even peers which may be compromised.

Various other approaches are used to support VPP security. Some of them include the integration of security in both the cyber and the physical components of the grid. Techniques such as multi-agent approach to system security, hierarchical security architecture, software defined network technology, application of artificial intelligence for system monitoring and intrusion detection, system of system technology for integrating security at various levels of smart-grid architecture as well as cryptography are used extensively.

Conclusively, the literature review has shown that several aspects of the subject matter have been addressed. However, there are still some open issues that remain unresolved. In this regard, the concluding remarks in the next paragraph discuss some of these open issues.

2.4.4 Concluding Remarks

The following general remarks can be made based on this part of the survey:

1. Various CN organizational forms, principles, concepts, and technologies start to have some level of penetration in the energy domain, particularly within the VPP space. This observation is perceived as a good basis for further exploring the integration of CN principles and mechanisms into this domain. This can help expedite the maturity of the VPP concept using knowledge from the CN domain.
2. Furthermore, VPPs form various strategic and dynamic collaborative alliances, which are similar to various CN organizational forms. These include goal-oriented networks, VBEs, grasping opportunity-driven networks, and continuous production

driven networks. It is therefore reasonable to suggest that these VPP alliances could improve if they integrated the collaboration principles that guide the functionality of these CN forms into their operations.

3. Additionally, prospects for new and hybrid collaborative forms and mechanisms are very high as the energy ecosystem becomes more integrated, distributed, dynamic, and smart, with a high level of systems autonomy and heterogeneity. Some hybrid collaborative forms emerging include a hybrid between VBE and grasping opportunity-driven networks, as well as a hybrid between VBE and goal-oriented networks. This also presents a good research opportunity for both disciplines to explore and harness the benefits of hybridized systems in this regard.
4. It was also observed that the two communities use different languages or terminologies, although they refer to similar concepts. This suggests the need for the two communities to engage in further interactions to develop an inter-disciplinary knowledge base for the rapid evolution and development of the VPP concepts.

As such, some recommendation for future works can be derived:

1. The CN concepts constitute a mature discipline with a well-defined and clearly structured body of knowledge in various aspects and types of collaboration across diverse ecosystems. The adoption of this CN body of knowledge in the VPP collaborative environment could greatly enhance and expedite the quest to develop optimal VPPs and their associated technologies. It is therefore recommendable that future works consider a merge between these two disciplines to define a clear niche for a collaborative VPP/energy ecosystem.
2. Additionally, the smart grid, including VPPs, is susceptible to both manmade and natural vulnerabilities due to the increased number of disruptive events, happening simultaneously around the globe. This notwithstanding, VPPs are particularly vulnerable in the sense that they constitute, among other things, the integration of privately owned DERs, which by nature may represent a softer target among the entire energy ecosystem. This is because any adversary can easily infiltrate a private facility and pretend to be the DER owner or operator in order to gain access to the grid. Since aggregation in this environment is observed to be highly dynamic, it is very essential that VPP aggregators integrate security mechanisms to enable continuous monitoring and detection of unfamiliar behaviours of DERs that may pose a potential threat and have them eliminated on time to avoid failure of the grid. It is therefore observed that this aspect of VPP security, during the aggregation and operation stages of the VPP still remains an open research opportunity for the VPP and CN communities. Nevertheless, this is out of the scope of this research.
3. Again, VPPs have the ability to dynamically reorganize their compositions due to the stochastic nature of DERs and also based on the dynamics of demand and supply in the energy market. This dynamic reorganizing property of VPPs presents a good basis on which a resilient VPP architecture with collaborative reorganizing characteristics can be explored. For this reason, the notion of a “collaborative resilient VPP” is recommended for future works. This notion of “collaborative resilient VPPs” may function very well in the context of a VBE.

2.5 Part-2: A Review on Renewable Energy Communities

2.5.1 Introduction

This part of the review focuses primarily on RECs in general. The part is organized into two sections. The first section covers a brief or panoramic review of RECs. The objective of this preliminary section is to briefly present the state-of-the-art, focusing on the scientific concepts, trends, and models in the domain of RECs. In the second section, the review focuses on some selected REC cases. The key objective of the second section is to gain insight into the current state of implementation of these REC cases. The other objectives of this section are mentioned in the introductory paragraph.

2.5.2 A Brief/Panoramic Analysis of Renewable Energy Communities

In this section, a brief analysis of RECs from the scientific literature is performed. The focus areas involve the scientific concepts, trends, and models in four general areas: (a) technology, (b) energy management, (c) architecture, design, and planning, and finally (d) policy. Similar to the previous section, the systematic literature review methodology was used as well. To help identify the current concepts, trends, and models, as well as to gain a better understanding, insight and overview of the area, one guiding question is used to help define the scope of the review:

What scientific concepts, trends, and models are currently being used within the domain of RECs?

2.5.2.1 Article Search, Identification, Screening and Selection Processes

This section describes the various stages through which the articles for this part of the review are selected.

1. **Article search and identification stage:** At this stage of the review, the following search terms/words are used to search and select prospective articles. In Table 2.4, each keyword from column 1 is used in combination with the keywords from subsequent columns such as columns 2, and column 3 to search for prospective articles.

Table 2.4. A combination of keywords that were used to search for the articles

Column-1	Column-2	Column-3
Renewable energy	Communities Ecosystem	Scientific concepts Trends Models Technology

Column-1	Column-2	Column-3
		Policy Security

The search conducted with these search terms yielded a total of 92 articles.

2. **Article selection stage:** At this stage 70 articles are selected, and 22 articles are rejected. The selection of articles at this stage is based on their titles only. The rejected articles are due to duplication and out of scope titles.
3. **Article screening stage:** At this stage 19 articles are screened out and 51 articles are retained for further scrutiny.
 - a. **The inclusion criteria:** The following are the inclusion criteria for a paper to be included in the review: (a) The article must be published between the years 2010 and 2023, inclusive. The reason for selecting this period is to help provide a reasonable time window (13 years) within which sufficient evidence regarding the evolutionary trend of these concepts can be observed; (b) The article must discuss aspects of RECs defined in the focus area, namely: (i) technology, (ii) energy management, (iii) architecture design and planning of RECs and finally (iv) policy.
 - b. **Exclusion criteria:** All articles that failed to meet the inclusion criteria are automatically excluded.

Using the inclusion and exclusion criteria, the selected/screened articles are narrowed down from 51 to 35. This part of review is therefore conducted using these 35 articles.

2.5.2.2 Focus Areas

2.5.2.2.1 Technology

Technological support to RECs is discussed under three sub sections: (1) types of distributed energy resources, (2) blockchain and cyber-physical systems, and (3) hybrid systems.

1. **Types of Distributed Energy Resources:** Various types of resources can be found in literature. For instance, a small-scale, locally accessible decentralized energy system is described in (Belmar et al., 2023). The community uses Solar thermal energy, solar photovoltaic technology, solid biomass, and the burning of olive tree and olive kernel wood to meet the community's heat and electricity needs. The kinds of renewable energy technologies used in (Kazimierczuk et al., 2023) included a PV and wind system. A combination of solar, wind, biomass, and battery storage technologies are the key energy sources described in (Xu et al., 2023). Similar to this, a method for transforming solar energy into thermal energy is described in (Doroudchi et al., 2022). In order to support coastal communities, the idea of marine renewable energy technology is considered by (Kazimierczuk et al., 2023). Technologies that capture oceanic energy potential through waves, currents, tides, salinity, or temperature gradients and transform it into electricity or other useful types of energy are referred to as marine energy.

2. **Blockchain and Cyber-physical Systems:** An example that discusses a REC/microgrid developed using blockchain technology is shown in (Svetec et al., 2019). Similar to that, another proof-of-concept blockchain prototype is discussed in (Ioannis et al., 2017). Cyber-physical systems technology is widely used in this domain as well. In this regard, an IoT-aware model for optimization is for instance explored in (Giordano et al., 2020). Also mentioned and discussed in (Cicceri et al., 2023) is a deep learning-driven self-aware, distributed cyber-physical system for RECs. Finally, an example of blockchain-based form of governance is presented in (Chantrel et al., 2021).
3. **Hybrid technologies:**
 - a. **Hybrid between support technologies and energy resources:** Several hybrid technologies are in use in this area. For instance, a hybrid AI approach to improve energy management effectively in a REC is explored in (Conte et al., 2022). In another study, RECs are mentioned as adopting a prediction tool that combines machine learning with artificial neural network techniques (Zahedi et al., 2022).
 - b. **Hybrid between different storage systems:** hydrogen-battery energy storage system is mentioned in (Gandiglio et al., 2022). Studies like (Nastasi & Mazzoni, 2023) demonstrate that a solar hydrogen hybrid system, which involves creating green hydrogen by electrolysis supplied by solar panels, may compete with conventional electric batteries. To achieve energy efficiency in residential areas, a hybrid of energy retrofitting methods with renewable energy systems is explored in (Adly & El-Khouly, 2022).
 - c. **Hybrid power system:** Finally, the idea of power-to-X technology, which involves converting power from one state to another, is expounded in (Pastore et al., 2023). Some types of power conversion technologies, according (Zahedi et al., 2022), include power-to-gas, power-to-heat, power-to-vehicles, and power-to-power systems.

2.5.2.2.2 Energy Management

Energy management is here discussed under two sub sections: (1) automation, optimization and modelling, and (2) smart and intelligent management strategies.

1. **Automation, Optimization and Modelling:** The management of “energy sharing” activities in homes with surplus energy within a REC is explored in (Veichtlbauer et al., 2022) using a self-consumption and optimization model. Similarly, a strategy called stochastic model predictive control (MPC) that promises to reduce community energy expenses is discussed in (Scarabaggio et al., 2021). The MPC model is found to perform better in terms of maximizing self-consumption of on-site energy production while minimizing energy costs. An automated distribution mechanism for surplus energy in an aggregate where consumers may or may not have an energy storage system has also been detailed in (Menniti et al., 2020).
2. **Smart and Intelligent Management Strategies:** An example of article that describes how to construct smart integrated renewable energy systems (SIREs) by using intelligent techniques is proposed by (Maheshwari & Ramakumar, 2016). The article

describes how SIRES can be used to meet the basic necessities like biogas for cooking, water for domestic, potable, and irrigation needs, and electrical energy for lighting, communication, cold storage, education, and small-scale industrial needs in the REC. To help improve living and community welfare in rural communities, a smart control hub energy data aggregation platform (SCHEEDAP) is described in a related study. The study suggests a concept for smart communities using renewable energy sources that aggregates PV energy generation, storage, and controllable loads on a platform for smart energy management (Dumitraşcu et al., 2023). Another article that discusses a multi-agent reinforcement learning-based energy management system is presented in (Lai et al., 2022). In their proposed method, appliance scheduling is formulated as a game that can be solved by a group of agents. The management of energy in a REC is optimized using an IoT-aware model that is described in (Giordano et al., 2020). Artificial neural networks are used to evaluate a machine learning and prediction tool in (Zahedi et al., 2022). An AI-optimal technique intended to help increase the effectiveness of energy management in a smart REC is evaluated in (Conte et al., 2022).

2.5.2.2.3 *Architecture, Design and Planning of RECs*

A reference model that acts as a toolbox for designing RECs is presented in (Ubelmesser et al., 2022). It incorporates a social and operating model as well as a statistical model to accurately assess the success of RECs. (Hansen et al., 2020) investigate how technological innovations might be utilized to create systems that encourage people to work together as energy communities make the transition to sustainable energy use. The design and development of the Lumen prototype for the operation of RECs are discussed in (Zahedi et al., 2022). The prototype supports a small energy community in shifting domestic energy consumption practices to align with times of high availability of renewable energy. An article that discusses a solar energy production and distribution architecture that employs smart contracts to promote automatic and distributed energy exchange, enabling the establishment of a more open and productive energy micro-generation market from the end-user perspective is expressed in (Ioannis et al., 2017).

An evaluation and design approach for hybrid renewable energy systems (HRESs) is covered in (Xu et al., 2023). Furthermore, a tool to aid both the planning and operating phases of RECs is presented in (Lazzari et al., 2023). The study proposes and validates a set of optimization techniques to help REC members during both the planning and operation stages and, as a result, support them in obtaining the most possible environmental and financial benefit from their group initiative. Additionally, a mixed-integer linear programming-based planning strategy for communities using renewable energy is mentioned in (Cosic et al., 2021). Also covered is a study that models the effects of various energy community design alternatives on the overall economic and environmental performance of energy communities (Belmar et al., 2023). The study presented several energy community typologies, such as various participant types, prosumer types (with various technological features like solar PV systems, electric vehicles, or battery energy storage

systems), PV sizing scenarios (techno-economic and high-solar fraction), and various local electricity market models.

2.5.2.2.4 Policy

(Thompson, 2022), asserts that the laws governing RECs in the EU vary greatly according to geographic, cultural, economic, and political variables. According to Thomson, there are a number of general factors that should be taken into account in each member state in order to assist in the expansion of RECs. They talk about potential barriers to the successful implementation of Renewable Energy Directive (RED II) (European Union, 2019), such as geographic dispersion and temporal fluctuation of renewable energy potential, resistance from incumbents, and issues with representation and inclusion in community energy projects. Four aspects that are important for the creation of RECs are mentioned and discussed in another study by (Hoicka et al., 2021), namely electricity energy mix, renewable energy targets, renewable energy standard offer programs, and feed-in tariffs. The study comes to the conclusion that a long-term strategy is required to lessen the harmful effects of hydroelectric water fluctuation, taking into account the requirement to decommission several Canadian dams. The establishment of energy policies for cities that combine retrofitting procedures, including rules for community-scale retrofitting, is covered in (Adly & El-Khouly, 2022). The study establishes the framework and elaborates on the guidelines for structuring this process. The study demonstrates how to recognize communities that use renewable energy as legal entities that should be integrated into their own socio-legal institutions in order to promote a just new energy system.

2.5.3 A Review of the Areas of Convergence Between Renewable Energy Communities and Collaborative Networks

This part focuses on an in-depth review of selected cases of virtual/online renewable energy communities. The objectives of this part of the survey are as follows:

1. To glean adequate insight into the current state of implementation of some selected REC cases that are found in this type of energy ecosystem.
2. To ascertain if the interaction between members of the selected energy ecosystems can be described as "networking," "collaboration," "coordination," or "cooperation".
3. To identify the technological enablers and trends that underlie the establishment, operation, and service provision of these ecosystems.
4. To compare the characteristics and functions of these VPPs to those of renewable energy ecosystems to determine possible areas of convergence.

As mentioned earlier, the review is conducted using foreknowledge from the domain of CNs. The review is done by evaluating and interpreting available renewable energy cases under specifically defined focus areas that are relevant to both domains. To achieve these objectives, the following questions are adopted for this part of the case review:

PT2-RQ1: How can the interaction between members of the selected energy ecosystems be described? [Collaborative relationship]

PT2-RQ2: What technological enablers and trends underlie the establishment, operation, and service provision in these ecosystems? [Technological enablers and trends]

PT2-RQ3: How do the characteristics and functions of virtual power plants (VPPs) compare to those of renewable energy ecosystems? [Organizational forms]

2.5.3.1 Cases Search, Identification, Screening and Selection Processes

Here we describe the various stages through which energy community cases are identified and selected.

Case search and identification stage: At this stage of the review, the search terms/ words shown in Table 2.5 are used to search and select prospective cases. Each keyword from column 1 is used in combination with the keywords from subsequent columns such as columns 2, column 3, and column 4. At this stage, 68 cases are identified.

Table 2. 5—Keywords that were used to search for cases.

Column-1	Column-2	Column-3	Columns-4
Keywords describing the energy source	Keywords describing the type of interaction	Keywords describing the place of interaction	Keywords describing the type of ecosystem
Renewable energy Distributed energy Sustainable energy Green energy Distributed generation	Sharing Collaboration Cooperation Coordination Network Partnership Joint Co-evolution Coalition	Online Portal	Community Ecosystem Platform Portal Marketplace

1. **Case selection stage:** At this stage of the process, 62 cases are selected, and 6 cases are excluded.
2. **Case screening stage:** At this stage 12 cases are screened out and 50 cases are retained.
 - a. **The Inclusion criteria:** The inclusion criteria are as follows: (a) That all the cases must be relatively recent, thus, between the years 2010 and 2023, inclusive. (b) The primary source of energy and related services must be from renewable energy sources. (c) The focus of the community must revolve around renewable energy, sustainable energy generation, and consumption. (d) The place of interaction for the community must be online. Using the inclusion criteria, 34 cases are retained to be included in the review. The primary source of information that is used to analyse these cases is obtained from the case’s websites. Additionally, available white papers were also consulted. In most cases, these white papers provide more insight into the cases than the websites.
 - b. **Exclusion criteria:** All cases that did not match the inclusion criteria are excluded. At this stage, a total of 16 cases are excluded because they did not meet the inclusion criteria.

Using the inclusion and exclusion criteria, the selected and screened cases were narrowed down from 68 to 34. Therefore, part 2 of review is conducted using these 34 cases.

2.5.3.2 Overview of the Selected Cases

During the search and selection process, it was found that the promoters of these cases came from different backgrounds, and the cases are owned by different business entities. The category of entities that owned these cases included trading companies, financial/investment companies, solution developers, sole proprietors, limited liability companies, service providers (provides platforms as a service), non-profit organizations (e.g., Prosume Foundation) etc. Although diverse, they all share some common characteristics that are relevant to the study. For instance, in almost all cases, the business entity brings together sellers and buyers of energy on a single platform, portal, ecosystem, or community to facilitate the exchange of energy and related services that promote sustainable energy generation, consumption, and trading. In almost all cases, blockchain technology is used to facilitate secure and trustworthy transactions (e.g., LO3 energy/Brooklyn microgrid). Besides the fact that all these cases meet the Inclusion criteria, their inclusion in the study also helps to widen the scope of the study by providing diversity in the cases considered. In addition, the cases were also found to be at different stages of development. Some cases are in the conceptual stage, others are in the developmental/prototype stages, and some are active/operational businesses.

In this section of the study, a detailed analysis of the 34 selected cases is performed. In Table 2.6, a brief description of each case and its core functions are tabulated.

Table 2.6—A summary of the selected cases for the study

Index	Cases	Description	Core functions
1	BittWatt	A smart and flexible system that makes the most of all energy sources and enables users to exceed their customer's needs in a balanced and financially efficient ecosystem that learns and evolves. (BittWatt, 2018)	<ol style="list-style-type: none"> To provide blockchain-enabled peer-to-peer energy trading platforms and services. A new marketplace for electricity balancing and trading
2	Electrify Network	A technology start-up that aims to bring the process of investing in renewable energy plants, smart micro-grid deployment, transactive energy marketplaces, and self-sustained smart city development to a grass-root level (Electrify-Network, 2018).	<ol style="list-style-type: none"> To build renewable power systems and produce exclusively green energy that will be sold to utility providers and government-owned entities. To build a dynamic platform for peer-to-peer (P2P) energy trading using blockchain. Contribute to the building of self-sustaining smart city pilot projects. To provide venture capital for renewable energy projects.
3	Electrify.Asia	An ecosystem that allows consumers to buy their energy directly from peers or electricity retailers using the blockchain and smart contracts (Tan, 2017).	<ol style="list-style-type: none"> P2P energy trading platform. Promote the use of "synergy" and "marketplace 2.0," which are web and mobile application interfaces that let people make smart contracts with their energy providers.
4	ElectronConnect	Provides marketplace infrastructure, in the form of a multi-market launch and hosting facility, that enables network operators, distributed energy resource operators, and others to interact and unlock market-based efficiencies (Electron, 2018).	<ol style="list-style-type: none"> A service provider that provides a marketplace or platform as a service
5	EnergiMine	A platform that matches customers with small generators. Aims at creating a global ecosystem where users are rewarded with tokens for energy-efficient behaviours. For example, if a commuter is encouraged to use public transport by the local city authorities, they could be rewarded by being given an ETK token (EnergiMine, 2018).	<ol style="list-style-type: none"> A service provider with a platform that achieves two objectives: <ul style="list-style-type: none"> P2P marketplace for energy trading over the blockchain. Incentivization & reward scheme for energy-saving behaviours.
6	Energo Labs	Start-up with the intent of creating a P2P platform for a distributed energy system using blockchain technology with a particular focus on microgrids (Cleantechnica, 2017).	<ol style="list-style-type: none"> The company provides a platform that integrates blockchain technology into the energy sector to establish Decentralized Autonomous Energy (DAE) communities, enabling enterprises to convert energy into digital assets and use them in P2P, machine-to-machine, electric vehicle-to-virtual

Index	Cases	Description	Core functions
			grid, green card trading, carbon trading, and virtual net electricity billing forms.
7	Energy Web Foundation	A low-carbon, customer-centric electricity system that enables any energy asset owned by any customer to participate in an energy market (Energy Web, 2022).	1. Peer-to-peer energy trading service provider.
8	EnergyNet	A secure and cloud-based software-as-a-service platform that solves the most crucial challenges of Transactive Energy. Thus, compensation for providing distributed energy services via the distributed electric grid (Causam-eXchange, 2018).	1. To provide a blockchain-enabled peer-to-peer energy trading platform.
9	Enosi Foundation	The Enosi Platform permits energy providers to offer less expensive community-based energy programs. Using the Enosi Protocol, households with solar energy systems can become prosumers and sell excess energy to buyers of their choosing at prices they determine. They will be able to engage in peer-to-peer trading and community-owned generation, as well as take advantage of offers from innovative new energy retailers that benefit from the Enosi Platform's lower cost structure. (Enosi, 2018b).	1. Leverages smart meter technology that digitizes energy data, and combines this data with recent advances in distributed ledger technology to deliver: <ul style="list-style-type: none"> • A more efficient and secure transactive services platform. • Access to competition throughout the value chain • The ability for distributed renewable generation to be accessed through community energy schemes and markets. • Market-led adoption of decentralized energy solutions
10	EtainPower	A platform that creates a compelling new channel for global investors to access and invest in renewable energy projects (Etainpower, 2017).	1. To provide renewable energy financing and a trading platform that is empowered by both blockchain and AI technologies.
11	Greeneum	Blockchain-powered, sustainable, scalable, and secure energy and data trading platform (Greeneum, 2018).	1. Provide Software as a Service (SaaS) for grid operators and utilities 2. Premium services (obtain financial and performance reports, maintenance operation reports, and actionable insights that can potentially lead to higher profitability) for solar and green energy producers. 3. Provide smart contract services. 4. Advertisements: The platform will attract a high volume of repeat user which will allow companies to advertise their products and services for a fee.
12	Grid+	The Grid+ agent leverages AI to understand and predict consumers' energy usage habits. With real-time pricing data, the agent makes smart decisions on behalf of the purchaser of energy in the most cost-effective way with zero effort from users (Consensys, 2017).	1. Develop cutting-edge secure hardware and software to enable the use of cryptocurrency. 2. Management of digital assets 3. Trading in energy.
13	GridX	This provides a financial operating system to enable utilities, retail energy suppliers, distributed energy resource providers, energy service providers, and their customers to operate and participate in decentralized energy markets (GridX, 2017).	1. Enable utilities, retail energy suppliers, third-party energy services providers, and their customers to operate and participate in decentralized energy economies.
14	Hive Power	A turnkey solution to create and manage local energy communities on the blockchain called the "Hives", provides economic optimization for participants. A Hive is a distributed energy market platform regulated through smart contracts where every user can buy and sell electrical energy (Rivola et al., 2018).	1. P2P energy trading platform service provider.
15	Joulette (Spectral)	A blockchain-based platform that enables individuals and communities to manage and share renewable energy produced locally (Spectral, 2021).	1. Selling renewable energy. 2. Purchasing renewable energy.
16	KWHCoin	A blockchain-based solution for a platform that makes it easy and cheap to add renewable energy and distributed energy resources to the grid (KWHcoin, 2016).	1. A digital currency that uses a blockchain to turn information about distributed energy resources into digital tokens.
17	Lition	It is a P2P energy trading platform that connects renewable energy producers with smart consumers directly. (Lition, 2018).	1. Aims to make green electricity simple and flexible by directly connecting producers and customers.
18	LO3 Energy/ Brooklyn Microgrid	A blockchain-based platform that enables decentralized business models and innovative technologies related to energy. (LO3 Energy, 2017).	1. A blockchain-based platform that enables decentralized business models and innovative technologies related to energy. 2. They operate the Exergy System.
19	NAD Grid	A P2P energy exchange platform that is backed by advanced blockchain technology. (NADGrid, 2018).	1. A decentralized P2P electricity trading platform. 2. It enables buyers and sellers to trade electricity using the Eden token (cryptocurrency).
20	Peer 2 Peer Energy Protocol (P2PEP)	A distributed energy trading application that lets both small and large clean energy producers and consumers connect over the blockchain (Peer to Peer Energy Blockchain Protocol, 2017).	1. A blockchain-enabled P2P energy trading service provider.
21	Power Ledger	A trustful, transparent, and interoperable energy trading platform that supports a growing number of energy applications. (PowerLedger, 2018).	1. A platform that can provide real-time metering data, collection of big data, the right to access and dispatch assets, rapid transaction settlement, and network load balancing. This is applied in areas such as: P2P Trading, Neo-retailing, Microgrid/embedded network, Wholesale market

Index	Cases	Description	Core functions
			settlement, Autonomous asset (AA) management, Distributed market management: , Electric vehicles charging, Carbon trading, Transmission exchange.
22	Prosume Foundation	A Swiss foundation and non-profit organization with a vision of empowering communities to exchange energy assets in a P2P fashion using a blockchain-based online market. (Prosume, 2017).	1. Aims to develop a platform that will be used by utility companies, grid operators, system integrators, and communities to easily build local ecosystems and online marketplaces.
23	Pylon Network	A blockchain network designed to create an open renewable energy exchange community that will provide signals and financial incentives to the energy markets (Klenergy Tech, 2017).	1. To facilitate the growth of digital energy services, such as the transformation of the energy market to a consumer-centric and energy-as-a-service model, in the era of digitalization.
24	Share & Charge	A marketplace/community that provides solutions for electric vehicle charging. It enables simple, secure, and smart charging services based on the Open Charging Network (OCN) (Share&Charge, 2020).	1. A B2B service provider that provides simple, secure, and smart charging services based on the OCN.
25	Solar Bankers	Aims to develop a global network of self-sufficient, decentralized renewable energy communities and, through digitization, which is enabled by the Solar Bankers coin, which may transform electricity into a globally exchangeable commodity (SolarBankers, 2018).	1. An international renewable energy company that is focused on the development of a global network of self-sufficient, decentralized, renewable energy communities.
26	Solar IoT	A P2P blockchain energy grid, that allows individuals to buy and sell energy to others in a fully open marketplace on the Ethereum Blockchain, where prices are low and energy is abundant (Solariot - Home, 2018).	1. Financing of solar projects. 2. P2P energy trading service provider.
27	SonnenCommunity	A community where members (households) can store and use their self-generated energy using Sonnen's intelligent energy storage system, the SonnenBatterie. (Sonnen, 2017).	1. Develop and promote the use of the "sonnenBatterie", an intelligent energy storage system. 2. Communalization of energy storage. 3. Community-based energy sharing. 4. Provide e-mobility services.
28	Sun Exchange	Sun Exchange enables people to locate their solar panels in the optimal places on the planet for the good of the owners, and the energy users, as well as offering an indirect benefit to the entire world population (The sun exchange, 2018).	1. To provide a peer-to-peer solar leasing platform.
29	SunContract	A platform for trading energy that will create the SunContract energy pool and make it easier for people to buy and sell electricity directly from each other using blockchain technology.(SunContract, 2017).	1. A service provider that uses the SunContract pool for the sale and purchase of renewable energy.
30	Tarus Project	Using electric vehicles (EV) as a mobile power transmission network. (Buterin, 2015).	1. Blockchain-enabled peer-to-peer energy trading and EV charging services.
31	Toomuch.energy	Toomuch.energy transforms neighbourhoods into fully digital energy communities with a range of P2P services and market choices. (Vasylchenko, 2015).	1. To provide a blockchain-enabled peer-to-peer energy trading platform.
32	Verv VLUX	Verv combines innovations in machine learning, blockchain, AI, IoT, and energy storage to help develop peer-to-peer energy trading using the Verv Trading Platform (VTP). The ecosystem has been designed to facilitate trading at the grid edge (Vlux, 2018).	1. Peer-to-peer energy trading service provider. 2. Deployment of IoT devices such as the VHH to manage household energy consumption and data collection.
33	Volt Market	Volt Markets disintermediates traditional energy markets and enables monitoring, managing, and trading of energy and energy attributes in a P2P market on the Ethereum blockchain (Voltmarkets, 2021).	1. Providing a platform which is driven by smart contracts on the Ethereum blockchain. Volt Market says it will make a system that is more secure, clear, and efficient than the ones that are already in place
34	WePower	WePower is a blockchain-based green energy financing and trading platform. It connects energy buyers (households, investors, or market makers) directly with green energy producers to facilitate the upfront purchase of energy at below-market prices. It uses energy tokenization to standardize and simplify the currently existing energy investment ecosystem. It is claimed to provide access to live trade in renewable energy globally for everyone (WePower, 2017).	1. Financing green energy projects. 2. P2P energy trading service provider.

2.5.3.3 Summary and Cases Comparison

Table 2.7 provides a summary of the cases, detailing how they compare to each other. The corresponding cases and their total numbers are also shown in the table. Generally, all these cases can be categorized into two generic groups, namely:

1. Platform as a Service (PaaS). Under this category, we identified several types of sub-services:
 - a. IoT integration services.
 - b. Renewable energy project financing services.
 - c. Creation of a marketplace for trading.
 - d. Encouraging green behaviours.
 - e. Compensation schemes.
 - f. Provision of energy storage services.
 - g. Facilitation of the integration of renewable energy sources into the grid.
 - h. Offer of charging services for electric vehicles,
 - i. Offer of load balancing services.
 - j. Supporting the idea of a "smart city."
2. The second category is "software as a service." Under this category two key services are found:
 - a. Software to provide reporting services (financial, performance, and maintenance operation reports). Other services found include advertisements that could generate additional income for the platform/ecosystem.
 - b. Software for agent-based decision-making services.

Table 2.7—A summary and case comparison

Types of Services	Nature of service	Cases	Total number of cases
Platform as a Service	Facilitating IoT integration	Verv VLUX	1
	Financing of renewable energy projects	GridX, Solar Bankers, Solar IoT Sun Exchange, WePower, EtainPower, Electrify Network	7
	Facilitating a marketplace for trading	Electrify.Asia, ElectronConnect, EnergiMine, Enosi Foundation, EtainPower, Lition, LO3 Energy / Brooklyn Microgrid, NAD Grid, Peer 2 Peer Energy Protocol (P2PEP), Power Ledger, Prosume Foundation, Pylon Network, SunContract, Toomuch.energy, Verv VLUX Volt Market	18
	Promoting green behaviours	Energolabs, Power Ledger	2
	Facilitating compensations	EnergyNet	1
	Facilitating energy storage	SonnenCommunity	1
	Facilitating integration of renewable energy in the grid	KWHCoin	1
	Facilitating electric vehicle charging services	Tarus Project	1
	Facilitating load balancing	BittWatt, Power Ledger	2
	Facilitating smart city concepts	Electrify Network	1
Software as a Service	Facilitating the management of energy asset and data	Energy Web Foundation, Greeneum, Power Ledger, Volt Market, Power Ledger	5
	Reporting and Advertisement	Greeneum	1
	Agent-based decision-making	Grid+	1

2.5.3.4 Focus Areas

In this section of the review, the cases are analysed based on the following perspectives: (a) collaborative relationships, which corresponds to research question 1, (b) technological enablers and trends, corresponding to research question 2, and finally (c) organizational forms, which also corresponds to research question 3.

2.5.3.4.1 Collaborative Relationships

The outcome of the analysis of collaborative relationships is summarized in Table 2.8. To help answer this question, we studied each case to determine the presence of some key features that are used to describe collaboration. Ten key features are used. For a case to be considered as engaging in collaboration all of the features of collaboration must be visible in the case. In cases where these features are partially visible, the cases were further analysed to determine whether they could fit the description of networking, coordination, or cooperation. For this purpose, the following features are used:

1. *Is there evidence of communication and information exchange for mutual benefit?*
2. *Are the activities of the members in the ecosystems coordinated?*
3. *Is there evidence to support the presence of “joint planning” and “joint implementation”?*
4. *Is there evidence of a common plan that is jointly defined and pursued?*
5. *Is there evidence of mutual engagement resulting in the joint creation of a product or service?*
6. *Is there evidence of risk, resources, and rewards sharing?*
7. *Do members possess or assume a joint or collective identity?*
8. *Is there a common goal (or compatible goals) that is jointly agreed upon and jointly pursued?*
9. *Do members create value together?*
10. *Is there evidence of division of labour?*

Table 2.8—Analysis of cases to identify the features of Collaboration or Cooperation (RQ-1)

Index	Cases	Communication and information exchange for mutual benefit	coordinated activities	Joint planning and implementation	Common plan jointly defined	Mutual engagement for Joint creation	Sharing risk, resources, responsibilities, and rewards	Image of joint identity	Common goals	Value co-creation	Division of labour	Conclusion/Remarks
1	BittWatt	Partial	Partial	No	No	No	Partial	Yes	Yes	No	Yes	Cooperation
2	Electrify Network	Partial	Partial	No	No	No	Partial	Yes	Yes	No	Yes	Cooperation
3	Electrify.Asia	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
4	ElectronConnect	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
5	EnergiMine	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
6	Energo Labs	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
7	Energy Web Foundation	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
8	EnergyNet	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
9	Enosi Foundation	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
10	EtainPower	Partial	Partial	No	No	No	Partial	Yes	Yes	No	Yes	Cooperation
11	Greeneum	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
12	Grid+	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
13	GridX	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
14	Hive Power	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
15	Jouliette (Spectral)	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
16	KWHCoin	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
17	Lition	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
18	LO3 Energy / Brooklyn Microgrid	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
19	NAD Grid	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
20	Peer 2 Peer Energy Protocol (P2PEP)	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
21	Power Ledger	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
22	Prosume Foundation	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
23	Pylon Network	Partial	Partial	No	No	Partial	Partial	Yes	Yes	Aggregated value	Yes	Cooperation
24	Share & Charge	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
25	Solar Bankers	Partial	Partial	No	-	Partial	Partial	Yes	Yes		Yes	
26	Solar IoT	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
27	SonnenCommunity	Yes	Yes	Yes, using a self-learning software platform	Yes	Yes, using a self-learning software platform	Yes	Yes	Yes	Yes	Yes	Collaboration
28	Sun Exchange	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
29	SunContract	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
30	Tarus Project	Partial	Partial	No	No	No	Partial	Yes	Yes	No	Yes	Cooperation
31	Toomuch.energy	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
32	Verv VLUX	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation

Index	Cases	Communication and information exchange for mutual benefit	coordinated activities	Joint planning and implementation	Common plan jointly defined	Mutual engagement for Joint creation	Sharing risk, resources, responsibilities, and rewards	Image of joint identity	Common goals	Value co-creation	Division of labour	Conclusion/Remarks
33	Volt Market	Partial	Partial	No	No	Partial	Partial	Yes	Yes	No	Yes	Cooperation
34	WePower	Partial	Partial	No	No	Partial	Partial	Yes	Yes	Aggregated value	Yes	Cooperation

- Yes: means there is sufficient evidence to conclude.
- Partial: means there is some evidence, but not concrete or sufficient to conclude.
- No: means there is no evidence.

Summary of Review Outcome Concerning Collaborative Relationships:

1. ***Communication and information exchange for mutual benefit.*** In all cases considered, there is some form of information exchange across the platforms for the benefit of participants. For instance, considering Power Ledger, the platform facilitates information sharing that enables participants to identify and select different clean energy sources according to their desired preferences. In addition, members have access to information that enables them to select and trade with their neighbours. There is also information about incentives that is shared for the benefit of participants involved. Although there is evidence of information exchange, the objective of exchanging information is not aimed at solving a common problem or creating some value together. In other words, there is no common goal or agreed objectives, to which this communication is intended to contribute. Since the study found some level of communication and information exchange as well as some level of benefits, even though they are not mutual, we can say that the level of communication and information exchange is "partial" in almost all cases except SonnenCommunity. In this community, the households are installed with some intelligent batteries, which are managed locally using a proprietary intelligent energy management software. This software collects information about the household's energy generation and consumption. This information is shared with the central VPP software. The VPP platform collects similar information from all households in the community and uses this information to make decisions related to the provision of VPP services. The goal of sharing this information is common to all households, thus facilitating decision-making towards the provision of VPP services to the grid, which is a common goal for the community.
2. ***Coordinated activities.*** In all cases considered, there is some level of coordination between service providers and participants. There is also evidence of coordination among the participants. However, coordination among members of these ecosystems is not based on mutual or clearly defined common objectives or goals. Service providers often facilitate this coordination. From the perspective of collaborative networks, coordination is defined as the act of working together harmoniously to achieve a common goal. However, the intent behind the type of coordination observed in these cases is not aimed at a common or agreed-upon goal. The coordination found did not involve the alignment or altering of individual activities so that, mutually, more efficient results could be achieved collectively. The types of coordination found in these cases can best be described as administrative or managerial roles that are played by third-party entities or service providers. From our observation, activities that are carried out in these ecosystems are not coordinated with collaboration in mind. Thus, it might be fair to give a "partial" status to this feature in all the cases that are analyzed, except for the SonnenCommunity, which has clear evidence of coordinated activities that tend toward working together.
3. ***Common plan, joint planning, and implementation.*** In all but one of the cases considered, there is no evidence of a common plan as well as joint planning and implementation designed by mutual consent or agreement among the actors in these

ecosystems. However, as an exception, joint planning and implementation can be seen only in the SonnenCommunity. For this ecosystem, joint planning and implementation are achieved using a self-learning software platform (Shepard, 2015). Planning and implementation, in almost all cases, are performed in a quasi-independent manner, without the involvement of other participants. Individuals such as prosumers, investors, and consumers can engage in their planning and implementation activities without consulting other actors in the ecosystem. Therefore, the status of this feature for all the other cases can be described as “No.”

4. ***Mutual engagement in joint creation.*** Mutual engagement in joint creation means that parties come together to engage each other to jointly create a product, or a service, or increase the value of a product or service. In the considered cases, there is evidence of mutual engagement in most cases to help achieve the objectives of the various actors. However, in the case of the SonnenCommunity, it is completely different. In this case, the community uses a software platform to engage members in a way that allows the community to act as a VPP, selling renewable energy to the grid to create value. In this case, mutual engagement is visible, although mediated through a software application. In most other cases, the evidence is partially visible in the sense that value creation is observed. However, the process of creating value is not born out of any form of mutual engagement. Nevertheless, the types of products and services that are found can be the result of individual efforts that produce the results, without any underlying mutual engagement. It can therefore be inferred that value, in most cases, is created in a quasi-independent manner, without a common plan, agreement, or purpose. Thus, we consider that in most of these cases, mutual engagement for joint creation is "partial".
5. ***Sharing risks, resources, responsibilities, and rewards.*** There is evidence of partial sharing of resources, risks, and rewards. For instance, in the case of WePower, small energy producers who use WePower services and who cannot reach the 1 MWh certificate, which is the minimum requirement to trade in the energy market, are grouped as a single entity to sell their energy to the market. The constituents of this entity share the benefits proportionally among themselves. However, no explicit mention is made of sharing of risks and responsibilities. Similarly, the Pylon Network offers tools to simplify shared ownership processes through transparent, safe, and real-time monitoring of assets. This includes the distribution of profits or costs associated with the co-owned assets. Details about risk sharing are not explicitly mentioned in these cases. Moreover, it is observed that there is a common goal, namely, to aggregate energy and sell it to the grid. However, this goal does not result from a mutual plan based on a common objective with clearly defined roles or responsibilities for each member. Although the sharing of rewards and resources is explicitly mentioned in the Pylon Networks, the sharing of risks and responsibility is not. Because of this, we consider that sharing risks, resources, rewards, and responsibilities in these ecosystems is usually "partial."
6. ***Having an image of collective identity.*** Evidence of the notion of joint image or identity is found in almost all the cases considered. Although there is no explicit mention of a

joint or collective identity, it is acknowledged that all these communities possess name(s), which gives them some unique identity. Prior to joining the community, members may be conversant with the names, functions, and identities of these ecosystems. Nevertheless, they chose to join them anyway. Since members signed up for these communities knowing what they are, what they stand for and how they operate, our opinion is that identity is implied. Therefore, in all cases considered, this feature is considered present.

7. ***Having common or compatible goals.*** It is further observed in almost all the studied cases that sellers, buyers, investors, and service providers have “quasi-common” goals. These goals are found in two layers. The first observed layer is a sustainability goal. This goal is common among sellers whose primary objective is to generate, consume, and trade excess renewable energy, although this goal is not jointly conceived. Buyers, in most cases, also have a similar sustainability goal, which is to purchase and consume energy from renewable sources rather than fossil fuel-based sources. The goal of third-party actors, in the same sense, is to invest in renewable energy by creating a marketplace where sustainable energy and related services can be exchanged. These activities of third-party actors will consequently promote “sustainable consumption,” hence an implicit goal. The second layer goal is an economic one. The goal of sellers, in this sense, is to maximize revenue from their sales. The goal of buyers, on the other hand, is to minimize the cost of their purchases. The goal of third-party actors is to maximize revenue and minimize costs. In addition, it can also be argued that prospective actors in these ecosystems may often have prior knowledge of the aims, objectives, and possibly goals of these ecosystems before joining. Accepting the terms and conditions at the time of joining may constitute an implied acceptance and alignment of the goals. In a hypothetical sense, all these goals can be considered compatible, although implicit or tacit in their design. Since the focus of this aspect of the study is centred on identifying “common goals,” it may be reasonable to infer the existence of some form of common “sustainability” and “economic” goals, although it can be argued that these goals were not jointly defined. Therefore, it may be reasonable to generalize the conclusion about “common goals” as being “present.”
8. ***Value co-creation.*** This notion implies the involvement of the customer and local stakeholders in the process of collectively creating new products or services. In the context of collaboration, it is usually not easy to clearly identify the amount of “added value” that each member has contributed. Subsequently, it is not easy to devise general schemes to distribute revenues and liabilities. There are other complementary factors that influence the behaviour of a network and thus its ability to generate value. These factors include the scheme of incentives, trust relationships and management processes, ethical code, collaboration culture, contracts, and collaboration agreements. These are key elements in a value co-creation environment. In almost all cases studied, these key value-creation elements or factors are not explicitly discussed. For instance, in the “Prosume” ecosystem, it is mentioned that “consumers will choose their energy provider according to their needs, possibilities, and ethics”. Ethics, as mentioned in this sense, is not about value co-creation. Also, an ecosystem like “EnergiMine” mentioned

incentives in its white paper, but this relates to behaviour change and not necessarily value creation. Although many of the factors that influence the behaviour of a network towards value creation, as stated in, are mentioned sporadically in several cases, they have no special connotation to value creation. Three exceptional cases were found. These are the “Pylon Network”, SonnenCommunity, and “WePower”. These cases make explicit mention of aggregated value, which can be synonymous with value co-creation. Except for these three cases, all other cases can be considered as not co-creating value.

9. ***Division of labour.*** Division of labour, according to (Economics Online, 2020), is the process of dividing a task or job into smaller, interconnected sub-tasks, thereby generating efficiency gains due to the positive effects of specialization. The available evidence from the studied cases suggests that each member plays specific and specialized roles to achieve individual objectives. For instance, prosumers play their respective roles as producers, while consumers also play their respective roles as consumers. Investors and service providers also play their respective roles accordingly. Although these actors are found to be playing their natural roles as independent business entities, it can further be argued that these roles are “implicit roles” in the sense that each actor is likely to have foreknowledge of their expected role before joining a community. Furthermore, these roles are highly specialized, and the ecosystem is able to achieve its objectives by aggregating the outcomes of each actor’s role. As a result, it may be commendable to infer that there are some forms of “division of labour” in these cases. However, they are more implicit and implied. The conclusion for this element is therefore in the affirmative.

2.5.3.4.2 *Technological Enablers and Trends*

The outcome of this analysis is summarized in Table 2.9. For this purpose, we studied each case to identify the key technologies being deployed in these ecosystems. Nine key technologies are observed, as briefly explained below:

Artificial Intelligence/Machine Learning. This element of the study focused on how artificial intelligence and machine learning technologies are being used in the studied energy ecosystems. Two subsections are considered under this section:

1. ***The integration of smart devices, IoT devices, smart meters, as well as intelligent agents.***

- a. ***Smart Devices, IoT Devices and Smart Meters:*** Under this item, we identified 29 out of 34 cases that integrate smart meters or IoT devices into their operation. Some examples include cases such as Electrify.Asia (Tan, 2017), which uses the Powerpod in its networks. Powerpod is simply an IoT gateway for reading and relaying real-time energy data to a central management system of the Electrify.Asia network, allowing an algorithm to match and process settlements. A second example is the Pylon network (Klenergy Tech, 2017), which relies on a generic smart meter. The device is called the Klenergy METRON (Andoni et al., 2019), and is described by the network as any digital meter, sub-meter, or electric vehicle charger that can record energy data on the Pylon Network's blockchain. A third example is the gridbox from gridx (GridX,

2017), which serves as a gateway to its Xenon platform, which is the interface to all connected DERs, and is used for data collection and management. The Verv vlux network also introduced its core IoT product called the Verv Home Hub (Vlux, 2018), which is a patented, self-installed energy hub that samples a home's electricity consumption approximately 5 million times faster than a smart meter. It uses machine learning algorithms to derive a real-time profile for key household appliances, providing homeowners with a view of their electrical appliances' current status (Vlux, 2018).

- b. **Intelligent Agents:** As an example of the use of software agents, Energy Web Foundation's Decentralized Autonomous Area Agent (D3A) is an intelligent software agent that performs grid communication and control functions for physical assets. D3A allows any energy-consuming or energy-producing device to interact with other devices in a trustless blockchain environment, helping to optimize operational decisions locally and based on user preferences and system conditions (Bronski et al., 2018). Another intelligent agent application is found in the case of Grid+. In this example, whenever a customer signs up for Grid+, he will purchase a Smart Agent and buy BOLT (a cryptocurrency) from the Grid+ web console. The Grid+ smart agent, once registered, will allow customers to transfer BOLT tokens to the Smart Agent to pay for electricity in real time. An automatic payment option can be set up so that it can be refilled automatically if a Smart Agent runs out of BOLT. (Brock, 2018).
- c. **Blockchain Technology:** In (Gupta, 2020), a blockchain is described as a distributed and immutable ledger that facilitates the recording of transactions and the tracking of assets within a business network. An asset can be either tangible (such as a house, automobile, money, or land) or intangible (intellectual property, patents, copyrights, branding etc.). In a blockchain network, almost anything of value may be recorded and sold. In the context of renewable energy communities, blockchain can give consumers greater control over their energy sources. Additionally, an immutable ledger provides secure and real-time updates of energy usage data and monitors trading between sellers and buyers. The transparency of public blockchains further reduces the chances of monetary or data exploitation (ConsenSys, 2022). Concerning the type of distributed ledger technology that is mainly used, it is found that all 34 cases studied use the public blockchain except one (the Enosi platform) that uses a private blockchain. In this case, the private blockchain allows most computations to be validated by it rather than by the public chain. Another case (Energolabs) also uses the Qtum blockchain. The use of blockchain technology in these emerging energy ecosystems is quite extensive and the following facets are worth mentioning:
 - i. **Distributed Applications (DApps):** Ethereum, launched in 2015 (Ethereum, 2023), is an open-source, blockchain-based decentralized software platform that can simultaneously integrate a cryptocurrency. Ethereum helps deploy Smart Contracts and DApps to be developed and executed without fraud, control, or interference from third parties. Ethereum offers both a platform and a programming language that runs on a blockchain and allows developers to

build and publish distributed applications. 29 out of the 34 studied cases use the Ethereum platform to deploy their distributed applications. The use of other blockchain variants, such as Hyperledger Fabric (Hyperledger Project, 2020), Qtum (Qtum Chain Foundation, 2021), and Skyledger blockchain (Solar Bankers, 2017), is also found in cases such as Lition, Energo Labs, and solar bankers, respectively.

- ii. **Trading Tokens (cryptocurrency):** Of the 34 cases that are considered, 29 use cryptocurrencies as tokens for trade. These cryptocurrencies differ from ecosystem to ecosystem, and their values also vary. They are used as the main medium of exchange in these ecosystems instead of fiat currency in the real world. Many cryptocurrencies are supported on decentralized networks based on blockchain technology. One defining feature of cryptocurrencies is that they are generally not issued by any central authority, such as banks, making them theoretically immune to government interference or manipulation. For instance, in some cases, like "WePower," cryptocurrencies are used to tokenize energy. Tokenization of energy is a contracting scheme that is established between an energy producer and an energy buyer. A pilot project that involves the tokenization of the entire grid in Estonia is reported in (Digital Substation, 2018)
- iii. **Smart Contracts:** Smart contracts (SC) are simply programs stored on a blockchain that run when predetermined conditions are met. SCs are computer protocols that facilitate, verify, or enforce the execution of a contract, thus making the need for a contract clause unnecessary. SCs often imitate the logic of contract clauses. SCs can support the exchange of money, property, shares, or anything of value in a transparent and conflict-free manner, avoiding the services of a middleman. Normally, a process would require payment to a middleman, a government agency, a bank, a lawyer, or a notary, and then a processing time before receiving goods or services. However, with smart contract technology, all these processes can be automated. In the studied energy ecosystems, information about transactions and arbitrations between sellers and buyers is achieved using smart contracts. Some real-life implementation of this technology can be found in (Suncontract, 2020), and (LO3 Energy, 2020).

d. Other ICT Software Approaches

- i. **Cloud-based Platforms:** Three cases are found to use cloud-based platforms: Energy Web Foundation (Energy Web, 2022), Verv VLUX (Vlux, 2018), and Electrify Network (Electrify-Network, 2018). For instance, Verv VLUX uses a decentralized cloud storage service to host the platform and related applications. Furthermore, the Verv Household Hub is designed to connect to the cloud via a Wi-Fi network and provide users with a central hub to control other cloud-connected household smart appliances (Vlux, 2018). Again, considering the Electrify Network, the platform sought to combine the reliability and robustness of the microgrids with intelligent, multi-tasking smart

meters. This is made easier by software that runs in the cloud and makes all transactions and exchanges smooth, safe, and easy (Electrify-Network, 2018).

- ii. ***P2P Network Technology.*** In all the cases considered, the platforms utilize the P2P network topology. For instance, (Peer to Peer Energy Blockchain Protocol, 2017) and (PowerLedger, 2018). There are two cases that emerged differently. These cases are KWHCoin (KWHcoin, 2016) and Sun Exchange (SunExchange, 2018).
- iii. ***Blockchain as a Service Platform (BaaS):*** BaaS is a relatively new development in the growing field of blockchain technology. For BaaS, a third-party service provider is responsible for setting up all the necessary blockchain technology and corresponding infrastructure for a fee. Once created, the provider continues to handle the complex back-end operations on behalf of the client. In almost all cases considered, third-party service providers are responsible for the blockchain infrastructure as a service offered to energy sellers and buyers.

Table 2.9—Summary of technological enablers for energy ecosystems

Index	Cases	Enabling Technology									References
		Artificial Intelligence/Machine Learning		Blockchain Technology					ICT Architecture		
		IoT devices/ Smart meters	Intelligent agents	Distributed Application (DApps)	Type of trading tokens/ cryptocurrency	Distributed ledger technology	Smart contracts	Blockchain as a service platform (BaaS)	Cloud-based platform	P2P Network topology	
1	BittWatt	Yes	No	Ethereum	BWT	Public Blockchain	Yes	Yes	No	Yes	(BittWatt, 2018)
2	Electrify Network	Yes	No	Ethereum	Eden Token	Public Blockchain	Yes	Yes	Yes	Yes	(Electrify-Network, 2018)
3	Electrify.Asia	Powerpod	No	Ethereum	ELEC Token	Public Blockchain	Yes	No	No	Yes	(Tan, 2017)
4	ElectronConnect	Yes	No	Ethereum	-	Public Blockchain	Yes	Yes	No	Yes	(Electron, 2018)
5	EnergiMine	Yes	No	Ethereum	ETK	Public Blockchain	Yes	Yes	No	Yes	(EnergiMine, 2018)
6	Energo Labs	Yes [EME 1.0]	No	Qtum blockchain	Qtum,	Qtum blockchain	Yes	Yes	No	Yes	(Cleantechnica, 2017)
7	Energy Web Foundation	No	Yes (D3A)	Ethereum	Tobalaba	Public Blockchain	Yes	Yes	Yes	Yes	(Energy Web, 2022),(Bronski et al., 2018)
8	EnergyNet	Yes	No	Ethereum	Fiat Currency, any crypto	Public Blockchain	Yes	Yes	Yes	Yes	(Causam-eXchange, 2018)
9	Enosi Foundation	Yes	No	Ethereum	Joul	Public Blockchain Private Blockchain	Yes	Yes	No	Yes	(Enosi, 2018)
10	EtainPower	Yes	No	Ethereum	EPR Token	Public Blockchain	Yes	Yes		Yes	(Etainpower, 2017)
11	Greeneum	No	No	Ethereum	Green tokens	Public Blockchain	Yes	Yes	No	Yes	(Greeneum, 2018)
12	Grid+	Yes	Yes: Grid+ Smart agent	Ethereum	BOLT	Public Blockchain	Yes	Yes	No	Future implementation	(Consensys, 2017)
13	GridX	gridBox		Ethereum		Public Blockchain	Yes				(GridX, 2017)
14	Hive Power	Yes	No	Ethereum	HVT	Public Blockchain	Yes	Yes	No	Yes	(Rivola et al., 2018)
15	Joulette (Spectral)	Yes	No	Ethereum	Joulette	Public Blockchain	Yes	-	No	Yes	(Spectral, 2021)
16	KWHCoin	Yes	No	-	KWHCoin	Public Blockchain	Yes	Yes	No	No	(KWHcoin, 2016)
17	Lition	Yes	No	Hyperledger Fabric, Ethereum	Lition tokens	Public Blockchain	Yes	Yes	no	Yes	(Lition, 2018)
18	LO3 Energy/ Brooklyn Microgrid	Yes	No	Ethereum	XRG	Public Blockchain	Yes	Yes	No	Yes	(LO3 Energy, 2017)

Index	Cases	Enabling Technology									References
		Artificial Intelligence/Machine Learning		Blockchain Technology					ICT Architecture		
		IoT devices/ Smart meters	Intelligent agents	Distributed Application (DApps)	Type of trading tokens/ cryptocurrency	Distributed ledger technology	Smart contracts	Blockchain as a service platform (BaaS)	Cloud-based platform	P2P Network topology	
19	NAD Grid		No	Ethereum	Eden Token	Public Blockchain	Yes	Yes	-	Yes	(NADGrid, 2018)
20	Peer 2 Peer Energy Protocol (P2PEP)	Yes			PED Token	Public Blockchain	Yes	Yes	No	Yes	(Peer to Peer Energy Blockchain Protocol, 2017)
21	Power Ledger	No	No	Ethereum	POWR Tokens & Sparkz	Public Blockchain	Yes	Yes	No	Yes	(PowerLedger, 2018)
22	Prosume Foundation	Yes	No	Ethereum	PEF Token	Public Blockchain	Yes	Yes	No	Yes	(Prosume, 2017)
23	Pylon Network	Klenergy Metron	No	Ethereum	Pylon-Coin	Public Blockchain	Yes	Yes	No	Yes	(Klenergy Tech, 2017)
24	Share & Charge	Yes	No	Ethereum	No	Public Blockchain	Yes	Yes	No	Yes	(Share&Charge, 2020)
25	Solar Bankers	Yes	No	SkyLedger	Skycoin	Public Blockchain	Yes	Yes	No	Yes	(SolarBankers, 2018)
26	Solar IoT	Yes	No	Ethereum	SolCredit	Public Blockchain	Yes	Yes	No	Yes	(Solariot - Home, 2018)
27	SonnenCommunity	Yes	Self-learning software	Not mentioned	N/A	Not mentioned	N/A	N/A	Not mentioned	Yes	(Sonnen, 2015)
28	Sun Exchange	Yes	No	Ethereum	SUNEX	Public Blockchain	Yes	Yes	No	No	
29	SunContract	No	No	Ethereum	SNC	Public Blockchain	Yes	Yes	No	Yes	(SunContract, 2017)
30	Tarus Project	Yes	No	Ethereum	TORUS	Public Blockchain	Yes	Yes	No	Yes	(Buterin, 2015)
31	Toomuch.energy	Yes	No	Ethereum	-	Public Blockchain	Yes	Yes	No	Yes	(Vasylenko, 2015)
32	Verv VLUX	Yes	No	Ethereum	VLUX Token	Public Blockchain	Yes	Yes	Yes	Yes	(Vlux, 2018)
33	Volt Market	Yes	No	Ethereum	RECs	Public Blockchain	Yes		No	Yes	(Voltmarkets, 2021)
34	WePower	No	No	Ethereum	WPR Token	Public Blockchain	Yes	Yes	No	Yes	(WePower, 2017)

2.6 How do RECs Compare to VPPs

The objective here is to establish or ascertain how each of the 34 cases of RECs compares to a VPP. The focus here is on their characteristics and functions:

1. **Characteristics;** under this section the following sub-research questions are considered. For each sub research question, a brief answer is provided after the question. These answers are obtained after reviewing each case.

a. **PT2 Sub-Research Question-1:** Are these cases composed of multiple stakeholders?

Answer: Yes. Some cases demonstrate the aggregation of distributed energy resources, although not many of them.

b. **PT2 Sub-Research Question-2:** Are these cases comprised of decentralized multi-site heterogeneous technology?

Answer: Yes. In all considered cases, these ecosystems are also found to be comprised of multiple stakeholders or actors. These stakeholders include prosumers, consumers, service providers, investors, communities, non-profit organizations, platforms, ecosystems, and many others.

c. **PT2 Sub-Research Question-3:** Are these cases formed by aggregating distributed energy resources?

Answer: Yes. Distributed energy resources in these ecosystems are decentralized and located at multiple sites. There is evidence of heterogeneous technology use. RQ-2 provides an additional explanation of the types of technologies that are currently being used.

d. **PT2 Sub-Research Question-4:** Are these cases supported by ICT?

Answer: Yes. The studied cases thrived with the support of computer networks. This is seen in all the cases studied. Community members are connected using an online portal.

e. **PT2 Sub-Research Question-5:** Are these cases characterized by a simultaneous flow of information and energy?

Answer: Yes. There is information flow between community members and power flow from suppliers to consumers. All of this happens simultaneously.

f. **PT2 Sub-Research Question-6:** Do these cases function like a virtual power plant, thus acting like a single power plant?

2. **Functions:** In the context of the function, the following sub research question is adopted:

a. **PT2 Sub Research question 7:** Does the studies cases of RECs function like VPPs, thus acting like a single power plant?

Answer: Table 2.10 is used to shed more light on the answer to this research question for each case.

Table 2.10—The outcome of PT2 Sub research question 7.

Index	Cases	Do the ecosystems function like a virtual power plant, thus acting like a single power plant?
1	BittWatt	No. Reason: Does not appear to focus on the aggregation of Distributed Energy Resources (DER), which is a key function that can enable these ecosystems to aggregate different energy generation units, which could result in the creation of some capacity that could enable them to act like a single power plant or a VPP
2	Electrify Network	No. Reason: Does not appear to focus on the aggregation of DERs.
3	Electrify.Asia	No. Reason: The focus is on the development and deployment of the “PowerPod” IoT device and P2P energy trading using the synergy and marketplace 2.0 applications
4	ElectronConnect	No, Reason: Focused on energy trading activities mainly
5	EnergiMine	Partial. Reason: Currently working with Elexon, a UK-based company to allow future aggregation of energy storage devices that can be traded on the platform to help balance the grid. Grid balancing is also one of the features of technical VPPs. Partial because this is yet to be implemented
6	Energo Labs	No. Reason: Does not appear to focus on the aggregation of DERs
7	Energy Web Foundation	No. Reason: Does not appear to focus on the aggregation of DERs
8	EnergyNet	No. Reason: Does not appear to focus on the aggregation of DERs
9	Enosi Foundation	No. Reason: The vertical hierarchical architecture of the Enosi network where consumers can only access the energy market through a Neo Retailer and subsequently a licensed retail supplier appears to limit the possibility of aggregating DERs to enable them to behave like VPPs.
10	EtainPower	No. Reason: Focusses on renewable energy project financing and not the aggregation of DERs
11	Greeneum	No. Reasons: Does not have the capacity to aggregate DERs.
12	Grid+	No. Reason: Act mainly as an energy trading platform with a focus on the deployment of the Grid+ Smart agents. No emphasis is placed on the aggregation of DERs
13	GridX	No. Reason: Does not appear to focus on the aggregation of DERs
14	Hive Power	Yes. Reason: Based on the notion of “Self-Consumption Communities” (SCC) the community can sell excess solar power to the national grid e.g., during summer days and receive financial remuneration. This action replicates the behaviour of a VPP
15	Jouliette (Spectral)	Partial. Reason: The “Spectral Energy Control System” enables the seamless integration and control of energy storage devices, wind farms, PV plants, heat pumps, generators, and a wide range of other energy systems. This feature of the ecosystem can enable it to function as a VPP although this is not explicitly stated as a function of the ecosystem.
16	KWHCoin	No. Reason: Current focus is to promote the KWHCoin as a digital currency for energy trading
17	Lition	No. Reason: Does not appear to focus on the aggregation of DERs.
18	LO3 Energy/ Brooklyn Microgrid	Partial. Reason: Have the capacity to support the local community in emergencies when the grid fails. -Has the potential to act as a single power source in future development
19	NAD Grid	No. Reason: Act mainly as an energy trading platform
20	Peer-2-Peer Energy Protocol (P2PEP)	No. Reason: Does not appear to focus on the aggregation of DERs
21	Power Ledger	No. Reason: The platform appears to focus on data collection, market management and/or pricing mechanisms
22	Prosume Foundation	Yes. Reason: One of the features of the platform is to facilitate the integration of Power-Plants and Micro-Grid management on the ESCO (Energy Sharing Company) model. This feature can enable the ecosystem to act like a VPP.
23	Pylon Network	No. Reason: The platform does not seem to support the aggregation of DERs to form the similitude of VPP although it is mentioned that stand-alone producers can sell surplus energy to the grid, there is no indication that this is achieved through aggregation of DERs.
24	Share & Charge	No. Reasons: The current focus is on EV charging. Does not have the capacity to aggregate DERs
25	Solar Bankers	No. Reason: Does not appear to focus on the aggregation of DERs.
36	Solar IoT	No. Reason: Does not appear to focus on the aggregation of DERs

Index	Cases	Do the ecosystems function like a virtual power plant, thus acting like a single power plant?
27	SonnenCommunity	Yes Reason: The Sonnen Virtual Power Plant achieves this through its digitally networked swarm of home storage systems. If the electricity demand is higher than expected the batteries feed electricity into the grid. In the event of an unexpectedly high level of electricity production, they absorb the excess electricity from the grid.
28	Sun Exchange	No. Reason: Does not appear to focus on the aggregation of DERs
29	SunContract	No. Reason: Does not appear to focus on the aggregation of DERs
30	Tarus Project	No. Reason: Does not appear to focus on the aggregation of DERs
31	Toomuch.energy	No. Reason: Does not appear to focus on the aggregation of DERs
32	Verv VLUX	No. Reason: The focus is on the development and deployment of the Verv IoT devices and P2P energy trading using the Verv Trading Platform (VTP).
33	Volt Market	No. Reason: Does not appear to focus on the aggregation of DERs
34	WePower	Yes. Reason: small energy producers using WePower services that cannot reach the 1 MWh certificate, which is the minimum requirement for them to trade in the energy market, are pooled together as a single entity to sell their energy to the market.

2.7 Other Relevant Characteristics of RECs and VPPs in Terms of their General Organization

Juxtaposing the VPP concepts with RECs, it can be found that both ecosystems are similar in a way. For instance, in terms of their organization, both RECs and VPPs have some similarities, such as having the capacity to aggregate several heterogenous entities or stakeholders into the equivalent of a single unit that functions like a traditional power plant. In this sense, both VPPs and RECs can aggregate energy and send it to the grid. In Figures 2.4 and 2.5, we show how these two ecosystems compare in terms of their organization. The key differences between the two are as follows:

1. ***RECs are focused on:***
 - a. Common or compatible interests.
 - b. Driven by the general citizenry.
 - c. Participation and membership are voluntary.
 - d. Community inclusion, participation, and cohesion.
 - e. Addressing energy democracy.
2. ***VPPs, on the other hand, are focused on:***
 - a. Aggregation of distributed energy resources.
 - b. The use of energy management systems.
 - c. Adopt scheduling, dispatch, and optimization techniques for efficient management.

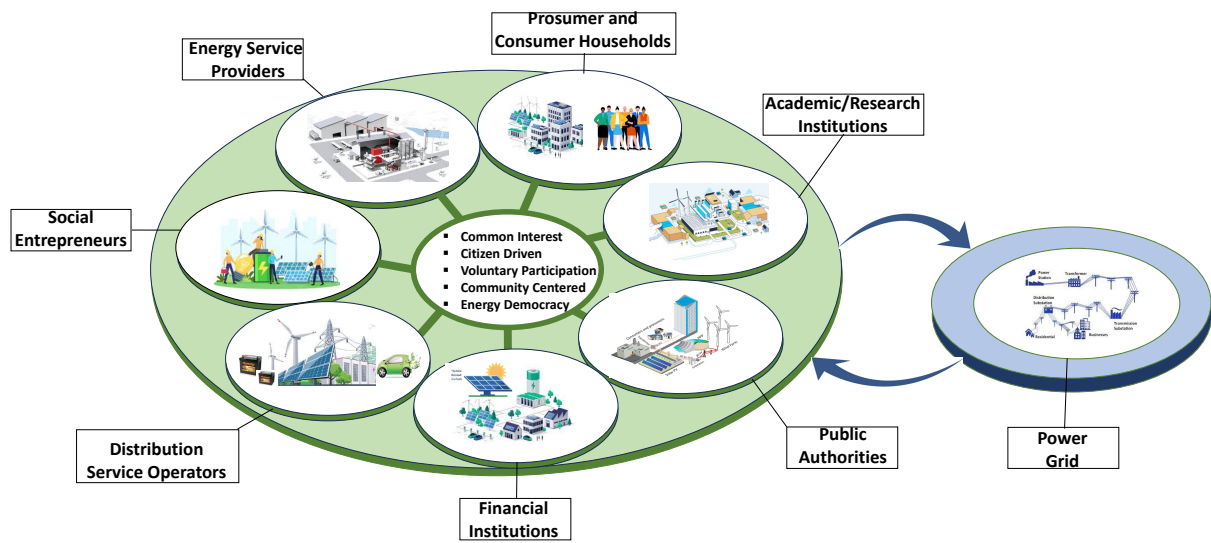


Figure 2.4— A REC is focused on common goals, citizen driven, voluntary participation, community centred and energy democracy.

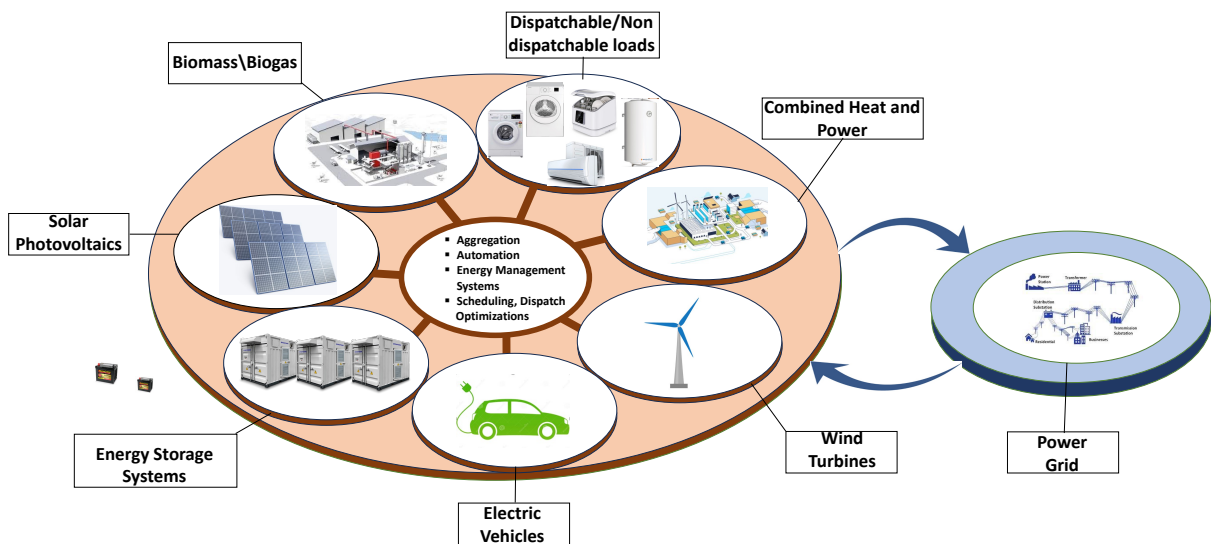


Figure 2.5— A VPP is focused on aggregation of distributed energy resources, the use of energy management system and adopts scheduling and dispatch of energy as well as optimizations techniques.

2.8 Summary and Conclusion of Findings

1. *The existence of the potential to act like VPPs:* The study reveals that most of these cases have access to diverse and vast numbers of DERs that are found to be connected in these networks. Incidentally, these DERs constitute a key asset for all VPPs. This, therefore, suggests that most of these ecosystems have access to the primary assets that could enable them to perform functions that may be similar to those of VPPs. Yet, in several of the studied cases, the ecosystems did not integrate

features that could afford them the capacity to aggregate connected DERs. The focus of these ecosystems is predominantly on P2P exchanges.

2. ***Limited use of collaboration and related concepts:*** Another significant finding is that most cases operate at the level of cooperation rather than collaboration. In such cases, it can be suggested that collaboration could be a plausible mechanism that would allow actors in these ecosystems to come together, devise a common goal, and engage in collective actions that could result in the aggregation of outputs from connected DERs so that they could perform some function similar to a VPP. Knowledge, concepts, principles, and mechanisms from the domain of collaborative networks could be useful to adopt. Future research direction could focus on this area.
3. ***Limited use of intelligent agents:*** The types of enabling technologies that are found, appear to be driving the energy industry in the direction of the energy digitalization (Blok & Cihlar, 2018). Some of the key highlights of these enabling technologies include the integration of AI, smart IoT devices, smart software agents, blockchain technology and related smart contracts, cryptocurrencies, and cloud-based applications such as platforms-as-a-service, software as a service etc. The direction of these ecosystems is towards greater flexibility (Reynders et. al., 2018), sustainability, autonomy, individualization, digitalization, and virtualization (Mackinnon, 2018). It is realized that these developments may introduce some complexities in terms of choices, decision-making, and preferences that may seem overwhelming and cumbersome for human users to single-headedly adopt and use. The need for some form of autonomous and complementary decision-making assistance to help navigate this myriad of options for optimized choices and decisions could be useful. However, the study reveals that all but two cases did not consider the integration of software agents into their ecosystems, although this concept has been shown to have good prospects in the implementation of complementary decision-making entities.
4. ***Cross-platform trading and interoperability between cryptocurrencies:*** Another noteworthy observation is the lack of evidence of cross-platform trading and interoperability between cryptocurrencies. Furthermore, unlike fiat currency, which can be converted from one currency to another, evidence of interoperability between the various cryptocurrencies is also lacking. With such limitations, the actors in these ecosystems are restricted in terms of choices and access to diversity in terms of affiliation, diverse energy sources, and related services.

2.9 General Remarks About RECs as Observed in the Review

From the conducted study, a number of conclusions can be derived:

1. RECs are promising energy sources, ecosystems and communities that can help to reduce the demands on the power grid by providing grid connected or off-grid power supply services to communities. Although these communities in some cases can become self-sufficient in terms of energy supply, they also end up being environmentally sustainable communities in the sense that their activities promote sustainable lifestyle within the resident community. In some cases where these communities are connected to the grid, they could provide some ancillary services like sharing their surplus energy with the grid.
2. RECs provide an effective and less expensive alternative to the financing of electrical infrastructure which usually requires a huge initial cost of investment, therefore, making it attractive to only large utility companies (Verde & Rossetto, 2020).
3. The concept of RECs helps to break the monopoly of big utility companies (Wainer et al., 2022) and foster energy democracy which is currently being advanced by grassroots activists in the United States and parts of Europe (Szulecki & Overland, 2020). The idea of energy democracy besides many other things also promotes individuals within communities to become investors and economic beneficiaries of energy infrastructure and contribute to the governance and management of these infrastructures (Melnik et al., 2023).
4. RECs are currently empowering communities to use a bottom-up approach to advance environmental sustainability issues and promote sustainable consumption behaviours at the local community level which is more effective than traditional methods.

2.10 Summary of Research Gaps

In summary, some key gaps that were found in the literature after the review include:

1. **Collaboration Mechanisms:** There is a gap in the literature regarding how collaborative mechanisms can be used to enhance several aspects of the REC ecosystems. Some areas that have been identified as promising for the integration of collaborative mechanisms include:
 - a. **Aggregation of DERs:** In this area, new research into developing flexible, scalable, dynamic, adaptable, and collaborative techniques for aggregating DERs in various community frameworks could be useful. Research in this area should focus on creating mechanisms that provide flexibility to DER owners and can also be applied in different contexts, from urban neighbourhoods to rural villages.
 - b. **Collaborative structures:** Research into how the dynamic formation of collaborative structures can be utilized to harness the capacity and capabilities of energy asset in RECs. These structures can provide ancillary services to the

power grid and even to other communities if collaborative techniques are integrated into their organization and operations.

- c. **Governance models:** Examining different governance structures within RECs and how they can impact on decision-making, project success, and long-term sustainability. This may involve researching the effectiveness of democratic or cooperative models and their adaptability to various situations.
 - d. **Incentives and motivation:** Investigating the role of financial and non-financial incentives in encouraging collaboration within these communities is also another area that needs further work. This includes understanding what motivates community members to participate and invest in renewable energy initiatives or participate in sustainable energy behaviours and endeavours.
2. **Resilience and Reliability:** Assessing how aggregated DERs can enhance community resilience and reliability. In this sense, investigating how collaboration can contribute to resilience in the face of climate-related disasters and other emergencies. This could include studying the effectiveness of collaborative microgrids, collaborative backup power systems, and collaborative community-based disaster response plans.
 3. **Policy and Regulatory Challenges:** The need for further studies into policy and regulatory hurdles that collaborative renewable energy communities face and proposing solutions for navigating these challenges. Research may involve case studies of regions with supportive policies and their impact on community projects.
 4. **Technology Integration and Interoperability:** Researching the technical challenges associated with integrating multiple renewable energy sources, energy storage, and grid systems within a community framework is needed. This may involve developing interoperable technologies and systems.
 5. **Community Engagement and Social Dynamics:** Analysing the social dynamics of collaboration in renewable energy communities, such as the role of trust, social norms, and communication. Research could focus on strategies for effectively engaging and mobilizing community members to approach problem solving from a collaborative point of view.

Although several research gaps have been identified in this comprehensive review, the thesis does not address all of them. However, the thesis focusses on addressing the following gaps:

1. **Collaboration Mechanisms:** For this gap, the thesis explores how the integration of collaborative mechanisms such as (a) aggregation of DERs, (b) collaborative structures, and (c) incentives could facilitate sustainable energy consumption in the REC ecosystems.
2. **Proposition and Development of Concepts and Methods in Support of the Suggested Collaborative Mechanisms:** In this case, the following concepts are proposed to support the implementation of the collaborative mechanisms that are mentioned above. These include (a) the Collaborative Energy Ecosystem (CEE), (b) Cognitive Household Digital Twins (CHDTs), (c) Collaborating Digital Twins, (d)

the CEE Virtual Breeding Environment (CEE VBE), and (e) the CEE Virtual Organization (CEE VO). Similarly, the suggested methods include: (a) opportunity seeking by the CEE manager, (b) community goals proposition, (c) individual household value systems, (d) value systems compatibility with community goals, (e) delegation of deferrable loads (DDL), (f) delegated autonomy, (g) incentives, and finally, (h) influences.

3. **Development of Software Models to Test the Suggested Mechanisms and Concepts:** In this sense, the CEE and the CHDT models are developed in a simulation environment. The CEE model is used to represent the ecosystem virtually, and the CHDT model is also a virtual representation of the constituent members of the ecosystem, namely the physical households.

THE COLLABORATIVE ENERGY ECOSYSTEM MODELLING FRAMEWORK

This chapter presents the conceptual background of the artifact that is developed to help address our proposed research question. The chapter begins with a brief description of the formulation of the background concepts involved. The chapter further discusses the scope of the thesis, the architecture, modelling framework, and the formulation and definition of related concepts. In brief, the CEE is comprised of two key layers: the collaborative/cyber layer and the physical layer. A detailed description of each layer and their corresponding blocks is discussed in subsequent sections of the chapter. Additionally, the collaborative behaviours of two key members of the ecosystem, namely the CEE manager and the constituent households, the CHDTs, are also introduced and discussed.

3.1 Background and Conception of the CEE Notion

The core inspiration for the CEE notion is based on the combination of the concepts of virtual power plants (VPP), Renewable Energy Communities (REC) and Collaborative Networks (CNs).

The VPP idea is relevant because it helps to provide grounds upon which DER contribution to the power grid can be enhanced, if not maximized. The key characteristic of VPPs that makes them suitable for adoption for this purpose is their ability to aggregate DER into the equivalent of a traditional power plant. The literature shows that the penetration of DERs in the grid environment is growing rapidly (Alam et al., 2020). This is because of rising environmental concerns (Achuo et al., 2022) and falling prices for residential battery storage, which is mostly used with photovoltaic panels (Kobou Ngani & Hadji-Minaglou, 2023). These DERs, although they come as small generating units (Hargroves et al., 2023), could be aggregated, resulting in a virtual entity that could operate like the equivalent of a traditional power plant (Liu et al., 2023).

To help advance the idea of aggregation, consideration is given to RECs as a suitable environment within which DER aggregation could be tested and further explored. RECs are considered because they also introduce the perspective of citizen participation, which has the potential to help increase the involvement of the citizenry in matters concerning sustainable energy generation and consumption as well as addressing environmental concerns within communities. While considering the need for increased citizen participation and involvement,

it is equally important to consider how these can be achieved in a flexible manner. The notion of collaboration is therefore identified as a suitable organizational and management strategy that can help citizens to get involved, participate, and flexibly contribute to the energy transition. In this regard, collaborative concepts and mechanisms are borrowed from the domain of collaborative networks and introduced into the REC environment, resulting in a novel ecosystem, here named the “collaborative energy ecosystem” (CEE). Figure 3.1 illustrates how these various concepts are integrated to form the CEE. The figure also shows the contribution each concept brings to the ecosystem.

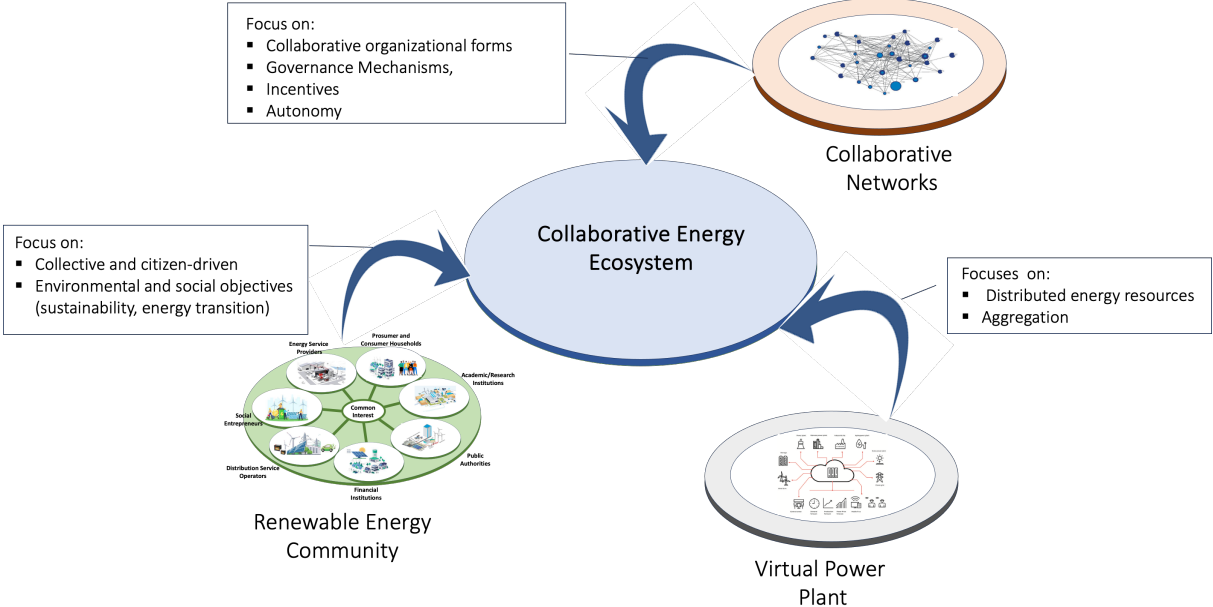


Figure 3. 1—The three concepts that are integrated to form the Collaborative Energy Ecosystem.

3.2 A High-level Architectural Framework of the CEE

To support the modelling and prospective development of the CEE concept, the high-level framework shown in Figure 3.2 is proposed. This multi-level "architecture" is intended to provide a visual understanding of how the ecosystem is organized. Furthermore, the architecture is intended to assist in the development of the artifact or prototype model that is used to answer the proposed research question. The diagram is suggested to be as generic as possible so that it can cover a wide variety of REC configurations. This framework can further serve as a point of reference upon which future experimentation and possible implementations of the CEE concept could be based. Other relevant aspects of the architecture, such as the description and definition of key working concepts and the organization of knowledge in this respect, are also presented. Further propositions of the adopted theoretical models and the computational models of the considered collaborative behaviours are also discussed in the following.

Typically, a CEE functions like a digital business ecosystem (Suuronen et al., 2022) or a community of practice (King et al., 2023). In terms of organization, a CEE is comprised of two key layers, namely (1) the physical layer, and (2) the collaborative/cyber layer.

1. ***The physical layer:*** It is comprised of the physical REC and all the related physical energy assets. It also includes the various stakeholders which may involve external entities as well. The actual composition of the physical layer of a REC may vary from one REC to another. However, some key stakeholders that may commonly be found include (i) prosumer and consumer households, (ii) research/academic institutions, (iii) public authorities, (iv) financial institutions, (v) distribution service operators, (vi) social entrepreneurs, (vii) various energy service providers, etc. The REC may also have influence over or be influenced by other external entities, such as (a) distribution service operators, (b) the power grid and related energy markets, and (c) weather forecasting stations. In many cases, these RECs are united by some common or compatible goals, which may include sustainability, economic, social, environmental, political, and infrastructural goals (Hielscher et al., 2013).
2. ***The collaborative/cyber layer:*** This layer is comprised of two levels. The first level is the "collaborative energy ecosystem virtual breeding environment" layer (CEE VBE), which is made up of the aggregation of digital twins of the physical actors that make up the REC and is organized in the form of a VBE. The CEE manager is located within the CEE VBE. The manager is an entity that is responsible for brokering collaborative opportunities for the ecosystem. The manager brokers these opportunities by coordinating with external actors or entities. Typically, these entities could be many, play several different roles, and have different attributes. However, for the purpose of this thesis, only three of these suggested entities are considered: (a) distribution service operators (DSO), (b) the power grid and related energy markets, and (c) weather forecasting systems. The second level is the "collaborative energy ecosystem virtual organization" layer (CEE VO). This is an ad-hoc layer that can be formed temporarily with the purpose of pursuing a particular business opportunity (equivalent to a virtual organization). The composition of this layer may vary from one opportunity to the other, subject to the interests of stakeholders regarding the type of opportunity. Once the opportunity has been explored or exploited, the layer can be dissolved.

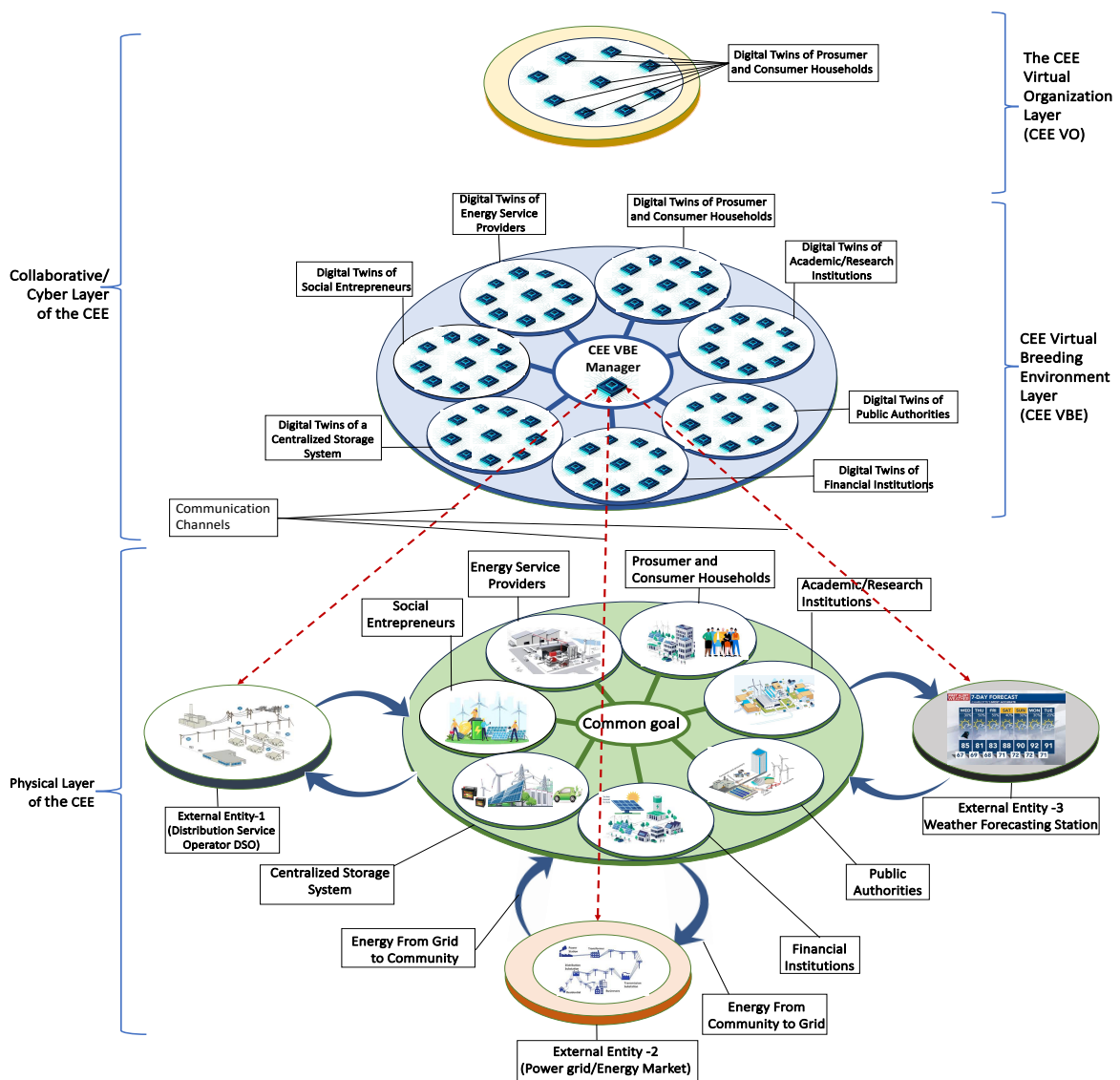


Figure 3. 2— A high level view of the Collaborative Energy Ecosystem

3.3 The Scope of the Thesis

The adopted approach for this work is based on software simulation. The reason is that by adopting this method, a prototype model of the real world can be created and used to experiment with or study the real world, since such systems are difficult or sometimes impracticable to conduct experiments on due to the cost, complexity, disruptions, and time involved.

Furthermore, it is acknowledged that the physical layer of the CEE ecosystem constitutes the integration of several and diverse energy assets as well as their related infrastructure. It is further acknowledged that modelling the physical aspects or layer of the ecosystem, would require the use of dedicated energy simulation tools such as Homer software (Homer Energy,

2016), Siemens power system simulation (Siemens, 2022), or GridLAB simulation software (GridLAB, 2023), etc. This is due to the complex and technical nature of this layer.

However, in this thesis, such dedicated software tools are not utilized because the objective of this work is not to simulate the low-level physical energy layer. Instead, the key focus of the work is limited to the high-level collaborative/cyber layer of the ecosystem, where behavioural attributes such as collaboration, decision-making and VO formations occur. For this reason, the details of the low-level technical factors relating to the physical layer of the energy infrastructure are not addressed, although it is recognized that these are essential parameters and components of the grid.

Nevertheless, in order to gain a reasonable insight into how the collaborative/cyber layer, (particularly decision-making and collaborative behaviours) affect the physical layer in terms of sustainable and flexible energy consumption, a system dynamics simulation technique is adopted to help model some aspects of the physical layer namely (a) Solar photovoltaic systems (PVs), (b) household appliances, and (c) energy storage systems. The system dynamics model helps to mimic the energy generation, energy storage, and energy consumption behaviours in a very simplistic way. In this case, adequate knowledge and insight are gleaned from the behaviour of the artifact regarding how the suggested collaborative behaviours translate into sustainable and flexible energy consumption outcomes within the ecosystem.

Also as mentioned above, a REC is comprised of several stakeholders who are assembled into a community based on some common goals or objectives. However, in the context of this work, only one category of REC stakeholders, namely households, is considered as the only member of the REC (refer to Figure 3.3). The motivation to focus on households is based on the fact that buildings have been declared the single largest energy consumer in Europe. The literature shows that buildings consume nearly 40% of global energy, 25% of global water, 40% of global resources, and contribute nearly 72% of global greenhouse gas (GHG) emissions (Hertwich & Peters, 2009). From the perspective of the European Union, buildings are responsible for approximately 40% of the EU's energy consumption and 36% of CO₂ emissions (European Commission, 2019). Furthermore, demand for energy has increased substantially in contemporary societies due to urbanization and industrialization (Rehman et al., 2022), population and economic growth (Pasten & Santamarina, 2012), as well as technological advancement (Jin et al., 2018). These dynamics are the result of the need to meet the energy demands of the people who are the occupants of these households.

Referring to Figure 3.3, the considered households in the REC are categorised into two groups: (a) prosumer households, and (b) consumer households. For each household, either prosumer or consumer, nine types of household appliances are possibly embedded. Details of these appliances are provided in Chapter 4. The occupants of the households are also considered in the thesis as "users/delegators." It is up to them to delegate in the CEE or not, the use of these household appliances. Finally, a centralized storage system is also integrated into the REC. The role of the centralized storage is to store surplus energy from the prosumer households and subsequently make this energy available to members of the ecosystem (both prosumer and consumer households) when needed or even to sell to the grid.

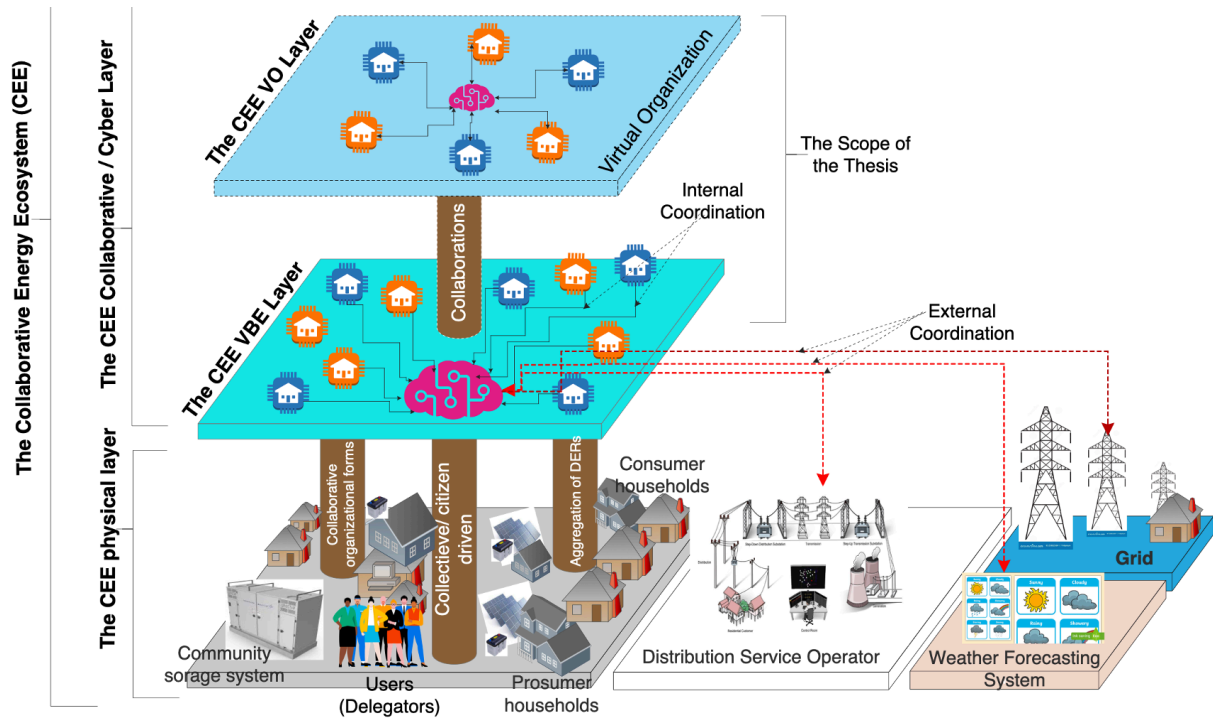


Figure 3.3 —The scope of the study

3.3.1 Collaborative Facets and Behaviours Considered Under the Scope of this Work

This section describes the kinds of collaborative facets and behaviours that are considered in this research. The collaborative behaviours, techniques and mechanism that are envisaged within the CEE are borrowed from the domain of Collaborative Networks. Discussed below are the collaborative mechanisms that are foreseen for the CEE.

1. **Community/Common Goals:** A CEE is driven by the notion of common goals. Decision making and collaborative endeavours that are undertaken within the CEE ecosystem shall mostly be based on these common goals. The CEE can have multiple goals and may pursue various goals concurrently. The goals of the CEEs can be dynamic and are determined by the CEE VBE manager when an opportunity is found.
2. **CEE Member Value System:** Members of a CEE may have their individual “value systems” which can be used to represent the preferences, priorities, expectations, and contributions of each member regarding how they intend to contribute to the mentioned community goals. Members of CEE can have multiple value systems, which can be ranked in order of priority. The notion of value system can empower members of the CEE to contribute flexibly to community goals.
3. **Goal Compatibility:** Goal compatibility is a decision-making process where members of a CEE compare their value system(s) with the proposed community goals to ascertain if there is a match or compatibility between their value system(s) and the community goal. Members of the CEE accept invitations to participate in community

coalitions or goals on the grounds that one or more of their values is compatible with the proposed community goal. In the instance of incompatibility between the members' value system and the community's goals, the invitation is declined. In reality, compatibility of value systems should not be sufficient or the only condition. It may also be necessary to consider the current context and current preferences of the member. But these aspects fall outside the scope of this work.

4. **Resource Sharing:** Resource sharing is a collaborative attribute that places emphasis on sharing or accessing underutilized goods and services, which prioritizes efficient utilization and accessibility over ownership. The fundamental resources that can be shared in a CEE may include both physical and virtual energy assets and services. These resources can be shared on a peer-to-peer basis or in a centralized architecture. In the context of this thesis, the resource that is shared is energy.
5. **Formation of Virtual Organizations (VOs):** In the context of a CEE the manager identifies a business opportunity on the grid ecosystem such as demand response or opportunity to sell energy to the grid. To pursue this opportunity, the manager sends invitations to members. Members whose value systems are compatible with the goal will accept the invitation. A VO constituting of members with accepted invitations is formed by the manager to pursue the opportunity.
6. **Incentives:** Incentive is another facet of collaboration that is relevant to materializing the CEE concept. An incentive is a crucial component of any collaborative endeavour. It has the ability to persuade a passive member of a community to become an active participant or collaborator based on a promise of some form of reward or acknowledgment. In a CEE, the use of incentives is intended to increase the willingness of members and motivate them to participate in collaborative endeavours and pro-sustainable behaviours.
7. **Delegation:** Delegation refers to the permission or authority that is given to the digital twin of a household (CHDT) to act on behalf of the household inhabitants. Due to the cognitive intelligence of these CHDTs, they can have cognisance of (a) whether they are delegated or not, thus, whether they are permitted to participate in collaborative endeavours or not, (b) the value system of the physical household, and (c) the proposed community goal(s).
8. **Delegated Autonomy:** This refers to the degree or level of permission that is given to each CHDT. It constitutes the specific "instructions" that a household owner may assign to its CHDT to be followed in carrying out its preferences and contribution towards community goals and collaborative endeavours.
9. **Collective Decision-making:** Collective decision is a situation in which people jointly decide among the options that are available to them. In such cases, the final decision can no longer be attributed to any particular person in the group. This is so that every person can contribute to the final result. In collective decision-making, individual choices and group decisions are in alignment. Collaborative decision-making is one of the most effective processes for gaining support from other stakeholders, establishing consensus, and fostering creativity. In a CEE, decisions are envisaged to be made on a

collective basis. This enables each member to contribute in one way or another towards the community's goals and objectives.

3.3.2 Energy Flexibility and Flexible Contribution

"Energy flexibility" in the electricity sector usually means the ability to reduce energy use or shift that usage to different times of the day in response to external factors, such as requests by the grid operator (Junker et al., 2018). This could be in response to a price signal, the grid frequency, or an activation signal from the grid operator. In this thesis, some behaviours of energy flexibility are observed. Energy flexibility behaviour occurs as the by-product or outcome of the collaborative efforts of CHDTs towards a given opportunity. For instance, in the instance of deferring loads to meet a specific business opportunity or community goals. However, the thesis also adopts and uses the term "flexibility" in a different sense. Flexibility, or flexible contribution in the context of this work, refers to the ability of members to contribute to community goals in a "flexible manner." In this case, users are able to make contributions to community goals at their convenience without having to infringe on their comfort or expected quality of service. This "flexible contribution" technique is quite different from the general term "energy flexibility," and the two need to be distinguished.

3.4 The CEE Modelling Framework

In this section, a detailed description of the building blocks of the CEE architecture under the two key layers is presented and discussed. Further explanation about how these blocks is integrated within the various layers, and how they subsequently work together to achieve the collective objective of the CEE, is elaborated.

3.4.1 The CEE Collaborative/Cyber Layer

This layer is comprised of two sub layers. These are (a) The CEE VO layer and (b) The CEE VBE layer.

3.4.1.1 The CEE VO layer

This is the topmost layer of the CEE model. This layer is a temporary layer that is formed only when a business opportunity is found and that there is the need for a formation of coalition to exploit the opportunity. The formation/creation of the coalition is coordinated by the CEE VBE manager who is located in the CEE VBE layer.

3.4.1.2 The CEE VBE layer

The CEE VBE layer is the middle layer of the CEE. It is the component of the CEE model where collaboration opportunities are conceived, and community goals are formulated and proposed. It is the layer where the formation of VOs, their operations, and dissolutions are coordinated. The CEE VBE is comprised of (a) the CEE VBE manager and (b) the population

of prosumer and consumer households, who are also referred to as “cognitive household digital twins” (CHDTs). In more details:

3.4.1.2.1 *The CEE VBE Manager*

One of the main roles of the manager is to foster collaborative behaviour in the ecosystem. The manager is able to promote these collaborative functions through the following means: (a) By coordinating with external entities that are located outside of the ecosystem and internal entities (ecosystem members); (b) Engaging in collaborative behaviours such as opportunity-seeking, goals formulation, goals proposition or invitation to form coalitions or VOs, and finally the formation, operation, and dissolution of coalitions or VOs. In the subsequent sections, the functions of the CEE manager are presented in detail.

1. ***The Coordinating Role of the CEE VBE Manager:*** The CEE manager engages in two levels of interactions with two different sets of actors. These actors are comprised of (a) external entities and (b) the community, which basically constitutes the population of CHDTs. Details of these interactions follow:
 - a. ***Coordination with External Entities.*** In the implemented prototype, we assume that the CEE VBE manager interacts with three external entities, although in reality there could be more than three. The manager formulates community goals or business opportunities, taking into consideration input from these entities. In the prototype model discussed in Chapter 4, these inputs are discussed as preconditions leading to the formulation of community goals. Referring to Figure 3.4, the manager is considered to coordinate with the following external entities:
 - i. ***Coordination with External Entity-1 (Distribution Service Operator -DSO):*** The coordination between the manager and the DSO enables the manager to formulate grid-related goals in response to grid management demands, such as demand response, which could be a time-based program, incentive-based programs, or energy-saving behaviours.
 - ii. ***Coordination with External Entity-2 (Power Grid/Energy Market):*** Coordination with this entity can enable the manager to formulate goals that are in line with market demands. This coordination can help energy ecosystems access the energy market and participate in the exchange of market-related goods and services.
 - iii. ***Coordination with External entity-3 (Weather Forecasting station):*** Information concerning the weather conditions is exchanged between the weather forecasting station and the manager through this coordination channel.

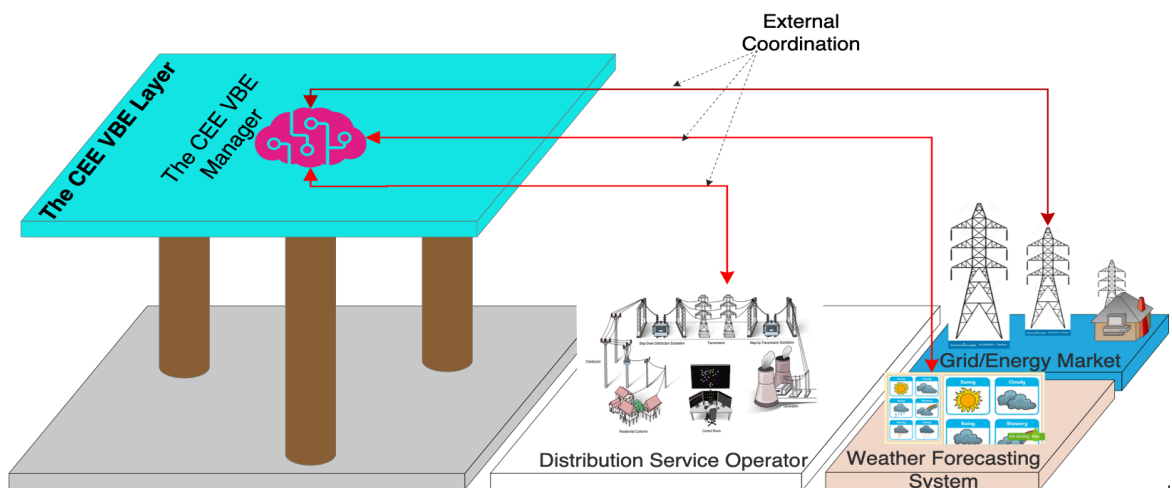


Figure 3.4 —External coordination between the CEE VBE manager and external entities

- b. **Coordination with Internal Entities (Ecosystem Members):** This coordination channel enables the manager to exchange information with ecosystem members, i.e., all the CHDTs within the ecosystem. Figure 3.5 illustrates this internal coordination.

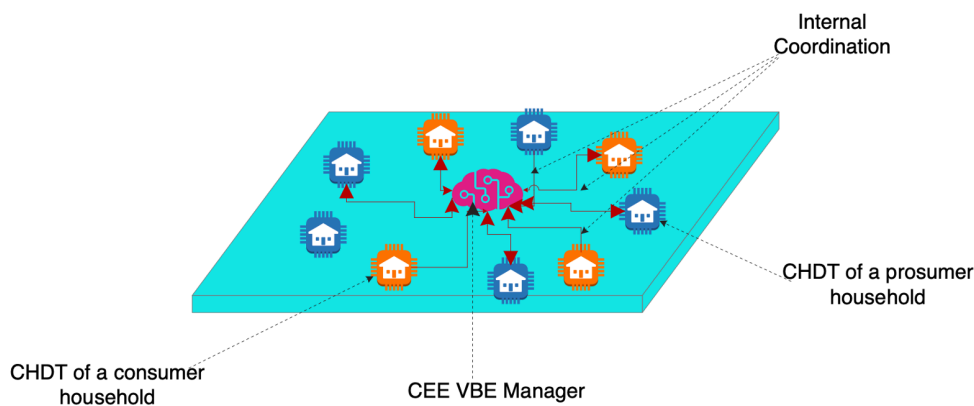


Figure 3.5 —The CEE manager coordination with CHDTs in the ecosystem

2. **The Collaborative Roles of the CEE VBE Manager.** According to (Afsarmanesh & Camarinha-Matos, 2005), in a typical CN environment such as a VBE, the following key roles are commonly found, and these roles are usually played by different entities. In the case of the CEE, these roles are played by the manager, as follows:
- a. **The CEE manager as an opportunity broker** – In this sense, the manager acts as an opportunity broker, i.e., it identifies, pursues, and acquires collaborative opportunities on behalf of the ecosystem. Technically, the broker is also responsible for the negotiation and acquisition of opportunities that are in line with the community goals and the marketing of the competencies of the ecosystem. The ecosystem may pursue multiple goals simultaneously. However,

for illustration purposes, here we just discuss a scenario of brokering two opportunities, namely "Community goal 1" and "Community goal 2":

- i. *Community goal 1 - A selling opportunity (SellOpp)*: This goal describes the case where the community finds an opportunity to sell energy to the grid. For this goal, it is assumed that the following three preconditions must be satisfied before it can be pursued:
 - *External demand for energy on the grid* (a precondition originating from the DSO as a result of the external coordination between the manager and the DSO). This precondition is represented as "precondition-1A" in Figure 3.6.
 - *Surplus generation of renewable energy available in the ecosystem* (a precondition originating from the internal coordination between the manager and the population of CHDTs in the ecosystem). This precondition is represented as "precondition-1B".
 - *High population of CHDTs having their value system in line with the community goal "SellOpp"* (a precondition from the population of CHDTs as a result of the internal coordination between the manager and CHDTs). This is denoted as "precondition-1C".
- ii. *Community goal 2 - A grid management opportunity*: For this goal, we consider the case where the community uses the control of energy assets such as washing machines, dishwashers, and clothes dryers to contribute to grid management by helping to reduce consumption from the grid during peak periods. These assets are often referred to as "deferrable or shiftable loads." The nature of these assets is that their use can be deferred to a later time without affecting the quality of service they provide to the user. Some examples that could be considered preconditions for this goal may include:
 - *Peak demand on the grid* (a precondition originating from the DSO as a result of the external coordination between the manager and the DSO). This can represent a daily, annual, or seasonal period when energy demand is significantly higher than average supply levels and could jeopardize power grid stability. Under such circumstances, one of the options available to the grid operators is to implement some demand response actions, such as encouraging a voluntary reduction in energy consumption for the period. This precondition is represented as "precondition-2A".
 - *A high population of delegated CHDTs with grid management as their value system* (a precondition originating from the internal coordination between the manager and the population of CHDTs in the ecosystem). This is represented as "precondition-2B".

- *The minimum energy savings required by the grid operator as contribution to grid stabilization can be met by the collective action of the community, a precondition originating from the internal coordination between the manager and the population of CHDTs in the ecosystem). This is named as “precondition-2C”.*

For either goal to be pursued, all three preconditions relating to that goal must be met. A goal cannot be pursued when only one or two preconditions are satisfied. The processes involved in opportunity-seeking are Illustrated in Figure 3.6 using the BPMN 2.0 modelling language. In this instance, it is assumed that the manager had made a prior request for information from the appropriate entities concerning goals 1 and 2. Referencing Figure 3.6, the opportunity-seeking steps for goal 1 are demonstrated as follows:

- iii. *Reception of opportunity preconditions:* The manager receives information from (a) the DSO (representing peak demand on the grid - Precondition 1A), (b) the population of CHDTs (representing CHTs having surplus generation - precondition 1B), and (c) itself (an internal database containing the value systems of the CHDTs - precondition 1C).
 - *Precondition analysis:* First, the manager checks if precondition 1A meets the condition for pursuing goal 1. If the condition is unfavourable (false), the process is terminated. However, if the condition is favourable (true), the manager proceeds to check precondition 1B. Second, if precondition 1B is unfavourable (false), the process is terminated. However, if precondition 1B is favourable (true), the manager proceeds to check precondition 1C. Third, if precondition 1C is unfavourable (false), the process is terminated. However, if precondition 1C is favourable (true), opportunity is said to have been found because precondition 1A is true, precondition 1B is true, and precondition 1C is also true.

The steps for goal 2 are not detailed here because the involved entities are the same and the BPNM representation for goals 1 and 2 are similar.

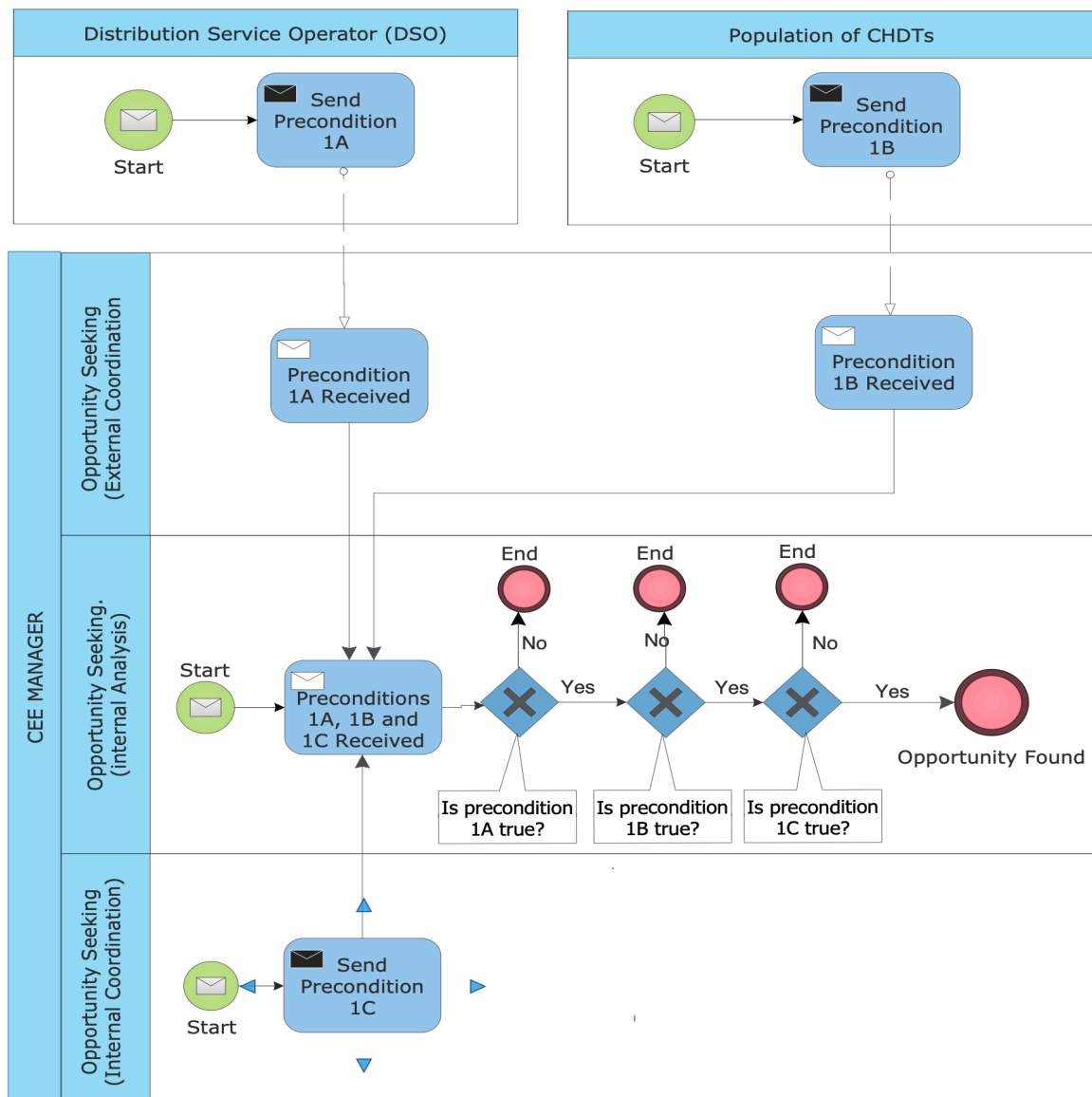


Figure 3.6 —Opportunity seeking process of the CEE manager

- *Demonstration of goal formulation by the manager:* If all three preconditions are unfavourable, an opportunity is said not to exist. As a result, the seeking process has come to an end. However, if all three preconditions are found to be favourable, an opportunity is said to have been found. As a result, the process continues. The manager proceeds to formulate the goal(s) that relate to the respective opportunity. If the opportunity is related to goal 1, the manager would formulate goal 1. If the opportunity relates to goal 2, the manager will formulate goal 2. In Figure 3.7, the BPMN notation for the formulation of goals 1 and 2 is shown. The figure further shows how invitations are sent to the community on the condition that either goal or both goals are formulated.

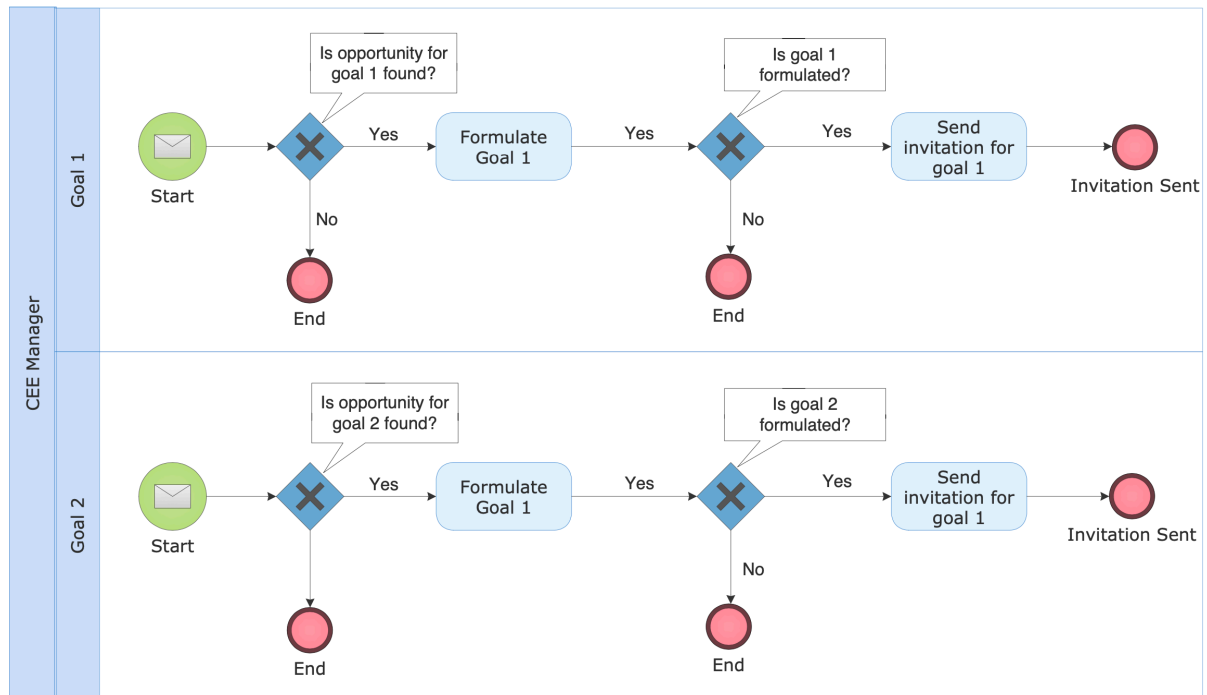


Figure 3.7 —Formulation of goals 1 and 2 and sending invitation for goals 1 and 2

- b. *The CEE manager as a VO planner, coordinator, and administrator.* The manager as a VO planner is responsible for the identification of goal opportunities using the preconditions and is also responsible for the formation of new VOs. As a coordinator, the manager is responsible for the VO lifecycle, namely, VO formation/creation, VO operation, and VO dissolution, to ensure that the goals that triggered the formation of the VO are met. For instance, referring to Figure 3.8, the manager receives inputs from prospective VO members, i.e., from prospective VO member 1, prospective VO member 2, and prospective VO member 3, concerning goal 1. It can be observed that all the prospective VO members accepted the invitation. Based on the outcome received responses, the manager can decide whether it would be profitable to proceed to form the VO or abort the opportunity.

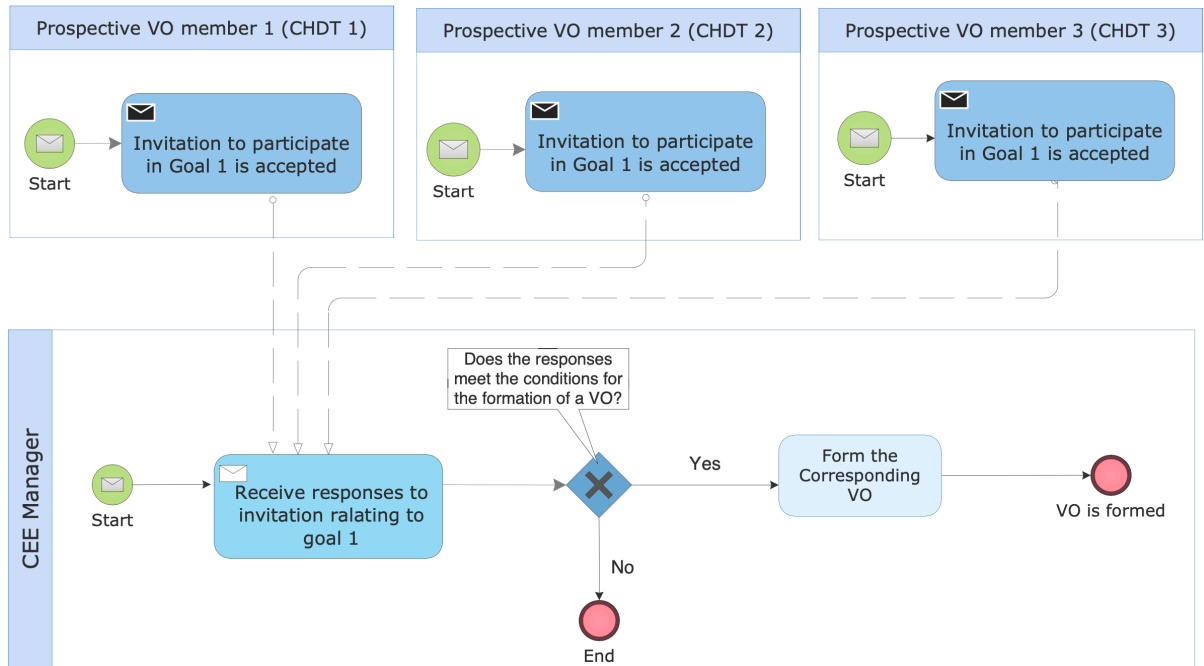


Figure 3.8 —The VO formation and planning process

3.4.1.2.2 The Cognitive Household Digital Twins (CHDTs)

In the proposed model, CHDTs can be perceived as digital twin depictions of the prosumer and consumer households of a CEE. CHDTs are modelled as software agents that have intelligence allowing them to perform complementary functions as independent decision-making entities that execute “delegated autonomy” instructions on behalf of their physical twin counterpart. Their decisions are expected to encourage collaborative behaviours that can help the energy ecosystem become more resilient and sustainable. In the following sections, the CHDT is discussed in detail.

1. **Architectural Framework of the CHDT.** Generally, a “digital twin” is a virtual model created to reflect a physical object in the cyberspace (Lord, 2022). The object may include a variety of sensors that produce data regarding various aspects of its performance, including energy output, temperature, and weather conditions, among others. This establishes a connection between the digital twin and its physical counterpart. Once the virtual model is fed with data, it can be used to run simulations, investigate performance issues, and generate potential improvements, all to gain valuable insights that can then be applied to the original physical object. Assuming that the physical object, besides sensing, can also receive commands to perform actions in its environment, the digital twin can then be used to control the physical object. In line with these features of digital twins, we propose the cognitive household digital twin (CHDT) concept. As such, we represent each unit of household within the CEE ecosystem by its replica in the form of a digital twin counterpart within cyberspace. In the developed prototype, each CHDT is modelled as a software agent that mimics the

actual household's traits and actions. These software agents are designed to live and interact with each other within a digital REC environment, namely the CEE. CHDTs are also designed to possess some cognitive capabilities, allowing them to serve as complementary decision-making agents on behalf of their physical counterparts. These software agents can make rational and autonomous decisions on their owners' behalf (owners of the physical households). In Figure 3.9, the logical structure of the CHDT is shown. This includes: (a) a cognitive block, (b) a decision block, (c) a functional output/control block, and (d) an influence block. The various blocks comprising the CHDT are discussed in the subsequent paragraphs.

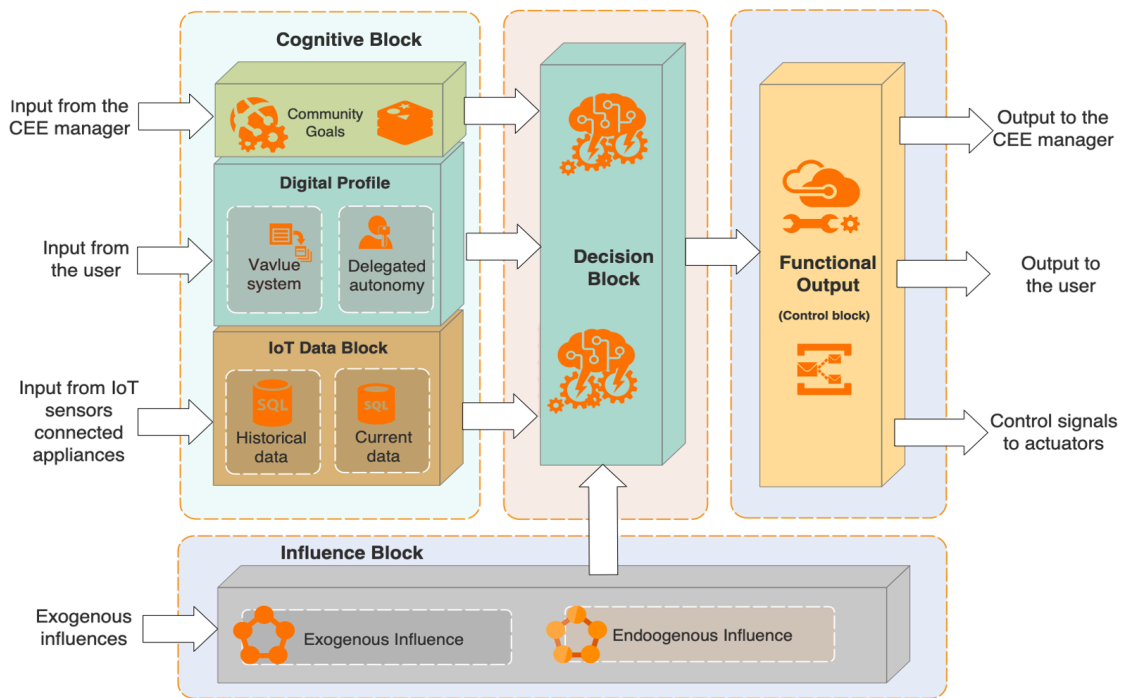


Figure 3.9 —The logical structure of the CHDT

- a. *Cognitive Block*. This component is used to represent the intelligent aspect of the CHDT. This block enables the CHDT to be cognizant of the following: (a) the community goal(s), (b) the digital profile, which is constituted of (i) the value system of the physical twin, and (ii) the delegated autonomy of the physical twin assigned to the CHDT, and (c) the IoT data block, which is also constituted of (i) the historic data and (ii) the current states of embedded appliances. The subsequent paragraph expounds on these blocks.
 - i. *Community goals*: As mentioned earlier, the focus of the CEE is usually to achieve some specific global goals(s) that are common to all members of the ecosystem. Technically, the community could pursue several goals simultaneously. For instance, the community could pursue a sustainability goal, an economic goal, a social goal, or a technological goal simultaneously. As part of its cognitive capabilities, a CHDT would often have cognizance of all the goals that are suggested or proposed by the community manager. Although it may possess knowledge of the community's goals, it would only

join a coalition or participate in collaboration activities that are compatible with the goals of its physical twin, and on the condition that it has been delegated to do so.

ii. *Digital profile*: The digital profile is the interface or aspect of the CHDT where the users can communicate their preferences and choices to their CHDT. It is composed of the value system and the delegated autonomy of the user.

- *Value system*: The value system represents the preferences, choices, and options of the physical twin that have been transferred to the CHDT. In the context of this work, the value system of a CHDT is a list of preferences that represent the values of the owner. These values are indicative of the measure of a member's contribution or expected benefit from the community, as mentioned in the problem statement. This informs the kinds of choices and decisions that the CHDT makes. Technically, the value systems of individuals may vary from one person to another, therefore, the notion of a value system enables the collective objectives of the community to be met, by each member making their contribution flexibly without compromising their expected quality of service. In Figure 3.10, we illustrate six types of value systems, although in real-life implementation, several other value systems, such as those discussed in (Plewnia & Guenther, 2021), could be considered. Based on Figure 3.10, the following value systems are discussed.

- 100% renewable sources value system: For this type of value system, the owner's preference is to consume energy from only renewable sources. Any other source of energy that is non-renewable is forbidden to this actor.
- Mixed energy sources value system: For this type of value system, the user considers the use of energy from mixed sources. These mixed sources may include a mix of renewable and non-renewable sources. It may be possible for the actor to specify the preferred ratio of renewable sources to non-renewable sources.
- Free rider's values system: Technically, this is not a value system. It rather represents an instance where the owner fails to define a value system.
- Cost savings value system: This represents users whose priority is to save money and therefore prefer to use certain appliances, such as "deferrable loads", at times when tariffs are at their lowest.
- Revenue or income values system: This may represent owners who want to participate in activities such as demand response actions to earn revenue or sell energy from their roof-mounted photovoltaic system (PV system) to earn additional income.
- Load management value system: This represents owners who are willing to have some appliances (interruptible loads) interrupted

for grid load management. Such action could be rewarded with incentives like energy credits, green certificates, etc. These actions could also be carried out voluntarily.

- Addressing multiple value systems: In the CEE, CHDTs can have multiple value systems. For instance, a prosumer CHDT could have a value system of first 100% renewable energy consumption, second revenue generation, and third cost-savings. However, these value systems should be arranged in a hierarchical order of priority (a priority list).
- Addressing collision of value systems: This can be addressed in two ways: (a) at the CHDT level. Here, the value system that is higher on the priority list of the CHDT will override the lower priority value system; (b) At the community level, the community may also define some community values, such as sustainability values, as a priority among the community goals. In such instances, sustainability values will always override any other values that conflict with them.

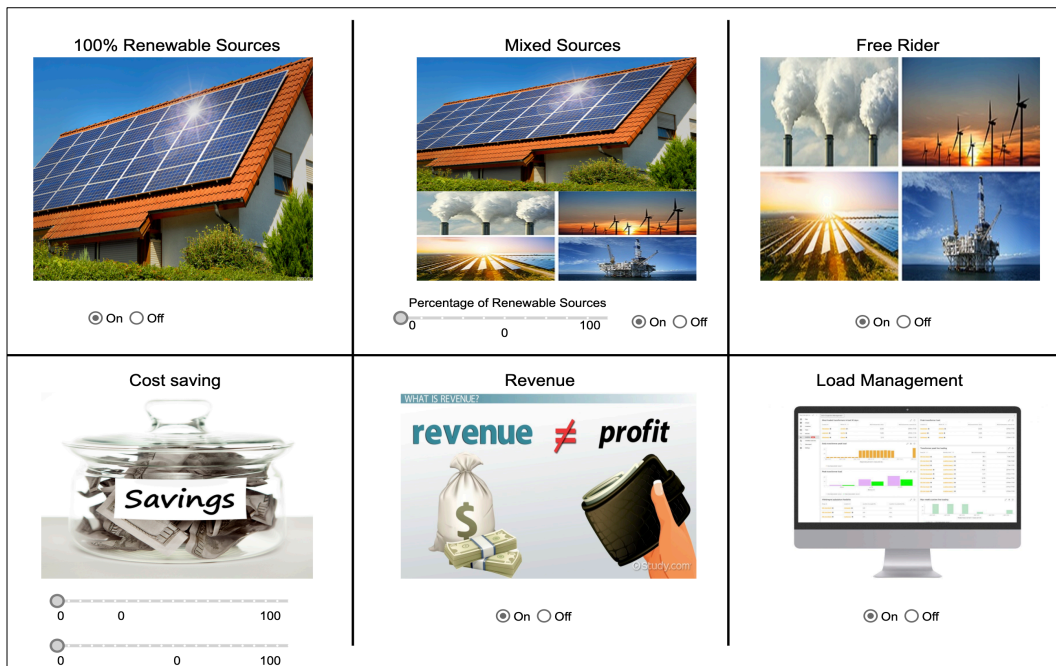


Figure 3.10 —Examples of value systems in the context of the CEE

- iii. *Delegated autonomy*: The notion of delegated autonomy is the specific instruction that a household owner assigns to its CHDT to be followed in carrying out or executing its value system. In the prototype, this may include delegating either a single appliance, any two appliances, or any three appliances. Delegation means deferring the use of these appliances until a later time without necessarily affecting the quality of service that these appliances provide to the user. The concept of delegation helps users to flexibly contribute

to community goals in the sense that loads can be shifted from one period of the day to another (Dragomir & Dragomir, 2023), helping to maximize consumption from renewable sources and minimize consumption from the grid. A simple interface such as that shown in Figure 3.11 can be used to achieve this purpose. An appliance can be delegated by selecting the “radio button” *Delegate*. By selecting *Undelegate* the appliance becomes undelegated.



Figure 3.11 —A simple interface to illustrate how “deferrable loads” can be delegated in the CEE

- b. *IoT data block*: This block represents the IoT interface between the household appliances and the CHDT. This block is constituted of two sub-blocks:
- *The historical data block*: This is a database that contains historical data on the usage behaviour of each appliance over time. By integrating AI techniques, the CHDT can glean some behavioural patterns from this historical data for prediction and decision-making purposes, on behalf of the physical twin.
 - *Current (status) data*: This block communicates the operational status of an appliance to the CHDT. Such data may include information such as whether the appliance is currently in the “on” or “off” states. For appliances such as refrigerators and air conditioners, sensorial data such as the operating temperature, etc., could be collected. In future studies, data about the thermal comfort of rooms or the living environment in households could also be useful for the CHDTs in their decision-making, particularly concerning the regulation of temperature in the living environment. In Figure 4.12, we illustrate how the integrated IoT components communicate with a central router to reach the CHDT that is hosted in the cloud. Control signals can also be sent from the CHDT via the router to the various appliances to enable control instructions to be carried out. A firewall at the interface ensures the

security of users. Generally, DTs are hosted and operated in an environment called the “Digital Twin Environment.”

The connection between physical and virtual objects can be achieved through several communication channels. For instance, the Institute of Electrical and Electronics Engineers has proposed a standard, namely IEEE 1451, which constitutes a family of smart transducer interface standards that define a set of open, common, network-independent communication interfaces for smart transducers (sensors or actuators) to achieve sensor data interoperability between cyber and physical components of CPS. The standard defines a “smart transducer” as either a sensor or actuator that can identify and describe itself, has the data processing capability to present sensor data or accept actuation values, respectively, in measurement units, has network communication capability, and is easy to use, enabling plug-and-play functionality (Mark & Hufnagel, 1996).

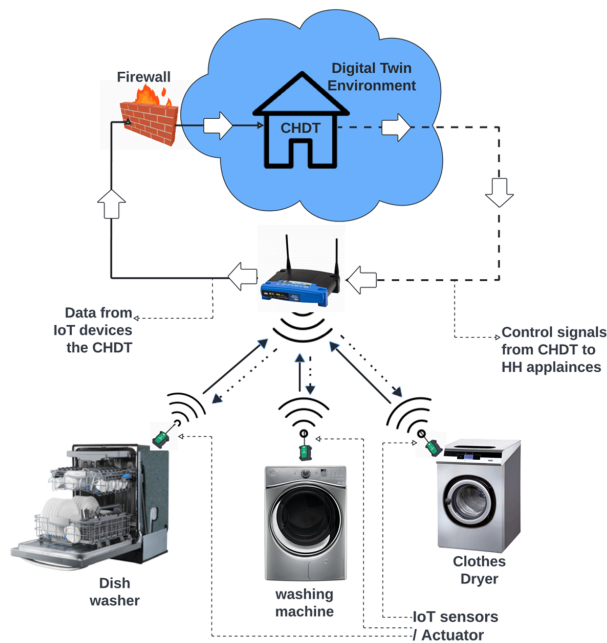


Figure 3.12 —How IoT sensors/actuators are connected between appliances and their CHDTs

- c. *The Decision Block*: This block’s output is accepted as input by the control block, and the control block’s output serves as input to actuators that are connected to each of the appliances (lately smart appliances). In the implemented prototype, basic control of the appliances, such as switching between the “on” and “off” states, is the focus. Other complex control mechanisms might be explored in the future. For instance, in scenarios that involve complex operations, such as controlling thermal comfort by monitoring and modifying room temperature or employing CHDTs in demand response techniques such as “load interruptions”, may require a more complex control mechanism.

In Figure 3.13, we illustrate how a CHDT makes decisions based on its digital profile. The figure shows a CHDT with three value systems that are arranged in order of priority. The first priority is "100% consumption from renewable sources", the second priority is to "consume from mixed sources" and the third is "free rider or indifferent option". It also shows three levels of delegated autonomy, thus delegate (control over) all three appliances, delegate any two appliances, and delegate any one appliance.

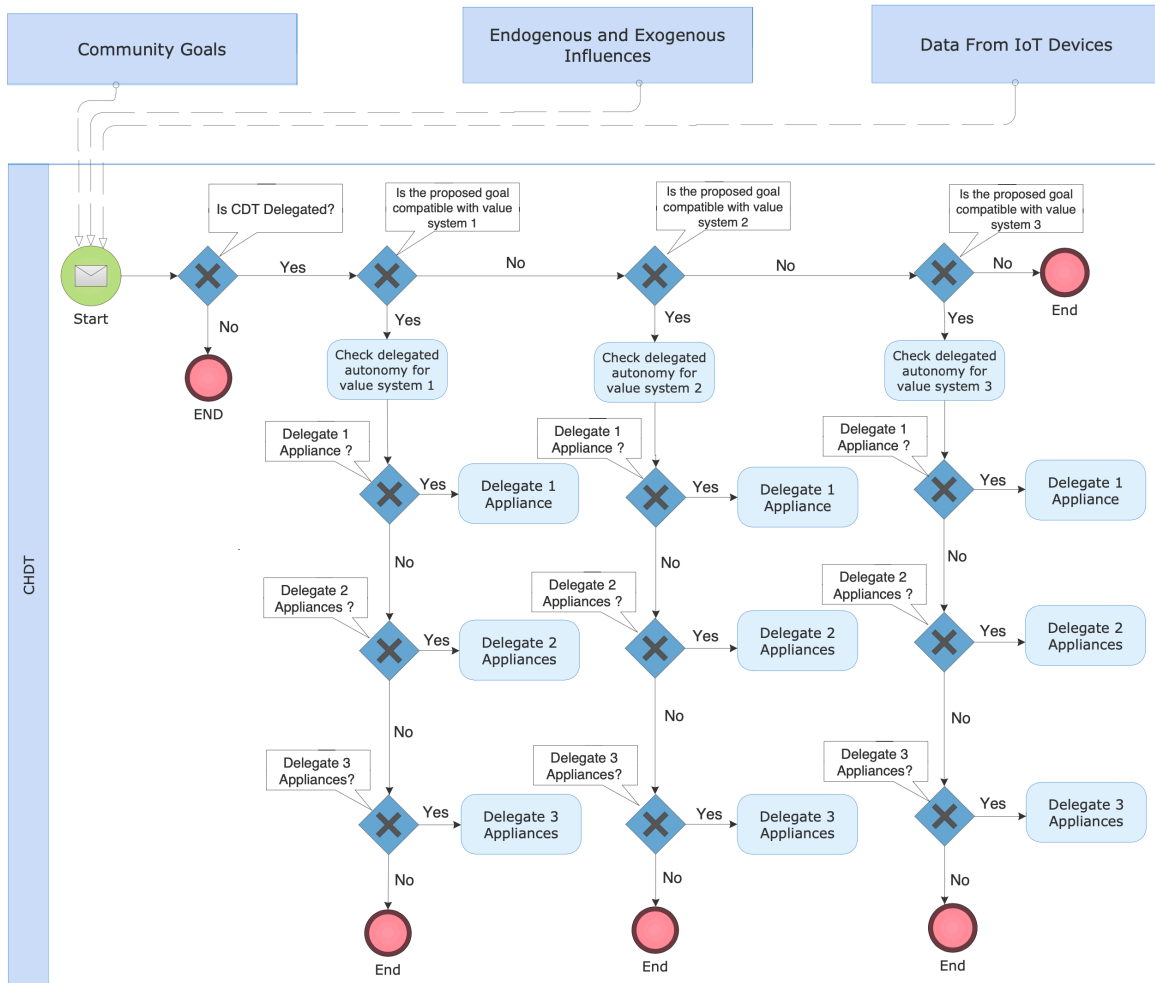


Figure 3.13 —A BPMN representation of the decision-making process of a CHDT

- ***Influence Block.*** Knowledge from social network analysis has shown that the decisions of participants on social networks can be influenced by network influencers. As claimed by (Geysers, 2022), people usually look up to influencers on social media to guide them with their decision-making. There are various strategies for spreading influence in a social system or network. One powerful strategy that has been used to favourably impact individuals in a variety of ways is the power of internet information dissemination (Chen et al., 2013) and (Hugo & Garnsey, 2002). Companies have used this technique, known as the "viral phenomenon" or "viral marketing," to encourage sharing amongst individuals with social connections, because it is recognized that

social recommendations may improve traffic to business websites, resulting in increased engagement and income. This concept of influence can also be adopted to facilitate the spread of incentives in the context of the CEE. A CHDT can experience two types of influences. These are endogenous and exogenous influences.

- *Exogenous influence*: This represents influences that originate from the external environment of a CHDT. This may constitute an influence from the community manager or other influencer CHDTs within the community. For instance, this could represent some kind of incentive proposed by the community manager.
- *Endogenous influence*: This could represent internal influences or the kind of influences that originates from inside of a CHDT.

These influences could originate from the CEE manager or other influential CHDTs within the ecosystem. Each influence possesses the following attributes: (a) polarity, (b) intensity, (c) impact, and (d) frequency of transmission. Polarity signifies whether an influence is positive or negative. The intensity, on the other hand, describes the magnitude of the influence. For instance, a positive influence may have a positive polarity, a minimum intensity or magnitude of “X,” and a maximum intensity or magnitude of “Y.” Likewise, the impact describes the severity (how strong or weak) of the influence on the CHDT. A high-impact influence affects the CHDT for a longer duration, while a low-impact influence has a short duration. The frequency of transmission describes how often an influencer CHDT propagates influence on the community. CHDTs make decisions based on a predefined threshold called the “decision constant,” which is represented by “ α ”. This parameter has a positive value and can be reached based on the aggregated outcome of all influences (both positive and negative) acting on the CHDT over time. A negative constant could also be adopted and used to determine when a CHDT makes a negative decision, such as refusing to participate in collaborative endeavours.

- d. Functional Output Block. The functional output block helps the CHDT to exchange communication with its external world. The decisions and responses of the CHDT are communicated through the output block. There are five output that originate from the CHDT:
 - i. *Output to the CEE manager*: This output enables the CHDT to communicate back with the community manager concerning community goals, collaborative opportunities, and VO formation. The CHDT uses this channel to inform the manager about acceptance and rejection of invitations. In other words, this output serves as the output interface between the CHDT and the manager.
 - ii. *Output to the user*: This output serves as the interface between the CHDT and the user. It enables the user to receive feedback from the CHDT concerning

the customization of the digital profile of the CHDT and feedback from collaboration outcomes.

- iii. *Control Block*: The control block is part of the output block. This block connects the CHDT to each of the embedded household appliances. The input of the control block accepts output from the decision block, and the output of the control block serves as input to actuators that are connected to each of the appliances (lately smart appliances). In this work, an open loop control system is considered. This is because the expected control actions at this level may include switching the asset twin between the “on” and “off” states. In future studies where complex actions like controlling thermal comfort by monitoring and adjusting room temperature or using CHDTs in demand response techniques such as interruption of loads are involved, other control models may be more suitable.

2. *The Collaborative Roles of the CHDT*. According to (Bianca, 2019) a common goal gives a group of entities a shared purpose. It inspires them to work together as a team to help them achieve the group’s objectives. Communication and information exchange are also crucial to the achievement of a group’s objectives. Therefore, under this subsection, we discuss the collaborative roles that CHDTs play in the ecosystem. These collaborative roles include: (a) communication and information exchange towards coalition formation, i.e., joining a VO, (b) sharing of a common resource, and (c) engaging in collective actions.

- a. *Communication and information exchange towards a goal*. This process is expected to precede every collaborative venture, e.g., to minimize energy consumption over a certain period. In other words, it is a process of forming a coalition (VO) to achieve some goal proposed by the CEE manager. In terms of information exchange, we show the major communication steps that are expected to occur. Referring to the BPMN model of Figure 3.14, the following steps are observed:
 - i. *Invitation*: The community manager extends invitations towards the achievement of Goal 1 to the entire community, particularly prospective CHDTs whose value systems or preferences are in line with Goal 1.
 - ii. *Receipt of invitation*: Upon receipt of the invitation, the CHDT first checks if it is delegated or not. If it is undelegated, it will reject the invitation based on non-delegation. However, if it is delegated, the next step is taken.
 - iii. *Check value system compatibility*: If the CHDT is delegated, it will proceed to check if the value system corresponding to Goal 1 is compatible with the proposed goal. If no compatibility is found, it will proceed to check compatibility with Values System 2. If non-compatibility is found, it will proceed to check Value System 3. If non-compatibility is found, the CHDT will decline the invitation based on non-compatibility.
 - iv. *Acceptance based on compatibility with value system 1 (VSI)*: If the proposed goal is compatible with Value System 1, the CHDT accepts the invitation based on goal compatibility with Value System 1.

- v. *Acceptance based on compatibility with value system 2 (VS2)*: If the proposed goal is compatible with Value System 2, the CHDT accepts the invitation based on goal compatibility with Value System 2.
- vi. *Acceptance based on compatibility with value system 3 (VS3)*: If the proposed goal is compatible with Value System 3, the CHDT accepts the invitation based on goal compatibility with Value System 3.

Throughout these processes, it is observed that information is exchanged at every step of the process between the CHDT and the manager. This shows the crucial role that communication and information exchange plays in the collaborate processes.

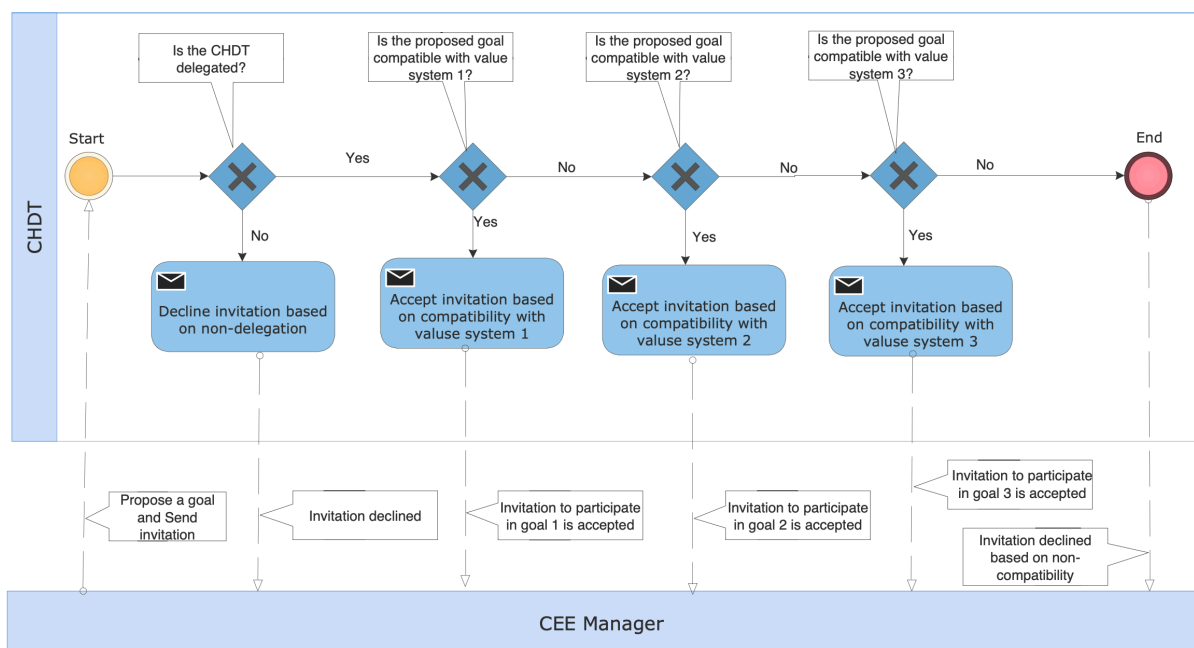


Figure 3.14 —Process of information exchange towards the formation of a coalition - joining a VO

- b. *Modelling sharing of common resources*. Resource sharing is a common characteristic of collaborative cases. In the CEE, members engage in resource sharing as one of their collective goals. The case shown in Figure 3.15 is used to Illustrate the sharing of common resources within the CEE. It shows two modes of sharing, level-1 resource sharing (L1RS) and level-2 resource sharing (L2RS). L1RS refers to sharing surplus energy that was produced by prosumer CHDTs with the community storage (charging the community storage). L2RS involves the sharing of energy that was stored in the community storage with either prosumer or consumer CHDTs within the community (discharging community storage). The following steps are used to describe L1RS and L2RS in detail (also assuming that a VO was previously established for this goal):

- i. *L1RS*. Under this mode of sharing, the surplus energy from several different CHDTs is shared with the community storage system. This is more of an aggregation process. Referring to Figure 3.15, L1RS can be achieved in three major steps:

- *Local PV resource availability:* PV availability is a time-dependent event. The CHDT is alerted to the availability of solar energy due to the presence of sunlight.
 - *Type of local energy demand:* For this step, the CHDT determines if there is a local demand for locally generated solar energy (local demand includes the demand for appliances to use the energy locally or to store it in the local storage). If local demand exists, the generated energy is consumed locally. If otherwise, the generated energy is considered surplus and is shared with community storage.
 - *Accept and store:* At this stage of the process, the shared energy is accepted and stored in the common storage system.
- ii. *L2RS.* Under this mode of sharing, the energy that was previously stored in the community storage is shared back with community members according to their various needs. The storage capacity is constantly being monitored to determine if the conditions for L2RS are satisfied. Typically, L2RS is enabled when the state of charge (SoC) is greater than a threshold, say $\alpha\%$ of the battery capacity " C ". If this condition is satisfied, the energy that was previously stored in the community storage is allowed to flow back into the community. L2RS is terminated when the condition changes, thus, SoC drops below another threshold, say $\beta\%$ of " C ", thus, When $SoC > \alpha\%$ of " C ", L2RS is enabled, When $SoC < \beta\%$ of " C ", L2RS is disabled. This can be used to represent the charging and discharging processes of the community storage system.

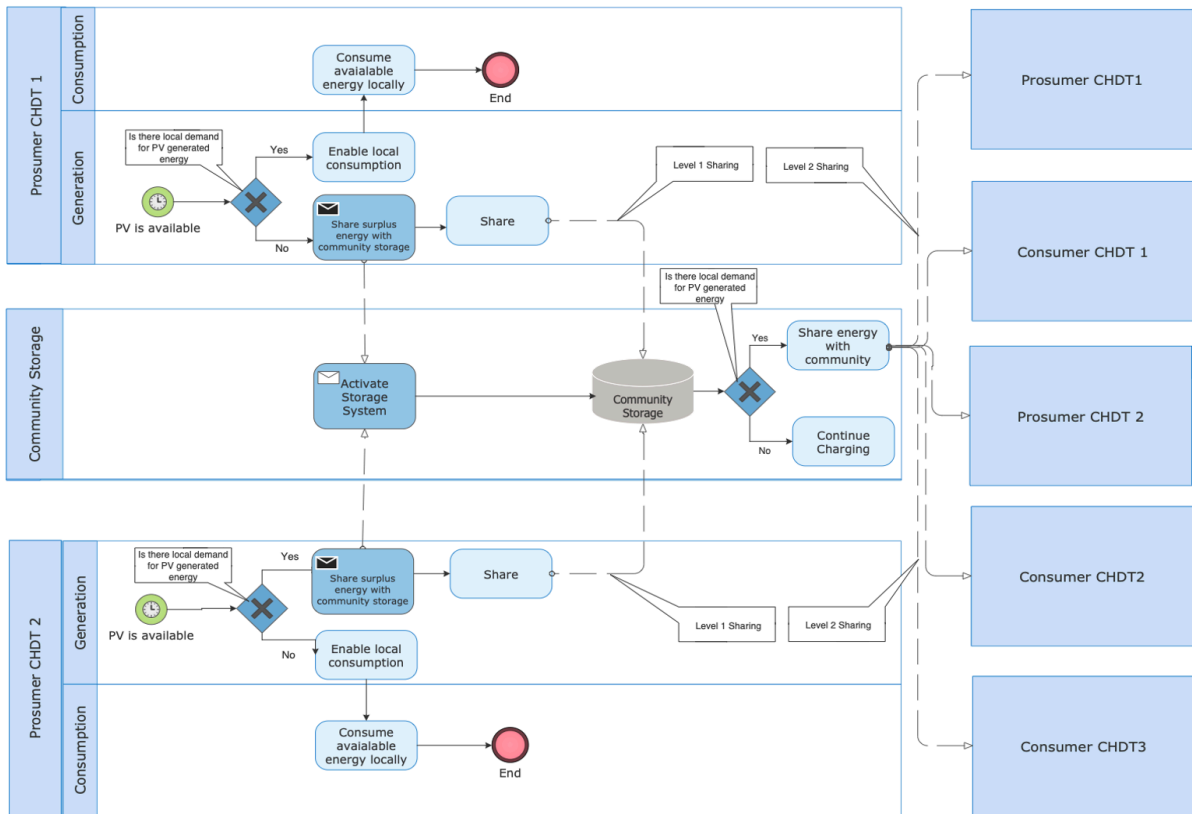


Figure 3.15 —The process of resource sharing

- c. *Modelling the collective actions*. Collective actions (CA) refer to the actions taken by a collection or group of entities, acting based on a collective decision. CA is also a key component of the collaborative behaviours that are exhibited in the CEE. In Figure 3.16, we illustrate the CA behaviours of three CHDTs that are based on a common goal. The resultant effect of their CA is shown to have a direct impact on the community-owned energy asset (community storage), which subsequently affects the power grid. There are three major steps involved in the CA process:
- i. *Condition-based decisions*: In this step of the process, a CHDT makes decisions based on some common goal conditions. For example, a condition such as SellOpp.
 - ii. *Execution of assigned delegated autonomy*: If the decision in step (i) is based on some specific goals, all CHDTs will execute their assigned delegated autonomy simultaneously, which will result in common behaviour.
 - iii. *Appliance use behaviours*: The effect of steps (i) and (ii) will show in the use-behaviour of the embedded household appliances for each respective CHDT. The resultant behaviours could also have a direct impact on the community-owned asset (community storage) and subsequently on the grid.

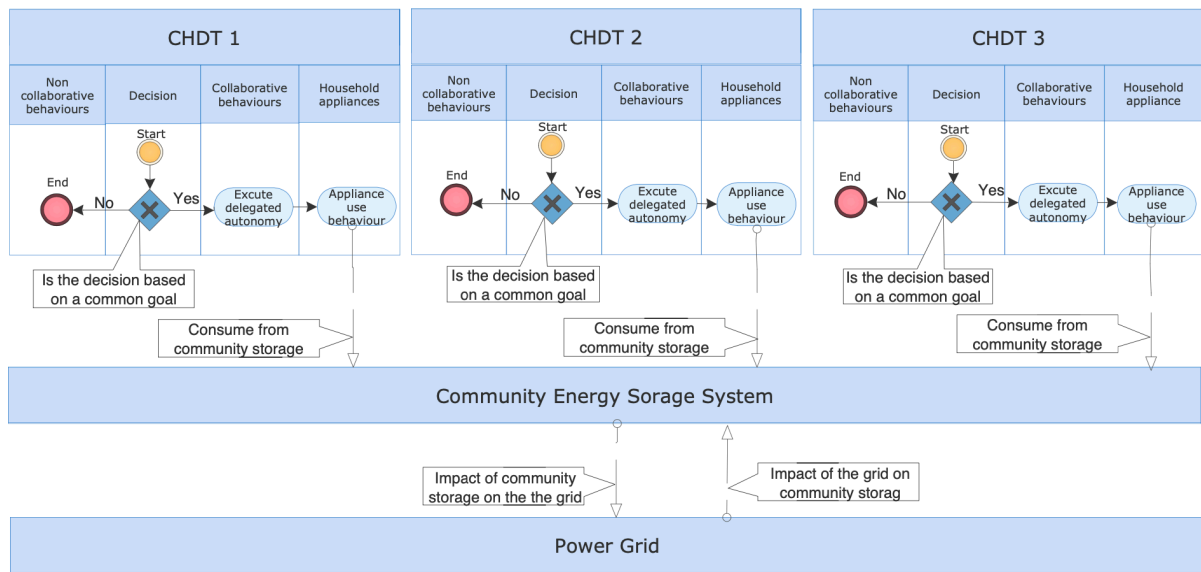


Figure 3.16 —The process of sharing a common resource

3.4.2 The Physical Layer

The physical layer is the second layer of the CEE modelling framework. This layer constitutes the physical energy infrastructure of the ecosystem. The considered energy infrastructure includes aggregation of prosumer and consumer households in the community. Both the prosumer and consumer households have embedded household appliances. Prosumer households have local PV and battery storage systems embedded. The community shares a common community energy storage system. Further details are provided below to illustrate each aspect of the physical layer. Since the focus of the thesis is on the collaborative layer, aspects of the physical layer are not discussed here.

The physical layer is constituted of the following components:

- a. *Prosumer households*: These are households within the ecosystem that own a combination of roof-mounted photovoltaic (PV) systems and a local battery storage system that can be used to generate renewable energy for local consumption. Surplus energy from these households can be stored or shared with the community storage system. These households can consume directly from their PVs, from their local battery storage system, from community storage, and from the grid. In the prototype model that is used for the study, all the prosumer household have nine embedded household appliances. These nine appliances are basic household appliances that are commonly found in many average households.
- b. *Consumer households*: These households do not own any generating units and are therefore unable to generate or contribute energy to community storage. However, they are able to contribute to community goals by delegating the use of their appliances. Consumers can consume energy from the grid and from the community storage. Similar to prosumer households, all consumer households also have nine embedded household appliances.

- c. Community Storage: This is a centralized, community-owned storage system located within the community. Prosumer households can send their surplus energy to this storage system. Both prosumer and consumer households can consume energy from this storage system when it is available.

THE CEE SIMULATION MODELLING

In this section, we introduce a simulation model for the CEE and CHDT in line with the proposed research question. The first part introduces the modelling components that are used by the CEE manager to perform its collaborative roles as explained Chapter 3. The second part addresses the collaborative roles of the CHDTs. As mentioned before, a CEE may typically pursue multiple goals simultaneously. However, for illustration purposes we discuss the scenario where the CEE pursues two community goals concurrently. For example, these two goals may constitute Community goal 1: A selling opportunity (SellOpp) and Community goal 2: A grid management opportunity.

4.1 The Modelling Methodology

The main method that is used in this study is software simulation. The primary reason for selecting this method is that in some instances when it is practically impossible or infeasible to perform such experiments in the real world, e.g., with a real energy community, due to the nature and extent of resources required, and the time it would take, as well as the cost implications, simulation can be used in combination with collecting feedback from focus groups, such as potential users of the system, to help understand the potential behaviour and prospects of the system. Through the use of models, a simulation replicates how systems or processes in the real-world work. The simulation shows how the model changes over time under various conditions, while the model itself depicts the essential behaviours and features of the chosen process or system.

As claimed in a whitepaper (Anylogic, 2018), simulation and modelling were historically based on a single method. This approach had severe limitations because modelling complex systems and the interactions between their components requires different functionalities. Therefore, to create an adequate model, an understanding of how the system is organized in the real world and how it can accurately be represented as a model is highly essential (Anylogic, 2018). Due to the limitations and trade-offs associated with single-method simulations, several researchers such (Borshchev, 2013) and (Yang et al., 2022) have suggested a multi-method simulation approach as a plausible solution although this approach may also have its own weakness, as its usefulness may depend on a particular system and the goals of the model. According to (Brailsford et al., 2019), a multi-method simulation is defined as a simulation/modelling approach that combines two or more simulation techniques into one.

In (Nguyen et al., 2021), the authors further claim that this approach has experienced near-exponential growth in terms of popularity, over the last two decades. The advantage of seamless integration of different modelling and simulation methods helps to overcome the drawbacks of a single modelling method and it enables the modeler to harness the strengths of each method. Combining different methods leads to efficient and manageable models without using workarounds. According to (AnyLogic Simulation Software, 2017), three major simulation methodologies are often integrated to yield a multi-method model, namely: (1) System Dynamics, (2) Multi-agent Systems, and (3) Discrete Event Modelling. In this research, the Anylogic platform was adopted, which supports the methods mentioned. However, several other tools such as NetLogo, Adaptive modeler, Jade, AgentScript, etc. could also be considered alternatively.

4.1.1 System Dynamics

System dynamics suggest that the characteristic behaviour of a system is affected by the interplay among its elements and their interaction with the environment. Furthermore, these elements are found to influence each other in a complex and dynamic environment over time. This modelling technique is often used to analyse the complex and non-linear processes and synergies that exist between several elements. According to (AnyLogic Simulation Software, 2017) system dynamics allows the integration of multiple perspectives of a complex and dynamic system into a software model for easy analysis. It can reduce complex problems constituting numerous variables or factors into a simple and dynamic process by adopting a framework that utilizes modelling blocks such as stocks, feedback, flows, delays, etc.

4.1.2 Agent-based Systems

Multi-agent System (MAS) technology, on the other hand, has gained immense popularity over the past decades due to its adaptable use in numerous emerging domains, such as artificial intelligence (An et al., 2023), distributed computing (Saxena & Abhyankar, 2020), software engineering (Linnenberg & Fay, 2018), smart grid (Saxena & Abhyankar, 2020), electronic commerce (Nanda & Patnaik, 2023), adaptive virtual environments (Lancel et al., 2023), and social networks (Li et al., 2023). MAS has been effectively utilized to solve/model a wide variety of problems spanning numerous disciplines. According to (Borshchev & Filippov, 2004) and (Gunal, 2012), MAS can be the basis for a simulation technique for modelling autonomous, dynamic, and adaptive systems that are founded on three fundamental concepts: agency, dynamics, and structure. Agency implies that agents are autonomous entities with distinct properties, behaviours, and potentially goal-seeking behaviours. Dynamics refers to the development, transformation, and evolution of both agents and their environment. Structure emerges from the interaction of agents. Agents inhabit an environment, perceive it, and determine what action to take at a given time based on the environment's current state, their own state, and predefined decision rules. Agents can have explicit objectives to minimize or maximize, as well as the ability to learn and adapt based on

their experience. Due to their autonomous capabilities, agents can be modelled to possess cognitive and intelligent attributes that enable them to perform tasks such as sensing, planning, scheduling, reasoning, and decision-making.

4.1.3 Discrete Event Modelling

Discrete Event Systems (DES) are discrete-state and event-driven systems in which the state changes depending entirely on the occurrence of discrete events over time. Examples of discrete-event systems include manufacturing systems (Rocha & Lopes, 2022), transportation systems (Zhang et al., 2018), service systems such as medical services (Mahdiraji et al., 2022), communication systems such as wireless networks (Obermaier et al., 2021), etc. Discrete event modelling techniques are useful for process modelling. Processes involving queueing, scheduling, priorities, delays, seizing a resource, releasing a resource (Choi & Kang, 2013), etc., can be modelled in an efficient manner using this modelling technique.

4.2 Scenarios for the Modelling of Collaborative Behaviours in the CEE

4.2.1 Scenarios for Modelling the Broker Role of the CEE Manager

Referring to the broker role introduced in Chapter 3, the broker is responsible for the acquisition of opportunities that are in line with the community's goals. The CEE may pursue multiple goals simultaneously. However, for illustration purposes, here we discuss the scenario of brokering two opportunities. For example, these two opportunities may constitute:

1. *Brokering for community goal 1 - A selling opportunity (SellOpp)*: This goal describes the case where the community finds an opportunity to sell energy to the grid. Considering this goal, it is assumed that the following three preconditions must be satisfied before it can be pursued:
 - a. External demand for energy by the grid. This precondition is represented as "precondition-1A" In Figure 4.1.
 - b. Surplus generation of renewable energy available in the community. This precondition is represented as "precondition-1B".
 - c. A high population of CHDTs having "SellOpp" as their value system, also denoted as "precondition-1C".
2. *Brokering for community goal 2 - A grid management opportunity*: For this goal, we consider the case where the community uses the control of energy assets such as washing machines, dishwashers, and clothes dryers to contribute to grid management by helping to reduce consumption from the grid during peak periods. The nature of these assets, often referred to as "deferrable loads", is that their use can be deferred to a later time without affecting the quality of service they provide to the user. Some examples that could be considered preconditions for this goal may include:

- a. *Peak demand on the grid*: This can represent a period that is daily, annual, or seasonal, when demand for energy is significantly higher than average supply levels and could jeopardize the stability of the power grid. Under such circumstances, one of the conditions available to the grid operators is to implement some demand response actions such as encouraging voluntary reduction in energy consumption for the period. This precondition is represented as precondition-2A.
- b. *A high population of delegated CHDTs with grid management as their value system*, also represented as precondition-2B.
- c. *The minimum energy savings required by the grid operator as contribution to grid stabilization can be met by the collective action of the community*. This is named as precondition-2C.

For a goal to be pursued, all three preconditions relating to that goal must be satisfied.

4.2.2 Scenario for Modelling the CEE

The models that are used to simulate these goals are composed of several components that are integrated to help each software agent perform the various collaborative roles. In the following paragraphs, an overview of the “integrated model” is first presented, and then subsequently, the components of the integrated model are discussed individually in more detail. The shown models and their related components are developed using either agent-based, system-dynamics, or discrete event modelling techniques.

4.2.3 Scenario for Modelling VO Formations

In the implemented prototype we consider:

1. The size of the CHDT population in the model = 100.
2. The percentage of delegated CHDTs is approximately 50% of the population.
3. Goals pursued simultaneously = 2.
4. The minimum number of goals that can be accepted by a CHDT = 0.
5. The maximum number of goals that can be accepted by a CHDT = 2.
6. Minimum VO formation threshold (this refers to the minimum number of accepted invitations that makes the formation of a VO a viable venture) = 25% of the population.
7. Simulation period = 5 hours.

4.2.4 Scenario for Modelling the Various Households and their Embedded Appliances

4.2.4.1 Scenario for modelling the various households

In the current Implementation the CHDT households are categorized into 5 groups:

1. CHDT with single pensioner.
2. CHDT with single non-pensioner.
3. CHDT with multiple pensioners.

4. CHDT with children and
5. CHDT with multiple persons with no dependent children.

The CHDT/household categorization and data that was used to model the corresponding appliances were obtained from (Zimmermann et al., 2012). In the prototype each household is embedded with nine household appliances, namely:

1. Washing machine, (Deferable load).
2. Tumble dryer, (Deferable load).
3. Dishwasher, (Deferable load).
4. Audio-visuals.
5. Microwave.
6. Electric cooker.
7. Lighting.
8. Refrigeration and
9. Oven.

4.2.4.2 Scenario for modelling the various household appliances

Modelling Energy Generation, Consumption, and Storage: To model the household appliances, we borrowed techniques from the field of system dynamics to replicate the dynamic characteristics of these appliances. Figures 4.1 and 4.2 show system dynamic blocks (stock and flow diagrams) that are used to mimic the generation, consumption, and storage behaviours of all the embedded appliances. In Figure 4.1, the "flow" element is used to simulate the rate of flow of any quantity (say, the flow of electrical energy in this example). The flow rate is determined by "Parameter A." This parameter is a constant and in the case of this work, it is used to represent the power rating of an appliance. The "stock" element acts like an accumulator for the amount that arrives from the "flow" element. Consequently, this "stock" element can be used to represent an energy storage device, such as a battery or a system that draws or consumes energy from a source. Finally, the "cloud" element represents an infinite source or supply, such as solar energy. Mathematically, the rate of flow is given by:

$$\frac{d(Flow)}{dt} = Parameter\ A \dots\dots\dots(1)$$

Again, the rate at which stock_1 gets accumulated is given by:

$$\frac{d(stock_1)}{dt} = \frac{d(Flow)}{dt} \dots\dots\dots(2)$$

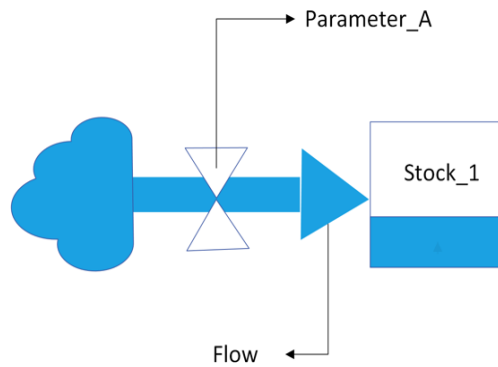


Figure 4. 1— Example of stock and flow diagram representing generation and storage.

Furthermore, Figure 4.2 depicts a flow from "Stock-2" into "Stock-3." The element Stock-2 can represent a finite supply source, such as the case of a battery storage system or the power grid, while Stock-3 can symbolize an item that draws a quantity, for example, energy, from Stock-2. The cumulative value of "Stock 3" may also be used to determine the quantity that has been drawn from "stock 2." Mathematically, the rate of flow is given by:

$$\frac{d(Flow)}{dt} = Parameter\ B \tag{3}$$

The rate at which stock_2 depreciates is given by the equation.

$$\frac{d(stock_2)}{dt} = - \frac{d(Flow)}{dt} \tag{4}$$

The rate at which stock_3 appreciates is given by the equation.

$$\frac{d(stock_3)}{dt} = \frac{d(Flow)}{dt} \tag{5}$$

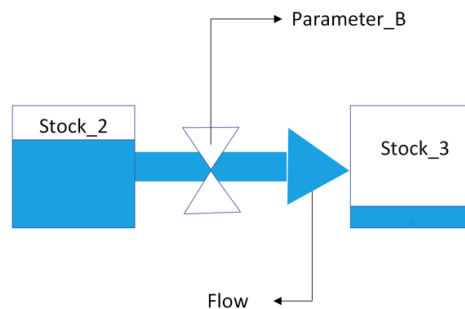


Figure 4. 2— Example of a stock and flow diagram of consumption

Additionally, to help model the appliance, use behaviours, the following metric are adopted:

1. **Appliances Frequency of Use (FoU):** This metric is used to represent the number of times per week an appliance is likely to be utilized. The FoU for each appliance is

generated using a Pert probability distribution function defined as *Pert distribution* (X, Z, Y), where X = minimum number of uses per week, Z = average number of uses per week, and Y = maximum number of uses per week.

2. **Appliances Power Rating (APR):** This metric is used to represent an appliance's power rating. The APR of each appliance is generated using a uniform probability distribution function, *Uniform distribution* (X, Y), where X = the lowest possible appliance power rating for that category of appliance, in kilowatts, and Y = maximum possible power rating for that category of appliances also in kilowatts.
3. **Appliances Duration of Use (DoU):** This metric is used to represent how long an appliance is used for each usage cycle. This parameter is generated with a uniform probability distribution function defined as *Uniform distribution* (X, Y), where X is the lowest duration in hours and Y is the maximum length in hours.

Provisional values for APR, DoU, and FoU, were sourced from (daftlogic, 2018), (Rosin et al., 2012), (Zimmermann et al., 2012) and (Le & Pitts, 2019).

Considering that the power rating of an appliance is denoted as APR in (kw), and the duration of use is denoted by DoU (hrs), then at every instant, the consumption (C) of the appliance is given by:

$$C \text{ (kwh)} = APR \times DoU \dots\dots\dots(6)$$

Also, for “ n ” number of use (also FoU) per week, the total consumption is given by:

$$\sum_{i=1}^n C_i \dots\dots\dots(7)$$

4.2.5 Scenario for Modelling Mutual Influence

This scenario is used to model how influences are propagated in the CEE. In this scenario influences are conveyed and received in the form of “pulses” that are transmitted sporadically from several sources (i.e., from the various influencer CHDTs) to random destinations (influencee CHDTs). The pulsating characteristics of the influences are modelled using a probability distribution function. These functions are expressed as follows: (a) Positive influence = uniform distribution (+a, +b), (b) negative influence = uniform distribution (-c, -d), (c) frequency of transmission = uniform distribution (e, f) times per hour, days, weeks, months, or years. (d) Impact = uniform distribution (g, h) per hour, days, weeks, months, or years, (g) decision constant = ∞ . Where +a, -c, e, and g are the possible lower limits, and +b, -d, f, and h are the possible upper limits for each related element of the influence. In the model, the following parameters are defined and used.

1. Positive influence is modelled as: *uniform distribution* (0, 2), where “0” is the minimum polarity and “2” is the maximum polarity.
2. Negative influence is modelled as: *Uniform distribution* (-2, 0), where “-2” is the minimum polarity and “0” is the maximum polarity.

3. Frequency of transmission is modelled as: *Uniform distribution (0, 3) times per week*, where "0" is minimum frequency and "3" is the maximum frequency per week.
4. Impact is modelled using a probability distribution expressed as: *Uniform distribution (0, 5) hours from the moment of receiving the influence*, where "0" is the minimum magnitude of the impact and "5" is the maximum magnitude of the impact.
5. Decision constant (α) = 50. This is a tentative value.
6. Total CHDT population = 100

4.3 Modelling Collaborative Roles/Behaviours of the CEE Manager

The integrated model of the manager is illustrated in Figure 4.1. It is composed of six components that work together to model the various collaborative roles played by the manager. The considered components are:

- (a) the opportunity seeking/goal condition for goal 1 components,
- (b) the opportunity seeking/goal condition for goal 2 components,
- (c) the goal formation component,
- (d) the goal proposition and invitation component,
- (e) the VO formation/dissolution for goal 1, and
- (f) the VO formation/dissolution for goal 2 components.

Opportunity Seeking / Determination of Goal Conditions for Goals 1 and 2 Components. The types and numbers of goals to be pursued at any given time are often determined by the manager. The manager may brokerage the opportunity by gathering inputs, which are the preconditions described in Section 4.4.1. These inputs (preconditions) may be collected from sources such as weather forecasting systems, distribution service operator, the energy market, the value systems of CHDTs, etc., to determine whether the preconditions for the formulation of a specific goal can be met. If these preconditions are met, it can be inferred that an opportunity has been found. According to (Dictionary.Com, 2017) an opportunity is a situation or condition that is favourable for the attainment of a goal. Once an opportunity is found, the manager formulates the goal and proceeds to invite members of the community towards the formation of a temporary coalition or virtual organization (VO) to pursue the found opportunity. The coalition that is formed can then be dissolved after the opportunity has been accomplished.

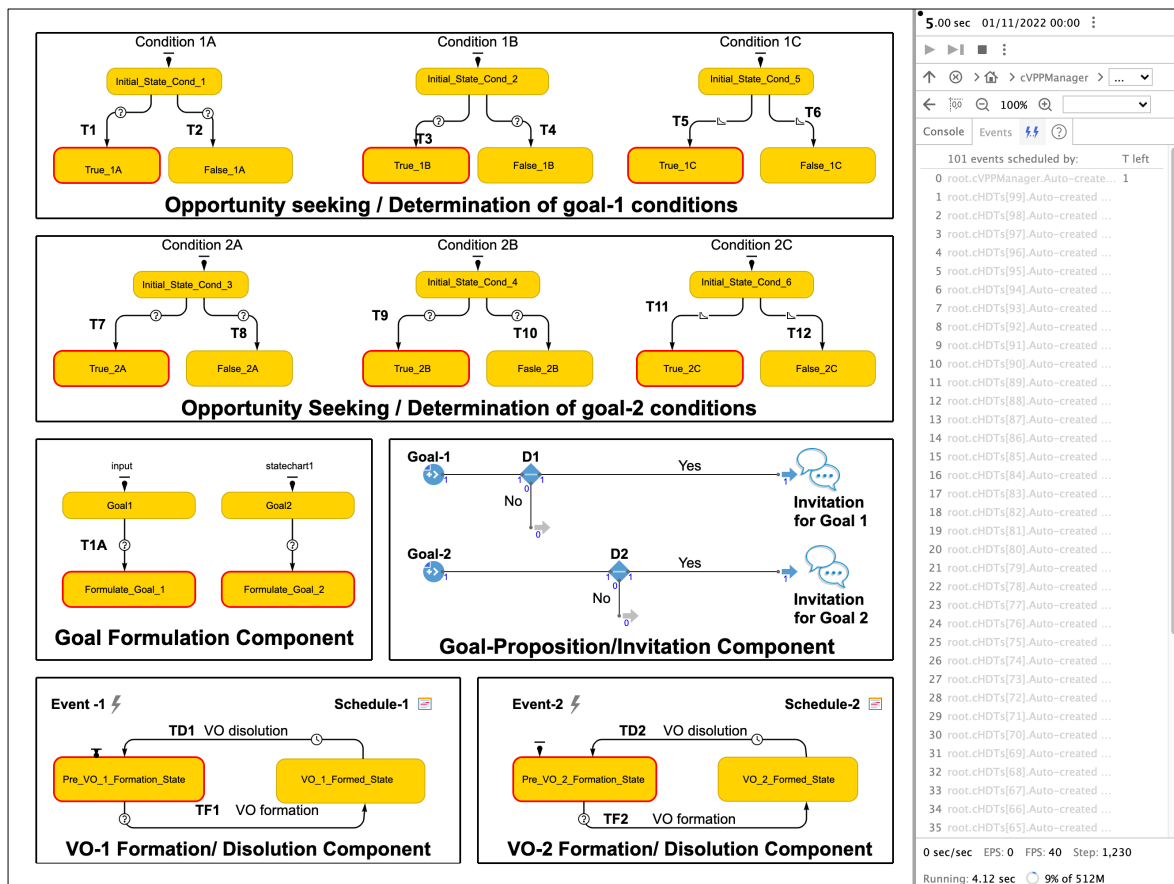


Figure 4. 3—Illustration of the integrated model of the CEE Manager

Modelling Opportunity Seeking / Determination of Goal Conditions for Goals 1&2 Components. The model's component that is used to simulate “opportunity seeking” or “determination of goal preconditions” by the CEE manager is shown in Figures 4.2 and 4.3. Agent-based techniques are adopted to simulate the preconditions for Goals 1 and 2. The figures show three preconditions for each goal, namely preconditions 1A, 1B, and 1C for Goal 1 and preconditions 2A, 2B, and 2C for Goal 2. Each precondition can only be in one state at a time, thus either in the true state (active) or in the false state (inactive). T1 to T12 are stochastic transitions that enable each precondition to transition between the active and inactive states for every model iteration. In the prototype the probability of transitioning between these two states is 50% for each precondition. The active state is used to represent a prevailing condition, while the inactive state represents a dormant condition. The case illustrated in Figure 4.2 shows that all three preconditions (1A, 1B, and 1C) representing Goal 1, and all three preconditions, thus, 2A, 2B, and 2C, representing Goal 2, are in their true or active states, implying that they are the prevailing conditions for Goals 1 and 2, respectively. Therefore, it can be inferred that all preconditions for both goals are satisfied, and thus, Goals 1 and 2 can be formulated and subsequently pursued. On the contrary, in the case illustrated in Figure 4.3, we have a different situation where precondition 1B is in a false, inactive, or dormant state.

However, preconditions 1A and 1C are in the true, active, or prevailing state of Goal 1. Similarly, considering Goal 2 (Figure 4.3), it can be observed that Goals 2A, 2B, and 2C are all in their true or active states. The implication for this scenario is that Goal 1 cannot be formulated and pursued; however, Goal 2 can be formulated and subsequently pursued because all three of its preconditions are satisfied.

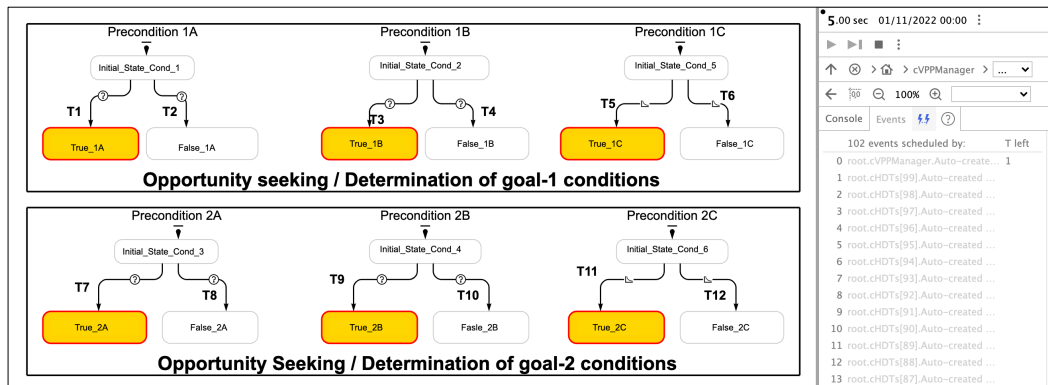


Figure 4. 4—All three preconditions for community Goals-1 and 2 are satisfied. Both community goals are formulated and pursued concurrently

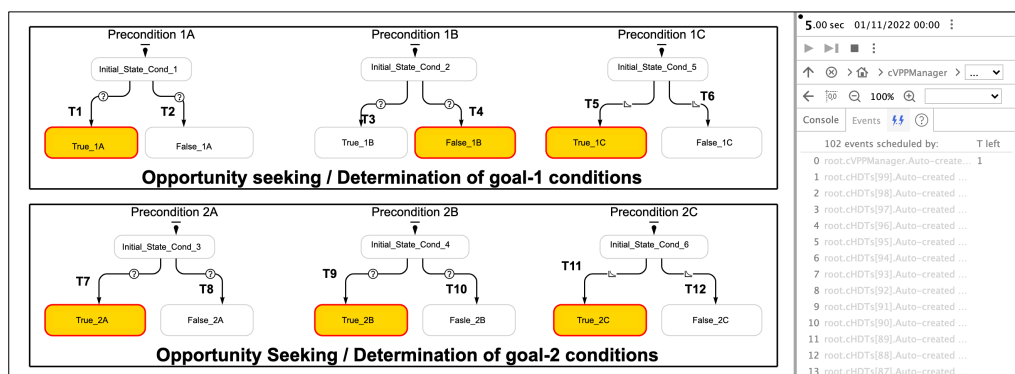


Figure 4. 5—All three preconditions for community Goal 2 are satisfied. Only two preconditions for community goal 1 are satisfied. Goal 2 will be formulated but Goal 1 will not.

Goal Formulation Component. The outcome of the opportunity seeking/goal condition explained using Figures 4.2 and 4.3 may either lead to the formulation of a community goal or otherwise. The formulation of goal(s), by the CEE manager, is very essential in the ecosystem as it forms the basis for the notion of a “common goal”. This is because, anytime a community goal is formulated or revised at the level of the manager, it is replicated or duplicated within each CHDT so that they can be cognizant of the active or prevailing community goal(s) and can make decisions based on these prevailing goal(s). In Figure 4.4, TG1 and TG2 are conditional transitions that are used to monitor the conditions for the formulation of goals. Transition TG1 is used to check the conditions for the formulation of Goal 1, i.e., if precondition 1A is true, precondition 1B is true, and precondition 1C is true, then formulate Goal 1. Similarly, Transition TG2 is used to monitor the conditions for the formulation of Goal 2, i.e., if precondition 2A is true, precondition 2B is true, and precondition 2C is true, then formulate Goal 2.

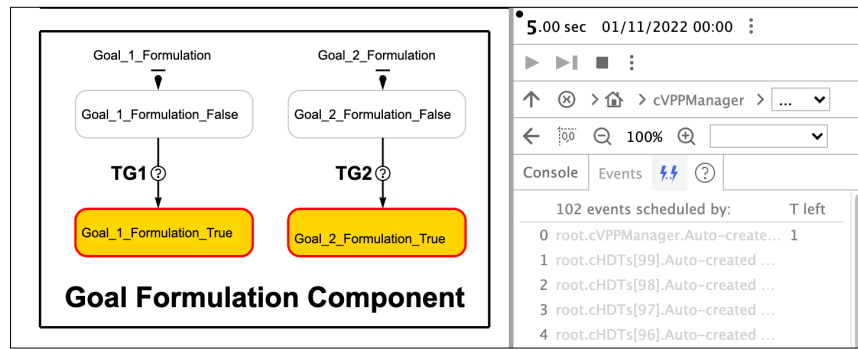


Figure 4. 6—Goal formulation component illustrating the formation of Goals 1 & 2

Goal proposition/invitation component. Once an opportunity has been found and a goal has been formulated, the CEE manager proceeds to invite CHDTs to form a coalition in pursuance of the specified goal(s). The invitation is broadcasted to the CHDTs in the form of a message. In AnyLogic, agents living in a common environment can communicate with each other using built-in messaging functionality. This mechanism allows the sending of a message from a single source (one software agent) to multiple destinations (several software agents). Figure 4.5 shows a discrete event component of the model that is used to broadcast messages from the manager to all CHDTs. The decision blocks D1 and D2 in this figure are used to check if Goals 1 or 2 have been formulated. If the condition returns true, a message symbolizing an invitation is broadcast to all CHDTs in the environment. Otherwise, no message will be broadcast. In all discrete event models, such as the one shown in Figure 4.5, the label “1” that is found near each modelling block indicates the “true” condition and the label “0” signifies the “false” condition. Referring to Figure 4.5 it is observed that D1 and D2 return “true” for both for Goals 1 and 2. Therefore messages corresponding to Goal 1 and Goal 2 are sent out.

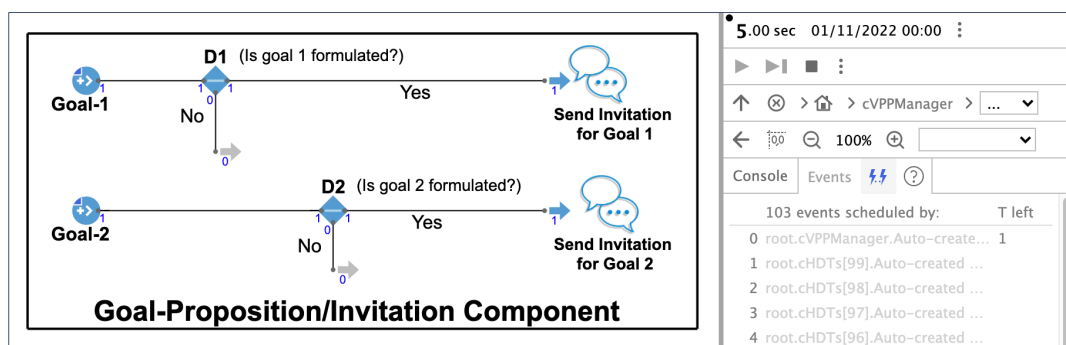


Figure 4. 7—A discrete event component that is used to broadcast invitations of goals 1 & 2 to the community.

In more detail:

1. *Invitation acceptance or decline.* This aspect of the process is performed by individual CHDTs. It is, therefore, discussed in detail in Section 4.4, where the roles of the CHDTs are discussed. In the subsequent paragraphs, we discuss VO formation and dissolution based on the premise that the CHDTs have received the invitations and

responded accordingly. A summary of the responses to both invitations during the simulation is illustrated in Figure 4.6.

2. *Virtual Organization (VO) formation or dissolution.* The VO formation and dissolution processes are performed by the CEE manager after it has received various responses from the CHDTs. The manager uses a threshold that is called the “minimum VO formation threshold” to make VO formation decisions. Several factors can be used to determine the VO formation threshold. In this work, the threshold was set based on a minimum percentage of the population that accepted an invitation to a particular goal. For instance, if we consider a minimum of 25% of the population, thus 25% of 100 CHDTs are considered, which equals 25 CHDTs. This means that for each goal, a minimum of 25 CHDTs must accept the invitation before a VO can be formed. Alternatively, a VO can also be formed in terms of the quantity of energy, thus, the minimum quantity of energy that can be aggregated based on the responses received from the various CHDTs.

In Figure 4.6, we illustrate the techniques and principles that are used for VO formation. This figure shows two components of the model that are used to represent (a) a VO for Goal 1 and (b) a VO for Goal 2. Each component of the model includes two possible states, thus, (i) the pre-VO formation state, and (ii) VO formed state. The pre-VO formation state is the default state of the component, while the “VO formed state” represents the state when a VO has been formed. When a VO is formed, the component remains in the “VO formed” state for the entire lifecycle of the VO. When the VO is dissolved, the component returns to the pre-VO formation state. The transition from the “pre-VO formation state” to the “VO formed state” is triggered by transitions TF1 for Goal 1 and TF2 for Goal 2. TF1 and TF2 are conditional transitions that check the minimum threshold and are triggered when the threshold is met or exceeded. Transitions TD1 and TD2 are used to dissolve VO 1 and VO 2 respectively, after the corresponding goal has been accomplished. Event 1 and event 2 are used to trigger the start and finish of both Goals 1 and 2 respectively. Schedules 1 and 2 are used to schedule the waiting time before the commencement of Goals 1 and 2, respectively. As can be seen in the statistical analysis of the example in Figure 4.6, the number of CHDTs that accepted Goal 1 is 29 out of 100 CHDTs, and the number that accepted Goal 2 is 22 out of 100. Furthermore, 14 CHDTs accepted both Goals 1 and 2. It can be observed from these statistical data that the number of CHDTs that accepted Goal 1 exceeded the minimum threshold of 25 CHDTs. In this case, it can be seen in Figure 4.6 that VO 1 is formed to pursue Goal 1. On the contrary, the number of CHDTs that accepted Goal 2 is 22, which is less than the threshold of 25 CHDTs, therefore, VO 2 is not formed.

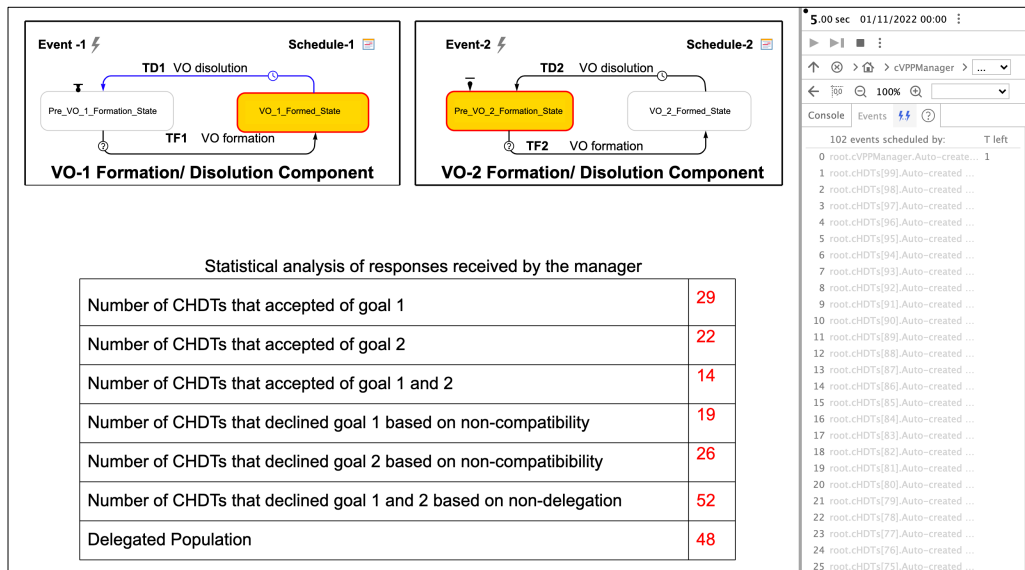


Figure 4. 8—VO formation, dissolution, and statistical analysis component

4.4 Modelling Collaborative Roles/Behaviours of CHDTs

4.4.1 The Integrated Model of the CHDT

The integrated model of the CHDT is illustrated in Figure 4.7. Each of the CHDTs in the ecosystem is designed according to this model. The integrated model is constituted by the components that are used by the CHDTs to participate in collaborations. The integrated model comprises the following components: (a) the community goal component, (b) the value system component, (c) the delegation components, (d) the decision-making components for goals 1 and 2, and (e) the delegated autonomy. In the subsequent paragraph, each component and its functionality are discussed in detail.

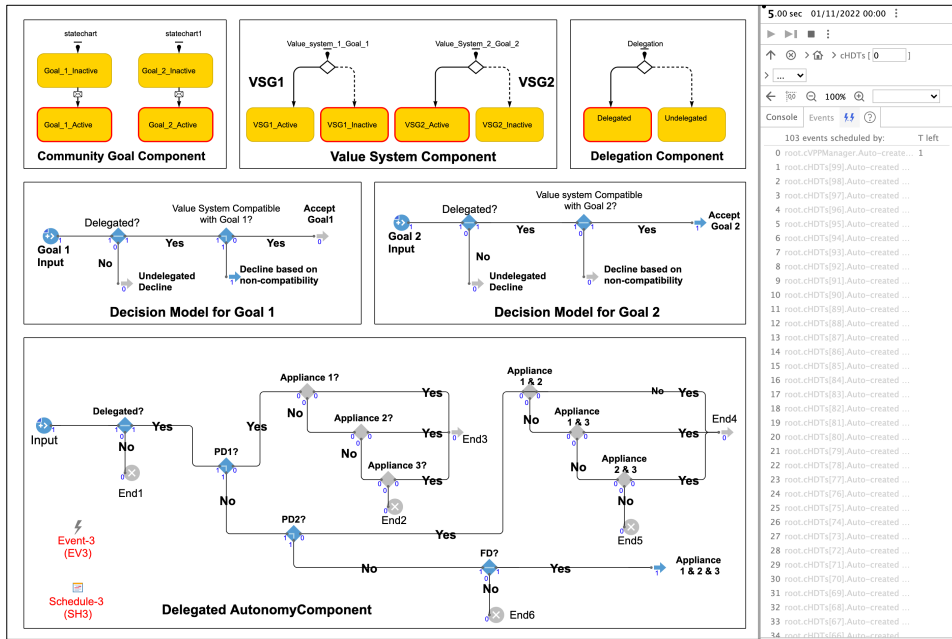


Figure 4. 9—The integrated model of the CHDT

Community Goals Component. In Figure 4.8 we show an extract of CHDT number 36 that illustrates how the community goal, which is originally formulated by the CEE manager at the upper level of the model (shown in section 4.3), is replicated at the CHDT level. Any time the community goal changes at the upper level, the change is replicated in the equivalent component that is embedded inside the CHDTs. This technique helps CHDTs to be cognizant of the prevailing community goal(s). The ability of all CHDTs to be individually cognizant of the community goals and have the capability to make autonomous decisions based on this knowledge fulfils the notion of a “common goal,” which is a key prerequisite for collaboration.

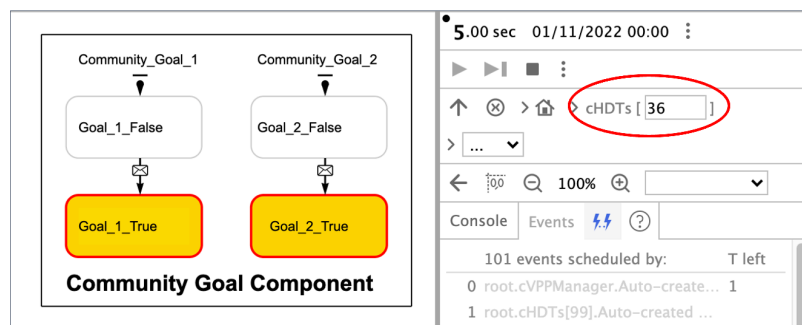


Figure 4. 10—A replica of the community goal that is replicated inside CHDT number 36

Value System and Community Goal Compatibility Components. Besides the community goal(s), each CHDT has a value system that is used to represent the needs, preferences, priorities, objectives, and expectations of a user. Furthermore, a CHDT may have several value systems to represent several needs, and these could be arranged in hierarchical order to represent different priorities and options. For illustration purposes, in this simulation study, we assume that each CHDT has two value systems, namely: (a) value system 1 (VSG1), and

(b) value system 2 (VSG2). A value system can be in one state at a time, either the “true/active” state or the “false/inactive state.” The true and false states of a value system are modelled using stochastic modelling techniques that give each state a 50% probability of occurrence. This technique helps to simulate different value system scenarios for all the CHDTs in the considered population. A value system that is in its true state implies that it is the prevailing value system for that CHDT, while a value system that is in its false state implies that it is dormant for the related CHDT. When the active state of value system 1 is in the “true” state (prevailing), it can be inferred that it is compatible with community Goal 1. In the same way, when the active state of value system 2 is the “true” state (prevailing), it can also be inferred that value system 2 is compatible with community Goal 2. However, if any of the active states of the value system are in the “false” state (dormant), that value system can be inferred to be non-compatible with the respective community goals. As an example, we show three different CHDTs, each with different value systems, in Figures 4.9 to 4.11. In Figure 4.9, CHDT number 61 has both value system 1 and value system 2 in the false state. This can be interpreted as a CHDT with no prevailing value system. Similarly, in Figure 4.10, CHDT 87 has one prevailing and one dormant value system. As such, it can be assumed that value system 1 of CHDT 87 is compatible with community Goal 1. For the same CHDT, the false state for value system 2 means that value system 2 of CHDT 87 is incompatible with community Goal 2. Finally, in Figure 14.11, both value systems 1 and 2 of CHDT 30 are compatible with community Goals 1 and 2.

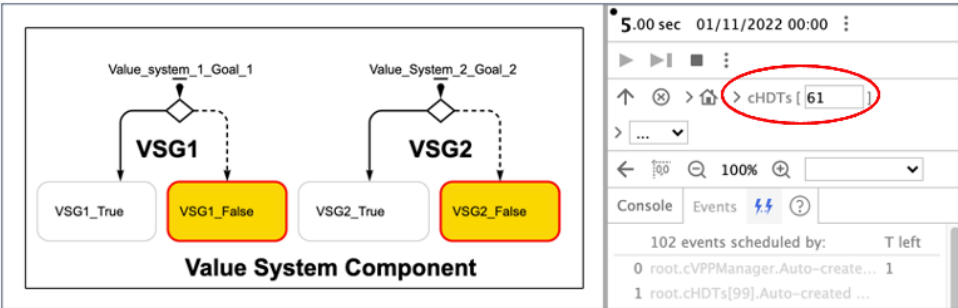


Figure 4. 11—Example of no prevailing value system. Both value systems are dormant for CHDT 61

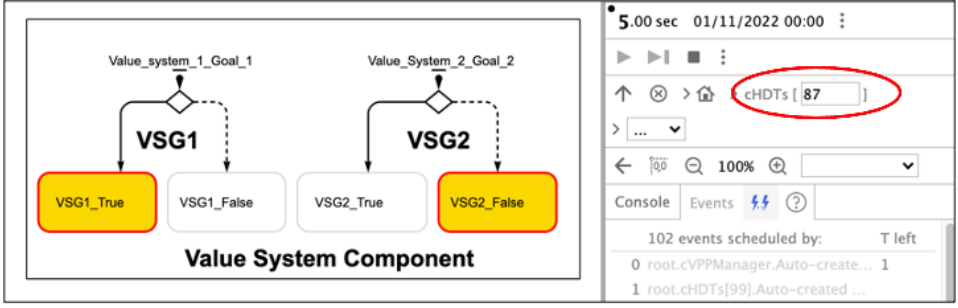


Figure 4. 12—Example of one active/prevailing value system (VSG1) for CHDT 87

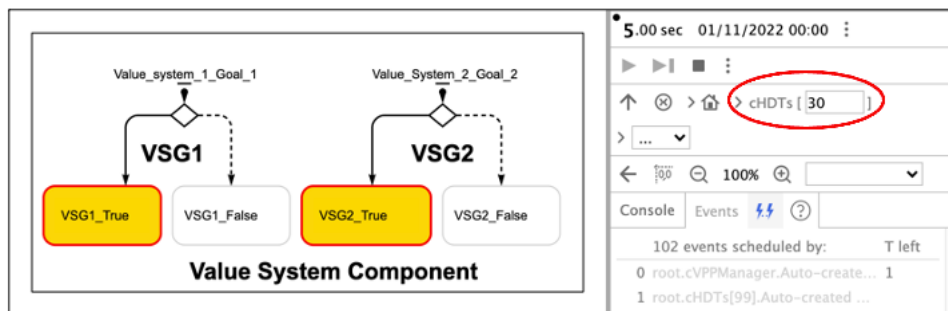


Figure 4. 13—Example of two active/prevaling value system (VSG1 and VSG2) for CHDT 30

Delegation Components. According to (Landry, 2021), delegation refers to the transfer of responsibility from one entity to another to execute some specific tasks on its behalf. In the context of this study, delegation refers to the process whereby the user or physical twin owner gives authority or responsibility to its CHDT, allowing it to act or take some rational decisions on his/her behalf. The component that is used to determine the “delegated” or “undelegated” condition of a CHDT is shown in Figure 4.12. In this delegation component, only one of the two states can be active at a time. When a CHDT is delegated, the “delegated” state becomes active. On the contrary, if the CHDT is undelegated, the “undelegated” state becomes active. Under the undelegated state, a CHDT is unable to make decisions on behalf of the physical twin and therefore cannot participate in collaborative activities. Figure 4.12 is therefore used to illustrate a delegated CHDT.

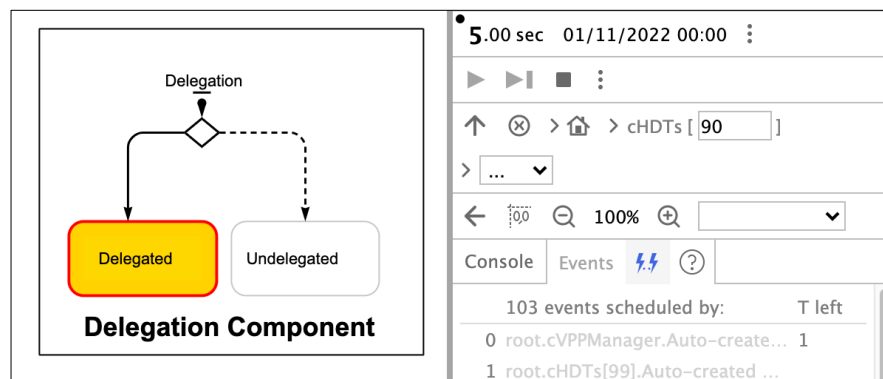


Figure 4 14—A delegated CHDT (CHDT 90)

Decision Components of the CHDTs. There are two decision-making components that are embedded in each CHDT. These blocks are used to simulate the acceptance or decline of an invitation. The decision component uses discrete event simulation techniques to process these behaviours. One part of the decision component is used to process invitations for Goal 1 while the other part is used to process invitations for Goal 2. Figures 4.13 to 4.15 are used to illustrate different scenarios of acceptance and decline of invitations broadcast by the CEE manager. Subsequent actions that are taken by the CHDTs after receiving the invitation include (1) checking the “delegated/undelegated” state of the CHDT, and (2) checking the value system and community goal compatibility, and finally (3) acceptance or rejection of the invitation.

1. *Checking the delegated/undelegated state of the CHDT:* After receiving an invitation, the CHDT first checks the delegation component to determine whether it is “delegated” or “undelegated.” If in an un-delegated state, the invitation is declined based on “un-delegation.” However, if the CHDT is delegated, the model proceeds to check the value system and community goal compatibility before deciding to accept or decline the invitation.
2. *Checking value system and community goal compatibility:* In the simulation, a value system is said to be compatible with a community goal when both are found to be in their respective true states. If one of the conditions is found in the true state and the other in the false state, the two are said to be incompatible. If both conditions are found to be false, the two are also said to be incompatible. The only condition for compatibility is when both conditions are found in their respective true states. In Figure 4.13, the behaviour of CHDT 61 is shown. It can be observed that this CHDT declined the invitations to both Goal 1 and Goal 2 based on “un-delegation.” (The label “1” near each modelling block shows the “true” condition, while the label “0” represents the false condition.) Similarly, in Figure 4.14, the behaviour of CHDT 62 is also shown. It can be seen that the CHDT declined Goal 1 based on non-compatibility of goals but rather accepted Goal 2 on the condition that it was delegated, and the value system and the community goal were compatible. Lastly, in Figure 4.15, the case of CHDT 91 is presented. It is seen from the output of the model that this CHDT accepted both Goals 1 and 2 on the basis that it was delegated. Furthermore, their respective value systems were also compatible with both Goals 1 and 2.

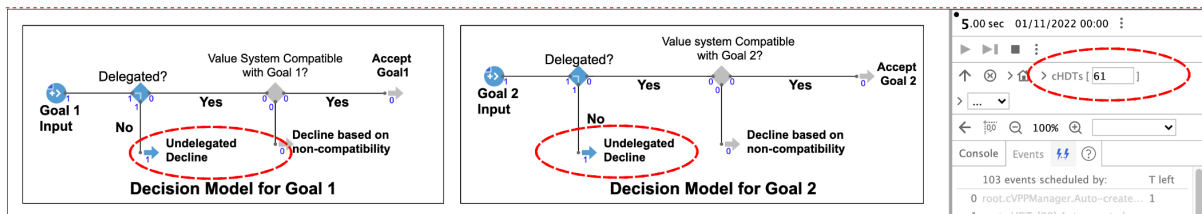


Figure 4. 15—The decision component shows the "decline" of Goals-1 and 2 based on un-delegation for CHDT number 61

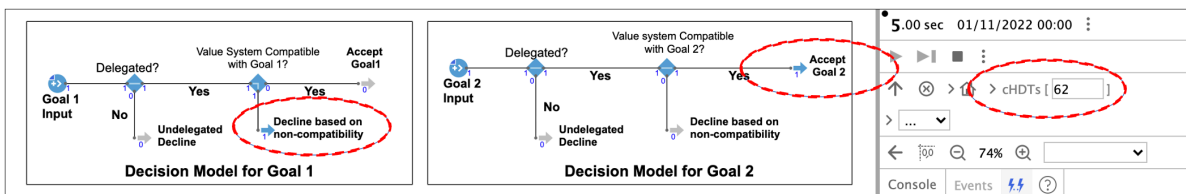


Figure 4. 16—The decision component shows the "decline" of Goal 1 based on non-compatibility and acceptance of Goal 2 for CHDT number 62

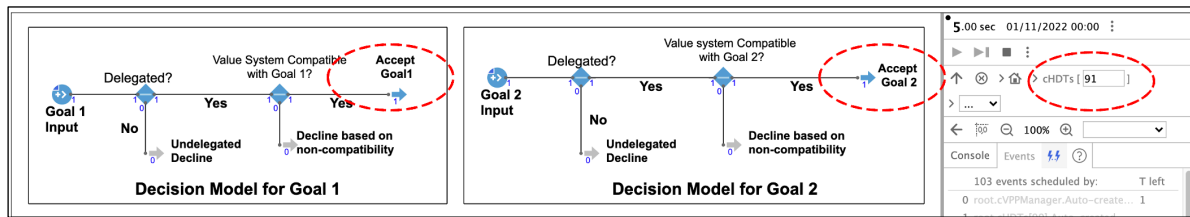


Figure 4. 17—The decision component shows the acceptance of Goals 1 and 2 for CHDT number 91

3. *Acceptance or rejection of the invitation:* These steps are explained in detail in the previous section (section 4.3) and using Figure 4.5 as the reference.

Delegated Autonomy Component. As mentioned earlier, delegated autonomy is the specific instruction that a household owner may assign to its CHDT to be followed in carrying out or executing its value system. In the implemented scenario, three appliances are considered for delegated autonomy: washing machine, dishwasher, and clothes/tumble dryer. Furthermore, we assume that delegated autonomy can be executed at three levels: (a) partial delegation for a single appliance (PD1), (b) partial delegation for double appliances (PD2), and (c) full delegation (FD). PD1 means that the CHDT has the authority to delegate any one of the three appliances. Similarly, PD2 means having the authority to delegate any two of the three appliances, and FD means having the authority to delegate all three appliances. Although delegated autonomy is reflected as the next step after acceptance of an invitation, this process does not occur immediately. This process is usually scheduled, and the schedule is communicated by the CEE manager. All CHDT execute their delegated autonomy in compliance with specific community goals. For this to be possible, all CHDTs must be cognizant of the specific community goals and the corresponding schedules for each particular goal, so that they can delegate their appliances in accordance with the schedule of that goal. For this reason, the schedule for every goal (which is determined by the CEE manager) is also replicated at the level of each CHDT. For instance:

1. *At the level of the manager (referring to Figure 4.1):* At this level schedule-1 is the schedule for Goal 1, and event-1 is used to trigger the start and finish of Goal 1. Similarly, schedule-2 is the schedule for Goal 2, and event-2 is used to trigger the start and finish of Goal 2.
2. *At the level of the CHDTs (referring to Figure 4.16):* At this level schedule-3 and event-3 replicate schedule-1 and event-1 for Goal 1 (at the level of the manager), while schedule-4 and event-4 are used to replicate schedule-2 and event-2 for Goal 2 (also at the level of the manager).

Figure 4.16 illustrates the delegated autonomy component for CHDT 75. Event-3 is used to trigger the commencement of delegated autonomy. In the process of executing delegated autonomy (referring to Figure 4.16), the component checks again to confirm if the CHDT is delegated or undelegated. If undelegated, the process is terminated (End1). If delegated, the model checks the condition for PD1. If the PD1 condition is true, the model will delegate either appliance 1, appliance 2, or appliance 3. If the PD1 condition is false, the model proceeds to check PD2. If the PD2 is true, the component will delegate either appliances 1 and 2, appliances

1 and 3, or appliances 2 and 3. If PD2 is false, the model component checks for the FD condition. If the FD is true, the model will delegate all three appliances. In the case of CHDT 75 shown in Figure 4.16, FD is true, therefore all three appliances are delegated.

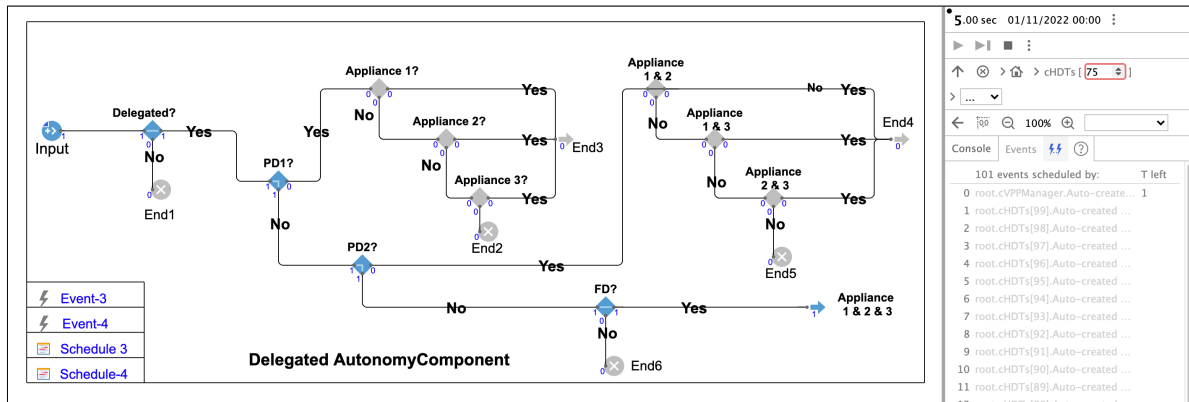


Figure 4. 18—Implementing delegated autonomy.

4.4.2 Modelling the Sharing of Common Resources

Collaborative consumption, a kind of “sharing economy,” has attracted a lot of attention since resource sharing is quickly gaining importance both in economic and social circles. According to (Shirado et al., 2019), these novel sharing solutions to socioeconomic challenges have the potential to significantly improve the efficient utilization of scarce resources. In the CEE framework, it is suggested that the ecosystem can possess a centralized and shared energy storage system through which prosumers can share their surplus energy. Consumers and prosumers alike can access this stored energy when needed. This technique can help reduce reliance on the power grid, helping to promote sustainable consumption within an ecosystem. In this prototype, two levels of sharing are discussed, namely: (1) level 1 sharing, which constitutes the sharing of surplus energy from prosumers to the community storage, and (2) level 2 sharing, which constitutes the reverse: a redistribution of energy previously stored in the community storage, back to the community. Figure 4.17 shows a system dynamics component of the photovoltaic (PV) and battery storage systems embedded in each prosumer CHDT. The example considers four PV systems, namely (a) DaSS = 3.22 KW, (b) BrainSystem = 6.93 KW, (c) Helious = 3.99 KW, and (d) BainBridge = 1.95 KW. Live data corresponding to these PV systems is sourced from (*PVOutput*, 2018). At the model initialization stage, one of the four PV systems is randomly assigned to a prosumer. This helps to diversify the capacities of PV systems in the ecosystem.

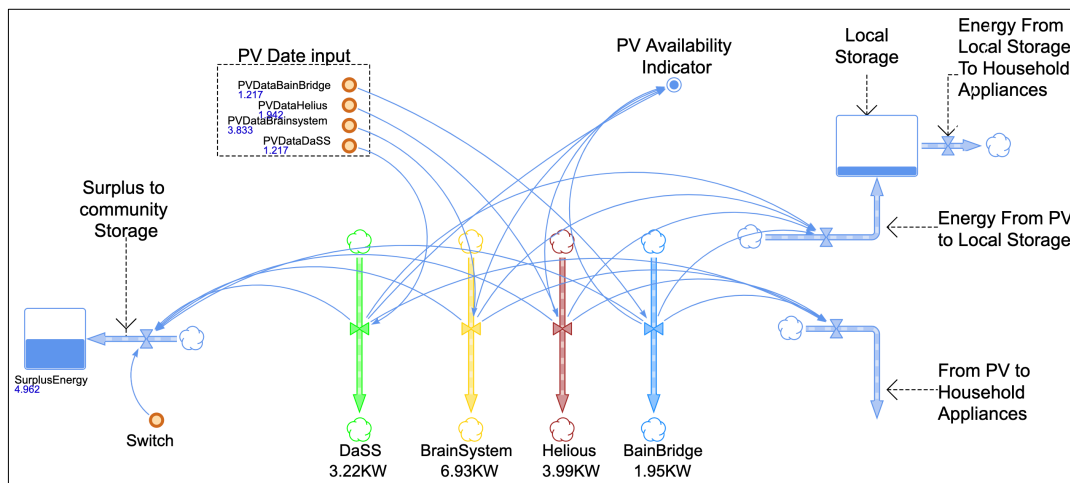


Figure 4. 19—A model of the four embedded PV systems with the integrated local energy storage system

Sharing surplus energy with community storage: For instance, in Figure 4.18, we show the codes that are used to share surplus energy from a prosumer CHDT with the community storage. The interpretation of the codes is as follows.

- Condition 1A: The code “InState(LocalBatteryFull)?” checks whether the local battery is in the “battery full” state. The “battery full” state is determined by whether the state of charge (SoC) is greater or equal to (\geq) 90% of the storage capacity.
- Condition 2A: The code “InState(NoLocalDemand)” checks if there is no local demand.
- Condition 3A: The code “instate (PVisAavailable)” is used to check PV availability.
- Condition 4A: If the checks from conditions 1A, 2A and 3A, return true, then data from one of the four embedded PV systems, depending on which one has already been assigned to the CHDT, will be activated. The active PV system could either be (PVfromBainBridge) or (PVfromHeliious) or (PVfromBrainSystem) or (PVfromDaSS). Since only one of these PV systems will be active at a time for a CHDT, data from that PV will flow into the community storage. All inactive PV systems will return zero.
- Condition 5A: If the checks from conditions 1A, 2A and 3A, return false, the output of the expression will be zero, which means no flow occurs.

Conditions for charging and discharging the batteries are as follows:

- Condition for discharging the battery: If state of charge (SoC) community storage is greater than X% of the storage capacity and there is community demand for energy, discharge the battery, or else keep charging.
- Condition for charging the battery: If SoC of community storage is less than Y% of the storage capacity, stop discharging the battery and charge, else keep discharging.
- In the prototype model X = 90% and Y = 30%.

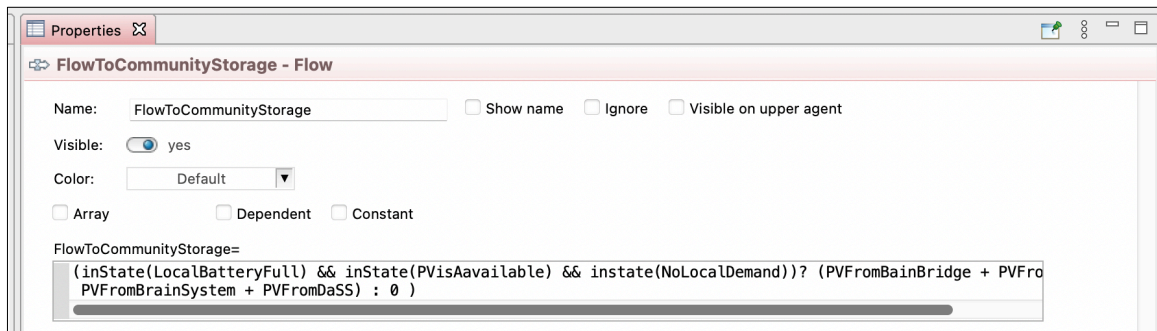


Figure 4. 20—Codes that facilitate the sharing of surplus energy from the photovoltaic source with the community storage

A model component of the community storage is shown in Figure 4.19. This model has inputs from the community (prosumer CHDTs) that are used for level 1 sharing. It also has an output back to the community, which is used for level 2 sharing. There is a third output that connects to the grid.

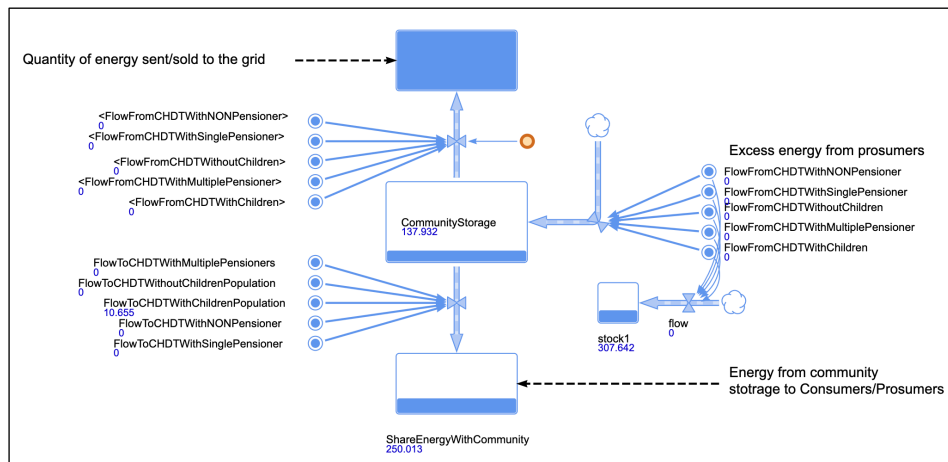


Figure 4. 21—The community storage System

Conditions for Charging Community Storage. Referring to Figure 4.21:

Condition 1B: The code “InState(CommunityStorageEmpty)?” checks if the community storage is in “battery empty” state. The “battery empty” state is determined by whether the state of charge (SoC) is less or equal to (\leq) 30% of the storage capacity.

Condition 2B: If condition 1B returns true, then the following expression: (FlowFromCHDTWithoutChildren + FlowFromCHDTWithChildren + FlowFromCHDTWithMultiplePensioner + FlowFromCHDTWithNONPensioner + FlowFromCHDTWithSinglePensioner) is activated. Where:

- FlowFromCHDTWithoutChildren = The sum of flows originating from PVs of all prosumers within the category of household without children.
- FlowFromCHDTWithChildren = The sum of flows originating from the PVs of all prosumers within the category of household with children.
- FlowFromCHDTWithMultiplePensioner = The sum of flows originating from the PVs of all prosumers within the category of household with multiple pensioners.

- d. $\text{FlowFromCHDTWithNONPensioner}$ = The sum of flows originating from the PVs of all prosumers within the category of household with non-pensioner
- e. $\text{FlowFromCHDTWithSinglePensioner}$ = The sum of flows originating from the PVs of all prosumers within the category of household with single pensioner.

Condition 3B: If condition 1B returns false, then the expression ($\text{FlowFromCHDTWithoutChildren} + \text{FlowFromCHDTWithChildren} + \text{FlowFromCHDTWithMultiplePensioner} + \text{FlowFromCHDTWithNONPensioner} + \text{FlowFromCHDTWithSinglePensioner}$) is equal to zero, which means no flow occurs.

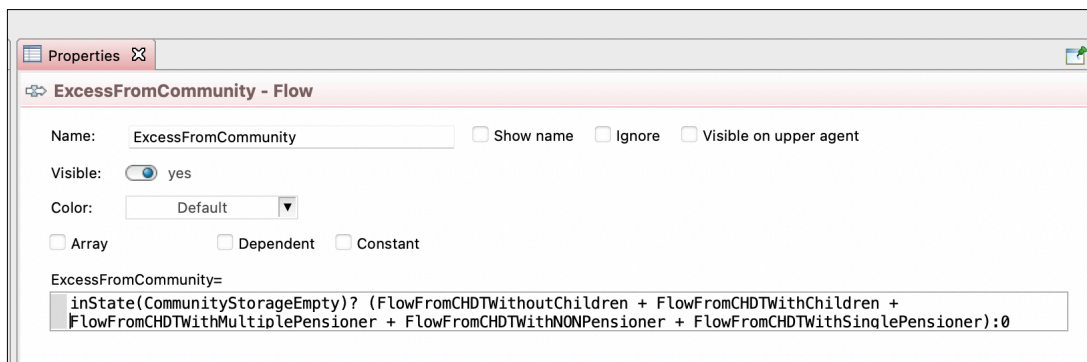


Figure 4. 22—Codes for sharing excess energy from the community (Charging the community storage)

Conditions for Discharging the Community Storage. Referring to Figure 4.21:

- a. Condition 1C: The code “ $\text{InState(CommunityStorageFull)?}$ ” checks if the community storage is in the “Community battery full” state. The battery full state is given by: If state of charge (SoC) is greater or equal to (\geq) 90% of the storage capacity.
- b. Condition 2C: If conditions 1C returns true, then the expression: ($\text{FlowToCHDTWithoutChildrenPopulation} + \text{FlowToCHDTWithChildrenPopulation} + \text{FlowToCHDTWithMultiplePensionersPopulation} + \text{FlowToCHDTWithNONPensionerPopulation} + \text{FlowToCHDTWithSinglePensionerPopulation}$) is executed. Where:
 - i. “ $\text{FlowToCHDTWithoutChildrenPopulation}$ ” = The sum of flow, equivalent to the total demand for energy originating from the category of household without children population
 - ii. “ $\text{FlowToCHDTWithChildrenPopulation}$ ” = The sum of flow, equivalent to the total demand for energy originating from the category of household with children population
 - iii. “ $\text{FlowToCHDTWithMultiplePensionersPopulation}$ ” = The sum of flow, equivalent to the total demand for energy originating from the category of household with multiple pensioners.
 - iv. “ $\text{FlowToCHDTWithNONPensionerPopulation}$ ” = The sum of flow, equivalent to the total demand for energy originating from the category of household with non-pensioner population

- v. $\text{FlowToCHDTWithSinglePensionerPopulation}$ = The sum of flow, equivalent to the total demand for energy originating from the category of household with single pensioner.
- c. Condition 3C: If conditions 1C returns false, then the expression $(\text{FlowToCHDTWithoutChildrenPopulation} + \text{FlowToCHDTWithChildrenPopulation} + \text{FlowToCHDTWithMultiplePensionersPopulation} + \text{FlowToCHDTWithNONPensionerPopulation} + \text{FlowToCHDTWithSinglePensionerPopulation})$ is equal to zero, which means no flow occurs.

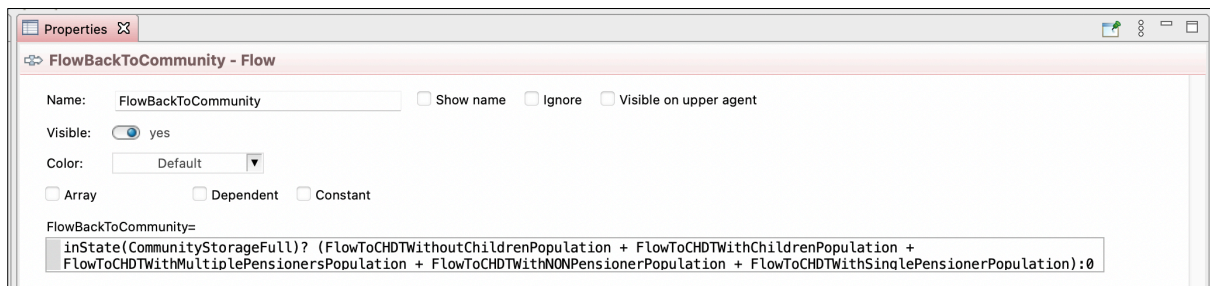


Figure 4. 23—Codes for sharing energy from community storage with the community (Discharging community storage)

4.5 Limitation of the Simulation Model

Despite the promising results as discussed in Chapter 5, the developed simulation model has some limitations that need to be addressed in future works:

1. **Limited goal conditions:** In this simulation model, we limited the number of goal conditions to three. However, in a typical or real-life situation, there may be several conditions that need to be taken into consideration before a goal can be formulated. For instance, the formulation of a goal that facilitates the selling of energy to the grid may require several factors or conditions that border around power quality (frequency and voltage), tariffs, and contractual conditions between the grid operators, energy market, and community.
2. **Condition for VO formation:** In the current implementation, we adopted the technique of threshold as the only condition needed for the formation of a VO. However, in a real-life scenario, the sheer number of accepted invitations may not be sufficient grounds to form a VO. Other technical details may have to be considered. For instance, in the case of exporting energy to the grid, as much as the number of accepted invitations may be useful, the contribution from each member may be equally vital. For example, the total contribution expected from all those who accepted invitations must match the expected projections of the community manager. Therefore, besides the numbers, other technical details could be useful.
3. **Limited value system:** Again, in the current implementation, it is considered that each CHDT in the model has two value systems, namely VSG1 for value system 1 and VSG2

for value system 2. However, in a practical sense, the number of value systems could be higher.

4. *Overrides*: The prototype assumes that, after acceptance, CHDTs would stick to their decisions. However, it is possible that, after acceptance, some users may change their minds and want to override the system and reverse their initial decisions. In this simulation model, such provisions were not taken into consideration, therefore CHDTs are unable to override their initial decisions.

VALIDATION

One of the major challenges confronting this research work is the lack of information within the various disciplines that could have been used to validate the proposed concepts. The reason could partially be attributed to the novelty of the concepts and also the interdisciplinary nature of the work, which make it a challenging feat to adopt a single validation approach. Furthermore, to the best of the author's knowledge, there aren't any other proposals concerning the study of collaborating household digital twins in a REC environment that aim to promote sustainable collaborative behaviours relating to energy generation and consumption. For these reasons, we adopted a two-step validation process: (a) by evaluating the appropriateness of the CEE and CHDT modelling frameworks through the deployment of the prototype simulation model using different simulation scenarios; (b) validating the concepts as well as the developed prototype in terms of its fitness for purpose through Interactions with the related research communities. Validating the concepts through the research communities is carried out in two ways: (1) Face validity which involves discussing the concepts and receiving feedback from the related research community that involved (i) the sustainable energy research community, (ii) the collaborative networks community, and (iii) the digital twin and IoT-related communities. (2) Validation through publications that were peer reviewed by experts from the related research communities.

5.1 Validation Through Simulation Outcomes

A model's accuracy, dependability, and acceptability can be evaluated through its validation process. For this reason, a validation instrument is said to be reliable if it yields the results that it was designed to measure (Sidik, 2018). Validation in design science is typically defined as “a process that ensures or instils confidence that the creation of a new system, model, or artifact has accounted for all significant aspects of a specified problem for which the creation is intended to solve” (Mohajan, 2017). Validation also involves the justification of claimed knowledge (Carvalho, 2012). Design science validation is also accomplished by constructing one or more artifacts that solve a domain problem in order to generate knowledge on how the problem can be solved and demonstrate how the solution is novel or superior to previous solutions (Carstensen & Bernhard, 2019). In the next section, validation of the developed simulation artifact is discussed.

Throughout this section, the population of CHDTs remains constant, thus involving 100 CHDTs for all the considered scenario. However, the simulation time for each scenario is different. This is because some scenarios require a longer simulation period to be able to observe the expected results, while others require a shorter simulation period. Although the total population of CHDTs remain constant in all the considered scenarios, different percentage of prosumer and consumer population sizes are explored in each scenario.

5.1.1 Scenario 1: Exploring the Relationship Between Delegation, Acceptance or Decline to an Invitation, and VO Formation

In this scenario, we attempt to explore how the population of delegated CHDTs affects the tendency for an invitation to be accepted and how this can subsequently affect the probability of a VO formation. We consider three different cases, as shown in Table 5.1. in which we consider 10%, 50%, and 90% of delegated CHDT population, respectively. As mentioned, the total population of CHDTs considered in the ecosystem is 100, and the VO formation threshold is set to 25, which is 25% of the total population. The model is run for 5 (simulation) hours. This is because this scenario requires a very short time to observe the expected results.

The outcome of this scenario is shown in Table 5.2, and, subsequently, in Figure 5.1. With reference to Case 1, it is observed that when the percentage of delegated CHDTs is low (10%), the percentage of acceptance of an invitation is equally low, i.e., 6% acceptance of Goal 1, 5% acceptance of Goal 2, and 3% acceptance of Goals 1 and 2. Subsequently, the chances of a VO formation for either Goal 1 or 2 were low (no, for both Goals 1 and 2). However, in Case 3, where the population of delegated CHDTs is high (90%), the percentage of the population that is likely to accept the invitation is high, i.e., 45% acceptance of Goal 1, 54% acceptance of Goal 2, and 25% acceptance of Goals 1 and 2. Subsequently, the chances of a VO formation for either Goal 1 or 2 were high (yes, for both Goals 1 and 2). At the midpoint, as in Case 2, when the population of delegated CHDTs is about 50 percent, the percentage of CHDTs that may accept the invitation could be difficult to predict. For instance, in Goal 1, 27% acceptance, which is higher than the VO formation threshold, is observed. In this example, a VO is formed. However, for Goal 2, 21% acceptance, which is lower than the VO formation threshold, is observed. In this example, the VO is not formed. For both Goals 1 and 2, 11% acceptance was observed. In this example too, the VO is not formed. It can therefore be inferred that the chances of VO formation are dependent on two factors, namely: (a) the minimum VO formation threshold, and (b) the number of population/members that are delegated in the ecosystem. Regarding the minimum VO threshold, this is a subjective value that is dependent on the expectations of the modeler. For each value chosen, either high or low, the model will behave differently. If a low value is used, the chances of VO formation will be high. Conversely, if a high value is chosen, the chances of a VO formation will be low. In the case of the number of populations that are delegated, it can be inferred that the higher the number of delegated CHDTs, the higher the chances of a VO formation.

Table 5.1 —Scenario for exploring the relationship between delegation, acceptance of an invitation, and VO formation

Case	Percentage of Delegated CHDTs	Population of CHDTs	The minimum threshold for VO Formation
Case 1	10	100	25 % of the population
Case 2	50	100	25 % of the population
Case 3	90	100	25 % of the population

Table 5.2 —Results of Scenario 1, acceptance to initiation for Goals 1 and 2, and VO formation

Case	Percentage of the population that accepted the invitation to Goal 1	Percentage of the population that accepted the invitation to Goal 2	Percentage of the population that accepted the invitation to Goals 1 & 2	Is VO for Goal 1 Formed?	Is VO for Goal 2 Formed?
Case 1	6	5	3	No	No
Case 2	27	21	11	Yes	No
Case 3	45	54	25	Yes	Yes

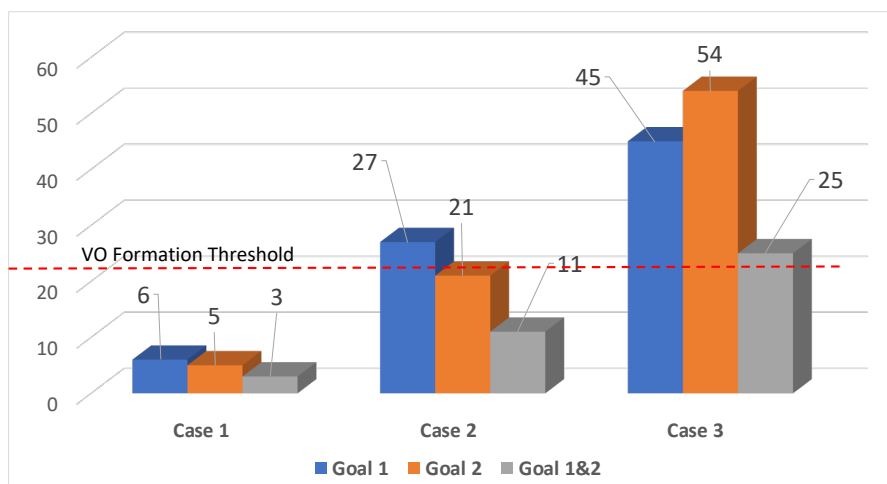


Figure 5.1—Relationship Between Delegation, Acceptance/Decline to an Invitation, and VO Formation.

Furthermore, in Table 5.3, the outcome of the model, showing the percentage of CHDTs that declined Goals 1 and 2 for all three cases, is presented. The results show that having a high percentage of delegated CHDTs may result in fewer declines based on non-delegation. Similarly, a low percentage of the delegated CHDT population also results in a high percentage of declines to invitations based on non-delegation. In terms of community goal versus value system compatibility, it is observed that a low population of delegated CHDTs results in few compatibilities, while a high population of delegated CHDTs results in many compatibilities. This is because the acceptance of an invitation is based on the condition that a CHDT’s value system is compatible with a particular community goal.

Table 5.3 —Results of scenario 1, decline of invitation to Goals 1 and 2

Case	Percentage of the population that declined the invitation to Goal 1		Percentage of the population that declined the invitation to Goal 2	
	Due to un-delegation	Due to non-compatible goals	Due to un-delegation	Due to non-compatible goals
Case 1	85	9	85	10
Case 2	46	27	46	33
Case 3	10	45	10	36

From the simulation outcome of this scenario, the following partial conclusions can be drawn based on the observed behaviour of the CHDTs:

1. That CHDT have the capabilities to receive, accept or decline invitation from the CEE manager.
2. CHDT can make autonomous decisions regarding invitation that it receives. The outcome of their decisions may result in the acceptance or decline of the invitation. These decisions are often based on their level of “delegation” and “value system” compatibility.

5.1.2 Scenario 2: Exploring the Notions of Value System and Delegated Autonomy

This section discusses the outcome of the simulation from a global or community viewpoint. The simulation is executed for 72 simulation hours, which corresponds to three simulation days. This simulation period is the minimum time frame within which the expected result can be seen. In this scenario, we consider the pursuit of Goal 1, which is an opportunity to sell energy to the grid. This scenario is used to demonstrate how collaborative/collective decisions made at the collaborative layer affect the energy infrastructure at the physical layer. For CHDTs to successfully make such collective decisions, each one of them must have cognizance of the following conditions: (a) their assigned value system, (b) their acceptance or decline to participate in a coalition (VO), (c) the VO schedule (waiting time), (d) the duration of the execution of the goal, which is technically the VO lifecycle (window of opportunity), and (e) the degree of delegation (delegated autonomy). Using the cases described in Table 5.4, the following global behaviours are observed at the physical layer, after the collective decisions have been taken at the collaborative/cyber layer. DDL as shown in the table means “delegation of deferrable loads.” It is used to represent the number appliances whose use can be deferred at a time.

Table 5.4 —Scenarios for testing delegated autonomy, degree of delegation, and VO size

Scenarios		Value Systems		VO population (%)	Percentage of delegated CHDTs
		Degree of delegation	Number of delegated appliances (DDL)		
1	Case 1	Full	3	100	100
2	Case 2	Full	3	10	10
3	Case 3	Full	3	90	90
4	Case 4	Partial	2	90	90
5	Case 5	Partial	1	90	90

The outcome, as shown in Figure 5.2, represents Case 1. In this case, a VO constituting all the population of CHDTs (100%) is formed. In terms of the degree of delegation, it is assumed that all the CHDTs were delegated with “full delegation” autonomy, which means they had permission to delegate all three DDL appliances. The results for Case 1, as shown in Figure 5.2, suggest that all the CHDTs took collective action at the same time by implementing their delegated autonomy, which involved the deferral of the use of all three embedded appliances when the VO schedule (waiting time) was due. The outcome of this collective action resulted in net zero consumption within the “window of opportunity.” The deferral lasted in accordance with the duration of the “window of opportunity,” and consumption was restored immediately after the period of deferral was over, thus, consumption was restored immediately after the selling period had elapsed. This confirms that the behaviours of the CHDTs, namely: (a) being cognizant of the VO/goal schedule and (b) being cognizant of their own value systems and executing the corresponding instruction in accordance with the VO/goal schedule, are consistent with the design expectations. It can further be observed that, during the selling period, all the requests for an appliance to be used that were received were put in a queue and were allowed to resume consumption on the basis of first-in-first-out to avoid the situation of high demand for energy, caused by having several appliances demanding energy at the same time, immediately after the window of opportunity.

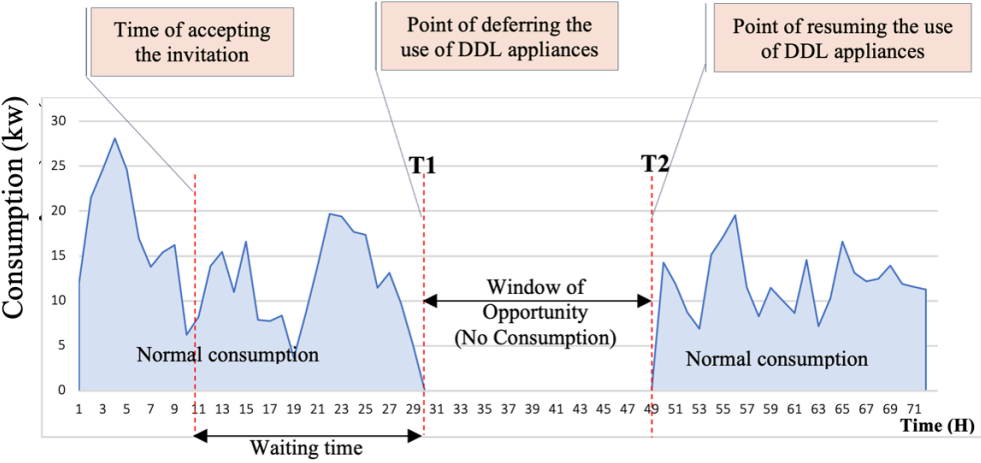


Figure 5.2—Case 1: A VO formed with 100% of CHDTs in the population with 100% full delegated autonomy.

In Figure 5.3, we consider Case 2, which represents the case of VO formation with a low population of delegated CHDTs, thus 10%. For this population, it is assumed that the degree of delegation is “full delegation” for the 10% delegated CHDTs. It can be observed from the window of opportunity in Figure 5.3 that energy consumption is relatively the same. The reduction in energy consumption that is observed is relatively insignificant (nearly unchanged). This is because the number of CHDTs that formed the VO and subsequently deferred the use of their appliances is small (only 10% of the population). The consumption that is observed within the window of opportunity is a result of the 90% of CHDTs that did not join the VO and therefore did not delegate their appliances.

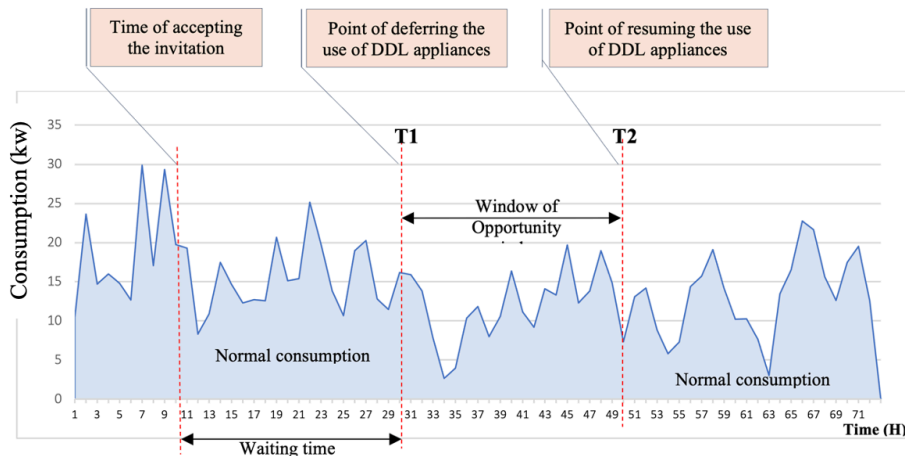


Figure 5.3—Case 2: A VO formed with 10% of CHDTs in the population, with 10% full delegated autonomy.

Furthermore, in Figure 5.4, we considered Case 3, which constitutes a high VO population of 90%. In this case, the model considers that a high population of CHDTs has their degree of delegation as “full delegation,” thus 90% of the population. In this scenario, it is observed that consumption was significantly reduced within the window of opportunity. This was because the majority of the CHDTs (90%) participated in the VO and were collectively involved in the deferral of all three DDL appliances during the window of opportunity. The relatively small consumption that was recorded is attributed to the 10% that did not join the VO.

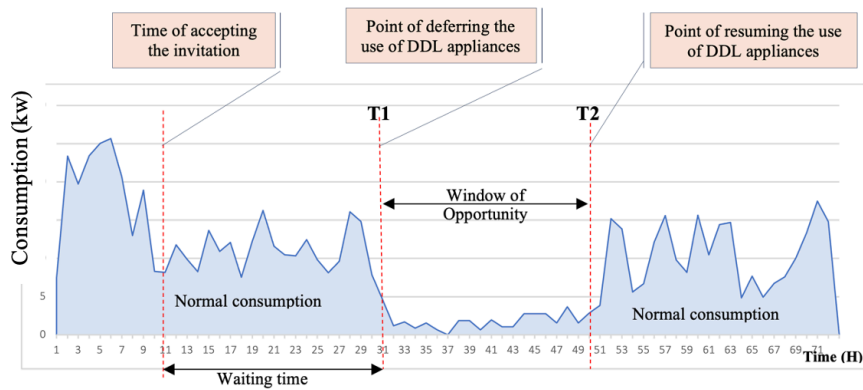


Figure 5.4 —Case 3: A VO formed with 90% of the population, with 90% full delegated autonomy.

The outcomes for Cases 4 and 5 are captured in Figures 5.5 and 5.6. In these two cases, the VO population is kept the same (90%). The only difference is that in Case 4, the degree of delegation is “partial delegation” with two DDL appliances, while in Case 5, the degree of delegation is also “partial delegation” with only one DDL appliance. The results revealed that partial delegation with two DDL appliances (Case 4, Figure 5.5) yielded more energy savings as compared to “partial delegation” with a single appliance (Case 5, Figure 5).

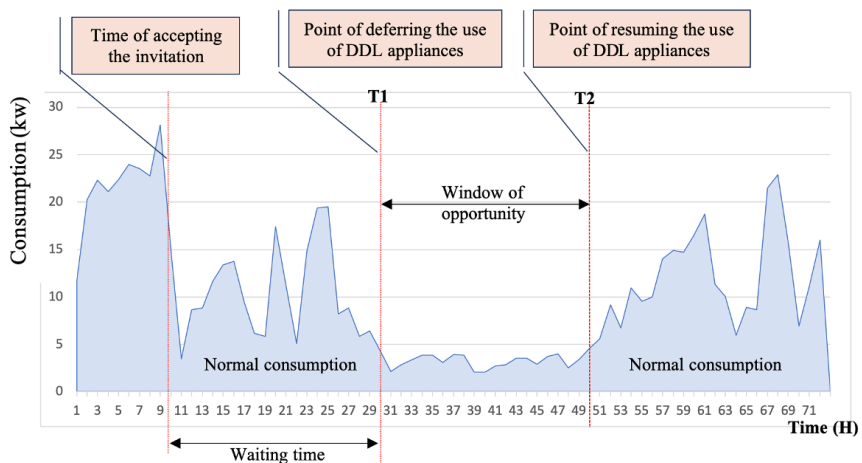


Figure 5.5—Case 4: High population of delegated CHDTs (90%), Low population of undelegated CHDTs (10%), partial delegation, double appliances

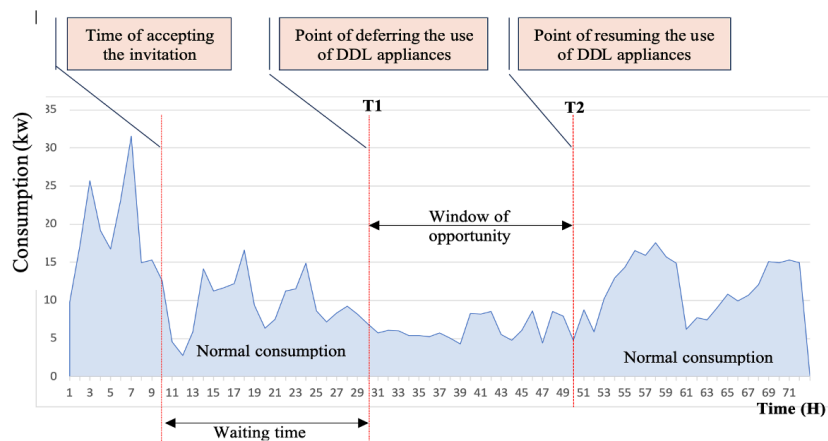


Figure 5.6—Case 5: High population of delegated CHDTs (90%) Low population of undelegated CHDTs (10%), Partial delegation, single appliance

The partial conclusion that can be drawn from this simulation scenario suggests that the outcome of the model is consistent with the expected results in the following ways:

1. That having a high population of delegated CHDTs, who have been given full delegated autonomy, can result in a significant amount of energy savings, which can facilitate the chances of selling energy to the grid. On the contrary, having a high population of undelegated CHDTs will adversely affect consumption, and this could minimize any chances of selling energy to the grid.
2. Having a high population with a full degree of delegation can result in higher energy savings than the same population with a partial degree of delegation.
3. Furthermore, partial delegation with two DDL appliances can result in higher energy savings than the same population with a single DDL appliance.

5.1.3 Scenario 3: How Value Systems Affect Sustainable Energy Consumption in the Ecosystem

This section also discusses the outcome of the simulation from a global or community viewpoint. The simulation is executed for 168 simulation hours, which corresponds to seven simulation days. This simulation period is chosen because it provides adequate time-window within which the expected result can be realized. This section's results are focused on using value systems to ensure sustainable energy consumption in the ecosystem. In this scenario, the community has sustainable energy consumption as its priority. To ensure every member consumes energy sustainably, the various energy sources in the community are arranged in order of priority. Table 5.5 shows the energy sources that are considered high priority and the ones that are considered low priority. The high-priority sources are arranged in a hierarchical order from the highest to the lowest. As mentioned earlier, the sources of energy available in the community include (a) directly from solar PVs, (b) from local battery storage, (c) from the community storage system, and (d) from the power grid.

In this scenario, the value system or delegated autonomy of the CHDTs enables them to focus on consuming energy based on the priority list; thus, they seek to consume energy from the highest priority energy source first. If this source is unavailable, they check the next in the order until the lowest. If only the grid (low priority source) is available, the CHDTs will defer the operation or function of their DDL appliances until a high priority becomes available. We distinguish the autonomy of consumers from that of prosumers. The autonomy of prosumers is assigned in such a way that they consume energy according to this order of priority: (a) direct consumption from local PV; (b) consumption from local storage; (c) consumption from the community storage system; and lastly, (d) consumption from the grid. The delegated autonomy of consumers enables them to consume energy based on the following order of priority: (a) the community storage system, which has the highest priority, and (b) the grid, which has the lowest priority.

Table 5.5 —Energy consumption priority list for prosumers and consumers

Priority from highest to lowest	Prosumers	Consumers
High priority sources		
1st	Solar PV source	Community storage
2nd	Local Storage	-
3rd	Community storage	-
Low priority source		
4th	The grid	The grid

In Table 5.6, we describe two cases under this scenario. The first case is composed of a consumer population of 10% (low) and a prosumer population of 90% (high). For this case, we analyse the community dynamics considering (a) 10%, 90%, 100%, and 0% of the population being assigned full delegated autonomy. In the second case, we consider a prosumer population of 90% (high) and a consumer population of 10% (low). In this case, we analyse the community dynamics considering that 90% (high) and 10% (low) of the population also have the autonomy to implement full delegation.

Table 5.6 —Delegation of deferrable loads

Cases	CHDT Population (%)		Percentage of the Population with delegated autonomy instruction out of the total	Type of Autonomy
	Prosumer	Consumer		
Case 1	10	90	a. 10 percent of the population	Full
			b. 90 percent of the population	Full
			c. 100 percent of the population	Full
			d. 0 percent of the population	
Case 2	90	10	a. 90 percent of the population	Full
			b. 10 percent of the population	Full

After running the model over the stated period (168 hours) with a CHDT population of 100, the results are presented in the subsequent paragraphs. The result from Case 1a is shown in Figure 5.7, and Case 1b is shown in Figure 5.8. In the Case 1a, we considered a population that is comprised of 10% prosumers and 90% consumers, while considering that 10% of the entire population has delegated autonomy. In Case 1b, we considered the same population as in Case 1a, except that the population with delegated autonomy was this time 90%.

When the outcomes for both cases (Cases 1a and 1b, Figures 5.7 and 5.8) are compared, it is clear that in Case 1a, when 10% of the population was delegated, the use of the grid was about 43%. When the population of delegated CHDT was increased to 90%, as in 1b, the use of the grid dropped to 20%. Considering the same cases, the community storage usage increased substantially, from 20% in Case 1a, when 10% of the population was delegated, to 49% in Case 1b, when 90% of the population was delegated. Case 1a has an average of 12% PV usage and 25% local storage usage, whereas Case 1b has an average of 15% PV usage and 17% local storage usage. The high grid utilization in Case 1a is caused by the 90 percent of undelegated CHDTs, whereas in Case 1b, the low grid utilization is caused by the 10% of undelegated CHDTs. Similarly, the increased consumption from community storage and PV in Case 1b as compared to Case 1a is a result of the 90% delegated CHDTs. 90% delegated CHDT means that 90 % of the population seeks to consume energy from high-priority sources only. This is therefore a clear case of sustainable consumption, as the usage of the grid dropped, while the usage of community storage and PV increased.

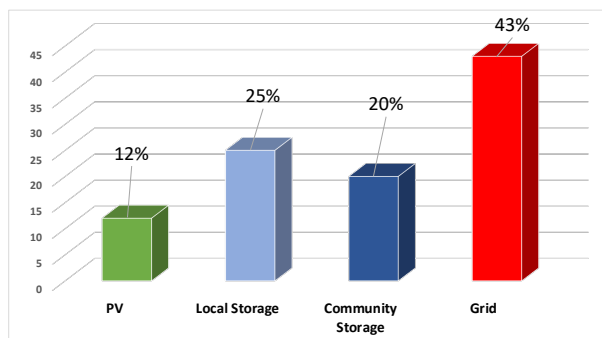


Figure 5.7—Case 1a: results for 10% prosumers, 90% consumers. 10% of the total population having full delegated autonomy.

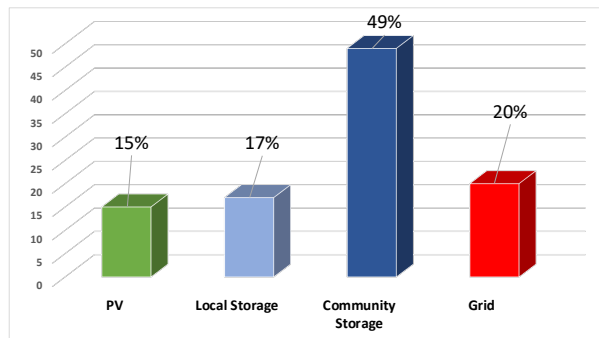


Figure 5.8—Case 1b: results for 10% prosumers, 90% consumers, with 90% of the total population having the full delegated autonomy.

In Case 1c (Figure 5.9), the population is the same as in cases 1a and 1b. The difference here is that 100% of the population is granted full delegated autonomy, and the results indicate that consumption from the grid dropped to zero. 100% full delegated autonomy means that the priority of all the CHDT in the population is to consume energy only from high-priority sources only. This resulted in 0% consumption from the grid. Additionally, consumption from the community storage system increases up to 58%, while consumption from PV and local storage also increases up to 18% and 24%, respectively.

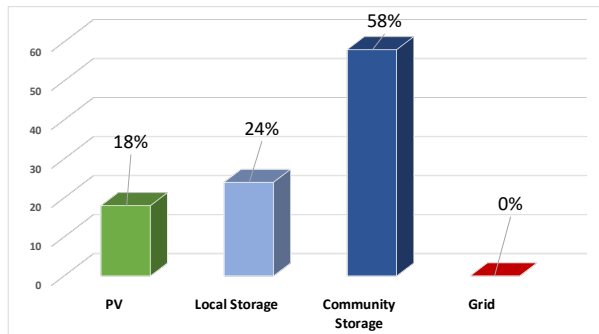


Figure 5.9 —Case 1c: results for 10% prosumers and 90% consumers, with 100% of the total population having DDL autonomy.

Lastly, Figure 5.10 depicts the model's output for Case-1d. In this situation, none of the CHDTs (0 percent) had delegated autonomy. In this situation, the usage of the grid climbed to 87%, while the usage of other energy sources decreased significantly. This is due to the large population of consumers (90%) who were without delegated autonomy.

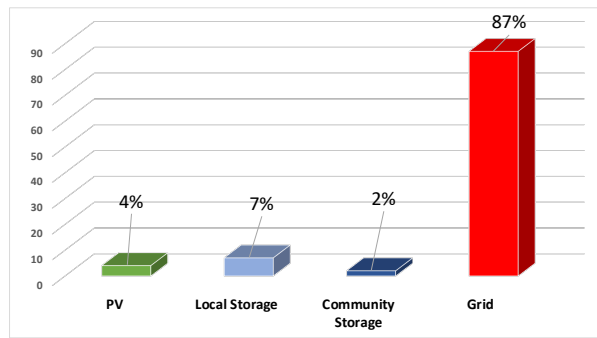


Figure 5.10 —Case 1d: results for 10% prosumers and 90% consumers with no DDL authority

Referring to Case-2 (Table 5.6), the number of CHDTs remained constant at 100. The composition of the population is 10% consumers and 90% prosumers. In Case 2a (Figure 5.11), we examined a scenario in which 90 percent of the population were fully delegated. Similar considerations are made for Case 2b (Figure 5.12). In this case, however, the entire population with DDL authorization has decreased to 10%. In contrast to Cases 1 (a, b, and c), where only 10 percent of the total population were prosumers, Cases 2a and 2b reveal much higher PV and local storage utilization. Moreover, with DDL implemented for both Case 2a and Case 2b, it is evident that grid consumption is relatively minimal compared to Case 1 (a, b, and c). This is due to the low percentage of the consumer population and the high percentage of prosumers. Comparing Case 2a (Figure 5.11) to Case 2b (Figure 5.12), it can be seen that 90 percent DDL reduces grid usage from 9% to 3%, whereas community storage consumption increases from 2% to 10%.

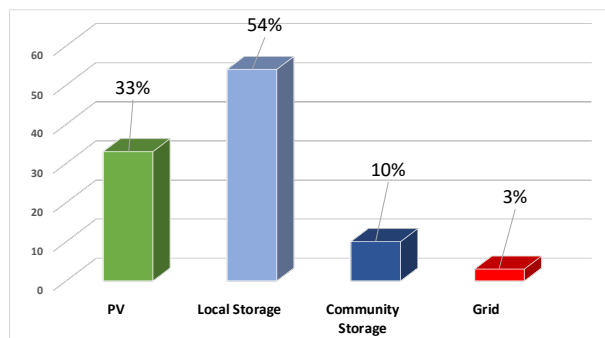


Figure 5.11—Case 2a: results for a population of 10% Consumers, 90% prosumers, and 90% of the population with delegated autonomy

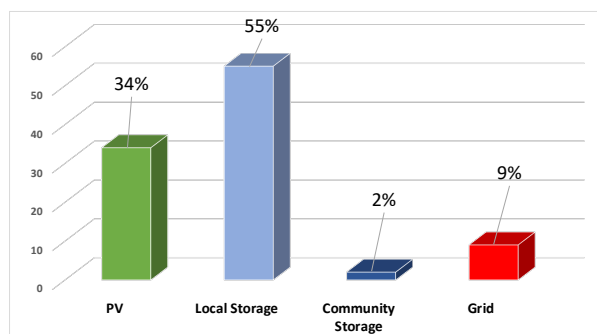


Figure 5.12—Case 2b: results for a population of 10% Consumers, 90% prosumers, 10% of the population with delegated autonomy

The partial conclusion that can be drawn from this simulation scenario suggests that the outcome of the model is consistent with the expected results in the following ways:

1. The idea of delegating CHDTs is conceptually plausible.
2. The CHDTs can execute instructions relating to their value system.
3. A high population of delegated CHDT in an ecosystem can result in a substantial reduction in energy consumption from the grid.
4. A population of CHDTs with full delegation can yield substantial energy savings from the grid than the same population with partial delegation.

5.1.4 Scenario 4: Exploring Mutual Influence and Collective Decision Making of CHDTs

This section shows the simulation outcome of the scenario concerning mutual influence. This outcome reflects a simulation lasting 728 hours (30 days). This simulation period is chosen because it provides adequate time-window within which the expected result can be realized.

Although this section is focused on the spread of influence in a social system or network, this technique is actually being deployed to help mimic and study how incentivization could work in such an ecosystem. In this particular instance, the power of information diffusion in a social system is utilized to positively influence CHDTs' decision-making. Such techniques are not new. They have been used, for instance, in the response to natural or man-made disasters (Chen et al., 2013) and also in the Hotmail phenomenon in the early 1990s (Hugo & Garnsey, 2002). The effect, which is often referred to as the "viral phenomenon" or "viral marketing," has been adopted by companies to encourage influence propagation among individuals with social connections, because it is known that social influence can affect the beliefs, perceptions, attitudes, or behaviour of consumers about a product or service (Wood & Hayes, 2012). Influence propagation in a social system can also be used to alter the decisions of consumers and can help increase traffic to the websites of businesses, resulting in higher engagement and revenue (Nafees et al., 2021).

In the cases considered, we assume that some percentage of the CHDT population has the capability to propagate positive influence, while others also have the capability to propagate negative influence. A positive influence influences a CHDT positively, while a negative influence influences it negatively. Incentives, for instance, can be a good example of a positive influence, while penalties can be a good example of a negative influence. The propagators of influence are called "influencers," while the recipients are called "influencees." In the simulation, we utilize influence propagation to propagate incentives, which could be monetary or social recognition in the ecosystem. The emphasis on mutual influence is predominantly focused on high-level decision-making at the collaborative layer by the CHDTs and not necessarily the human users.

5.1.4.1 Scenarios 4A: Modelling Collective Decision-making by CHDTs

As shown in Table 5.7, two different Cases, constituting different populations of influencers, “influencees,” positive influencers, and negative influencers, are considered. In all cases, the influencer CHDTs propagate influence in the form of messages to the “influencee” CHDTs to influence them to make pro-sustainable energy consumption decisions. When an influencee CHDT receives sufficient influence, usually positive influence, it makes a pro-sustainable decision and subsequently transitions into a pro-sustainable state. In this new state, the CHDT changes its energy consumption behaviour by beginning to delegate its DDL appliances to consume energy from sustainable sources only. The claimed sustainable energy sources are (a) solar PV, (b) local storage, and finally, (c) community storage for prosumers and, for consumers, the community storage only. The decision to transition into a pro-sustainable state is triggered based on the value of the decision threshold, if it reaches 50 or above.

Table 5.7—Two cases with varying population sizes are used to test collective decision-making

		Influencer population (%)	Influencee population (%)	Positive Influencer Population (%)	Negative Influencer Population (%)	Prosumer Population (%)	Consumer Population (%)
Case 1	a	90	10	90	10	20	80
	b	90	10	10	90	20	80
Case 2	a	10	90	90	10	80	20
	b	10	90	10	90	80	20

After the simulated period of 728 hours (30 days), the following sample behaviours were extracted from some selected CHDTs. In Figures 5.13 and 5.14, we show the characteristics of the modelled influence that was received by two different CHDTs, i.e., CHDT-1 and CHDT-2. The pulses that appear below the X-axis represent all the negative influences that were received by this CHDT during the 30-day period. The pulses that appear above the X-axis are positive influences that are received by the same CHDT over the same period. Figures 5.13 and 5.14 show the intensity, polarity, magnitude, and frequency of propagation of the influences that these CHDTs received over the 30-day period. It can be observed that the effects of these influences on each CHDT are completely different from each other

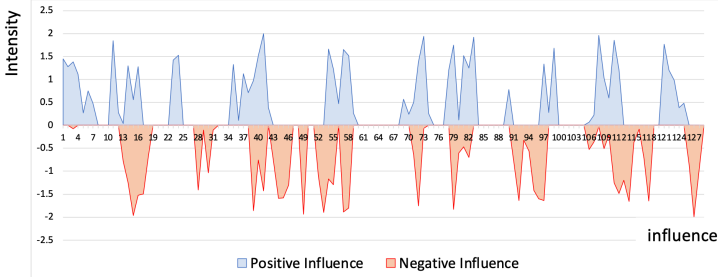


Figure 5.13—Influences received by CHDT 1.

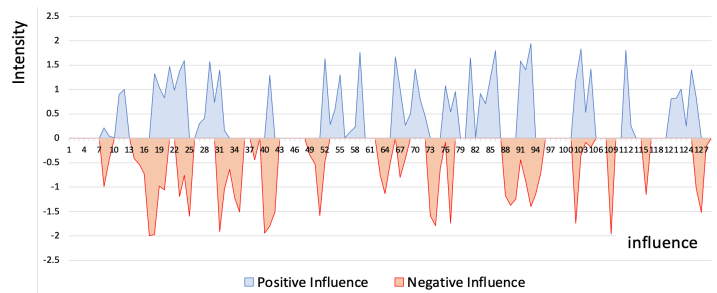


Figure 5.14 —Influences received by CHDT 2

In Figures 5.15 to 5.18, we show how the aggregation of influences over time can be used to determine the overall behaviour of a CHDT. We also illustrate how overall behaviour can be used in decision-making. For instance, Figures 5.15, 5.16, and 5.17, show CHDT numbers 3, 4, and 5 that initially behaved negatively right from the start of the model. This is because these influencee CHDTs initially received negative influence from the negative influencers in the ecosystem. However, the duration of their negative behaviours varied. For CHDT number 4, it lasted longer than for CHDTs 3 and 5. Eventually, all three CHDTs changed their behaviour from negative to positive, although at different times. This was because CHDT 3 was highly influenced positively in comparison to CHDT numbers 4 and 5. For this reason, CHDT 3 exceeded the decision threshold " ∞ " and therefore was able to decide within the simulated period (30 days), but CHDT 4 and CHDT 5 were unable. Finally, in Figure 5.18, CHDT 6 behaved positively right from the beginning of the model execution. Thus, CHDT was influenced positively right from the onset. For this reason, CHDT number 6 was able to make a decision much earlier than CHDT 3.

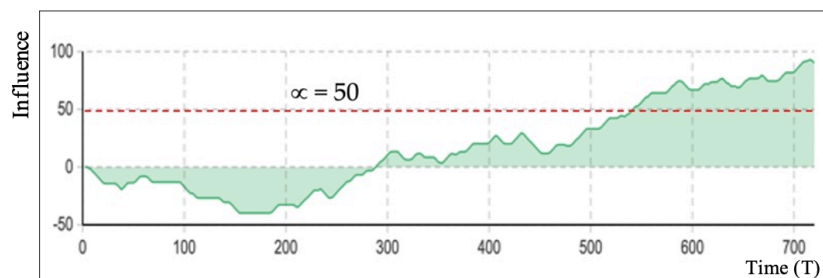


Figure 5.15—Behaviour of CHDT number 3. Initially influenced negatively, but the influence changed to become positive influence and the CHDT was able to make a decision.

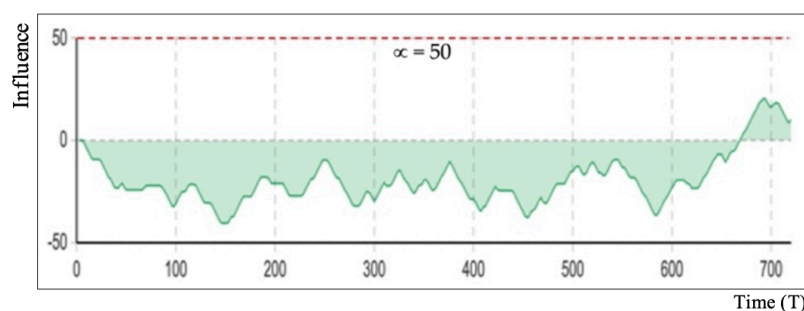


Figure 5.16—Behaviour of CHDT number 4. Initially influenced negatively, but the influence changed to become positive influence, however, the CHDT was unable to make a decision.

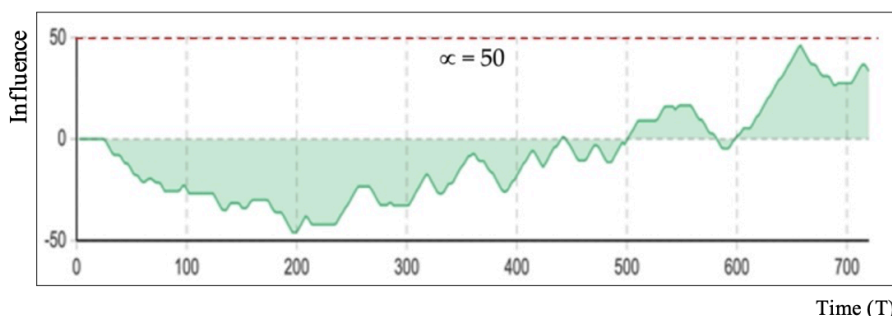


Figure 5.17— Behaviour of CHDT number 5. Initially influenced negatively, but the influence changed to become positive influence, however, the CHDT was unable to make a decision.



Figure 5.18—Behaviour of CHDT number 6. This CHDT was initially influenced positively, and maintained the positive influence until it was able to make a decision.

From the simulation outcome of this scenario, the following partial conclusions can be drawn based on the observed behaviour of the CHDTs:

1. It is possible for CHDTs to mutually influence each other.
2. The compounding effect of influences on a CHDT, over time, determines the overall behaviour of that CHDT.
3. CHDTs can make autonomous decisions (either negatively or positively) based on the level of influence they receive over time.
4. The notion of influence has good prospects for being adopted as a mechanism to propagate incentives in such energy ecosystems.

5.1.4.2 Scenario 4B: Using “mutual influence” to influence the decisions of CHDTs towards sustainable energy consumption.

Referring to Table 5.7, we hereby consider Cases 1a and 1b. The outcomes of the model for these cases are shown in Figures 5.19 and 5.20. In these cases, the population of prosumers, consumers, influencers, and “influencees” is the same. Additionally, the prosumer and consumer populations in these cases are, respectively, 20% and 80%. The only difference between the two cases is that the number of positive and negative influencers is different in each case. In Case 1b, 10% of the influencer population were positive influencers and 90% were

negative influencers. For this reason, the majority of the CHDT population was negatively influenced due to the high percentage of negative influencers (90%). This resulted in few pro-sustainable decisions being made, causing a high proportion of energy to be consumed from the grid (about 69%). Furthermore, it is observed that consumption from community storage was also low (about 13%). By comparing Case 1b to Case 1a, where the percentage of positive influencer population was high (about 90%) and the percentage of negative influencer population was low (about 10%), it can be seen that the majority of the CHDT population were influenced positively, resulting in more pro-sustainable decision-making, hence a reduction in the consumption from the grid to about 51% and an increase in the consumption from the community storage to 24%.

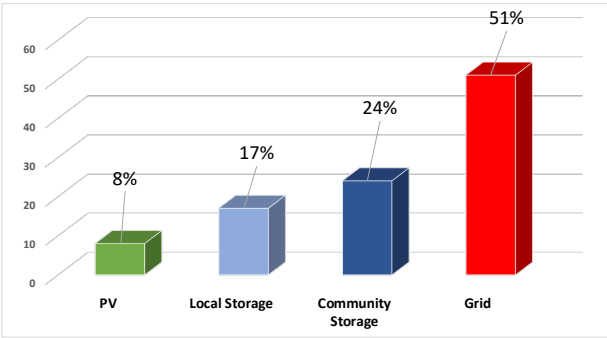


Figure 5.19 —Case-1a. 90% positive influencers and 10% negative influencers.

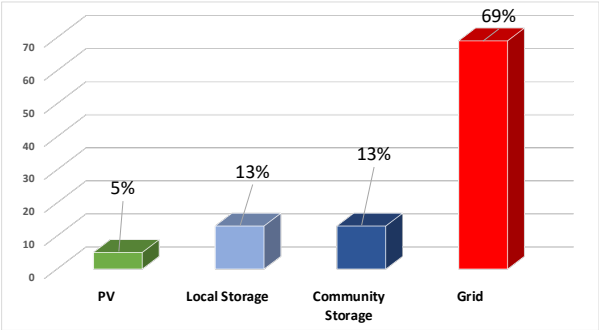


Figure 5.20 —Case-1b. 10% positive influencers and 90% negative influencers.

Still referring to Table 5.7, we hereby consider Cases 2a and 2b. In Case 2a, we consider 90% of the influencer population to be positive influencers and 10% to be negative influencers. However, the prosumer and consumer populations in this case are 20% and 80%, respectively. On the contrary, in Case 2b, we consider 10% of the influencer population to be positive influencers and 90% to be negative influencers. As mentioned earlier, the prosumer population is 80%, and the consumer population is 20%. The outcomes of these two cases can be seen in Figures 5.21 and 5.22. For Case 2a, where the population of positive influencers is high (90%), although there are fewer prosumers (20%) and more consumers (80%), the use of the grid is relatively low, about 53%, as compared to Case 2b (Figure 5.22) where the use of the grid is relatively high, about 60%, due to the rather low population of positive influencers (10%) and the high population of negative influencers (90%), even though there were more prosumers

(80%) and few consumers (20%). The use of PV and local storage was also significantly appreciated in Case 2a as compared to Case 2b. The difference in both cases resulted from the population difference between negative and positive influencers.

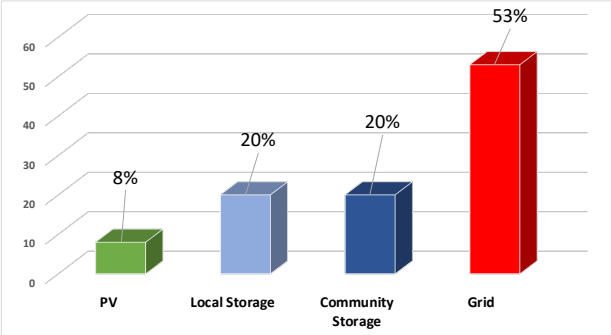


Figure 5.21—Case-2a. A high population of positive influencers (90%) despite a high consumer population (80%).

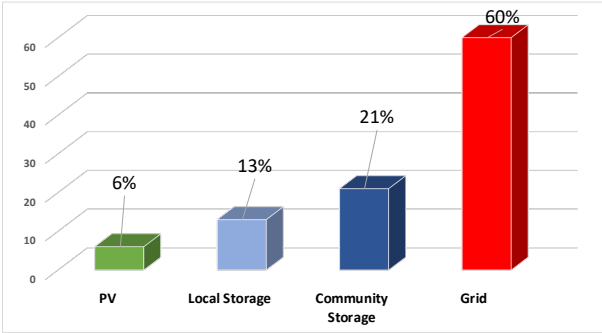


Figure 5.22—Case-2b. A high population of negative influencers (90%) despite a high prosumer population (80%).

The partial conclusion that can be drawn from this simulation scenario suggests that the outcome of the model is consistent with the expected results in the following ways:

1. Depending on the role of a CHDT (either as an influencer of influencee), a CHDT can either influence or can be influenced. In other words, a CHDT can propagate influence and can also be a recipient of influence.
2. The aggregation of influence over time can be used to determine the overall behaviour of a CHDT. This behaviour could be positive or negative. A positive behaviour could represent a pro-sustainable behaviour while a negative behaviour could represent a non-sustainable behaviour.

5.1.5 Scenario 5: Exploring Resources Sharing

This section of the work shows, how resource sharing occurs in the ecosystem. Resource sharing is demonstrated in two ways: implementation of “enable” and “disable” resource sharing delegated autonomy and demonstrating level and level 2 resource sharing.

5.1.5.1 Scenario 5A: Enabling and Disabling Resource Sharing

The **sharing economy**, or community-based resource sharing, offers an alternative to the hyper-individualized consumption that has taken hold in many affluent countries and the world in general. The idea behind the sharing economy is to use the capacity of goods and services that are currently available to reduce personal consumption and waste. Resource sharing is one of the key attributes of collaborations and is intended to maximize the use of resources in an ecosystem.

Resource sharing is possible in the CEE because, CHDTs can also engage in resource sharing. This section discusses the outcome of the simulation from a global or community viewpoint. The simulation is executed for 168 simulation hours, which is equivalent to 7 simulation days. Again, this simulation period is chosen because it provides adequate time-window within which the expected result can be realized.

Three cases are considered under this scenario. These cases are shown in Table 5.8. The cases consider different population sizes of prosumers and consumers. In each case sharing enabled and sharing disabled is analysed. The total population of CHDTs in this scenario is 100 CHDTs.

Table 5.8 —Different ratios of prosumer and consumer population with corresponding delegated autonomy

Cases	CHDT Population (%)		Kind of Delegated autonomy implemented	
	Prosumer	Consumer		
Case-1	90	10	a	Sharing disabled
			b	Sharing enabled
Case-2	50	50	a	Sharing disabled
			b	Sharing enabled
Case-3	10	90	a	Sharing disabled
			b	Sharing enabled

In Case 1, a CHDT population comprising 90% prosumers and 10% consumers is selected. Two separate situations of "delegated autonomy" are examined. These are (a) sharing disabled, and (b) sharing enabled.

In Case 1a where "sharing is disabled," the CHDTs are delegated not to share surplus energy with the community storage. On the contrary, the case with "sharing enabled" (Case 1b) is the reverse of "sharing disabled." For sharing enabled, the CHDTs are delegated to share surplus energy with the community storage. The outcome of Cases 1a and 1b is shown in Figures 5.23 and 5.24, the findings of the study indicate that, in the absence of energy sharing, 25% of the community's total energy consumption originates from the grid and 0% from the community storage system. On the other hand, Figure 5.24 shows that when energy sharing is enabled, the total quantity of energy used from the grid decreases considerably, from 25% to 16%. Additionally, community storage system utilization increases from 0% to 4% when sharing is permitted. Whether sharing is enabled or disabled, the proportion of photovoltaic and energy from local storage is rather large in both cases, due to the high percentage of prosumers population in this case.

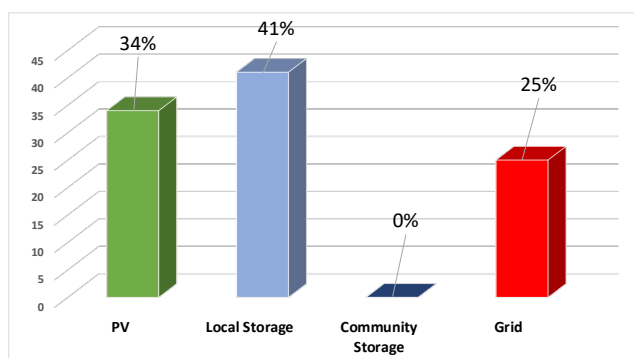


Figure 5.23—Case 1a: results for 90% of prosumers and 10% of consumers with “sharing disabled.”

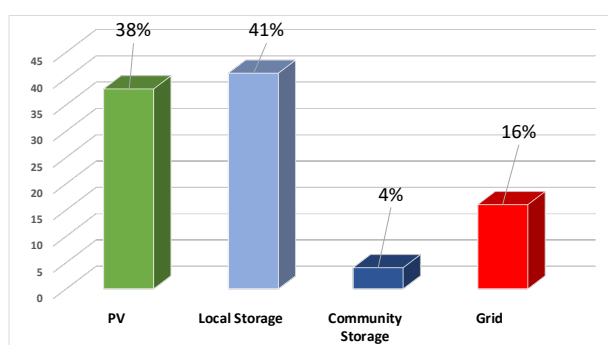


Figure 5.24— Case 1b: results for 90% prosumers and 10% consumers with “sharing enabled.”

Considering Case 2, as shown in Figures 5.25 and 5.26, we assume a homogenous CHDT population composed of 50% prosumers and 50% consumers. In Case 2a (Figure 5.25), the “sharing disabled” delegated autonomy is implemented, while in Case 2b (Figure 5.26), “sharing enabled.” Delegated autonomy is implemented. When the CHDTs are delegated to share surplus energy, the total energy consumption from the grid decreases from 64% to 55%, as seen in both figures. Similarly, the overall consumption from the community storage system increases from 0% to 10% when the CHDTs are granted “sharing enabled” permission. Comparing the scenario in Case 1 with Case 2, it is observed that the proportion of energy derived from photovoltaic and local storage sources is dramatically reduced in Case 2 relative to Case 1 (comparing Figures 5.23, 5.24, and Figures 5.25, 6.26). This result comes from the fact that the number of prosumers in this specific instance has dropped from 90% to 50%. In addition, the overall percentage of energy used from the grid has increased significantly compared to Case 1. This outcome can be attributed to the fact that the consumer population in Case 2 has also increased from 10% to 50%.

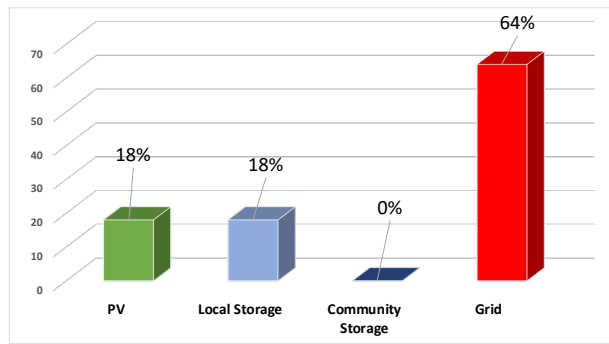


Figure 5.25— Case 2a: results for 50% consumers 50% prosumers with “sharing disabled.”

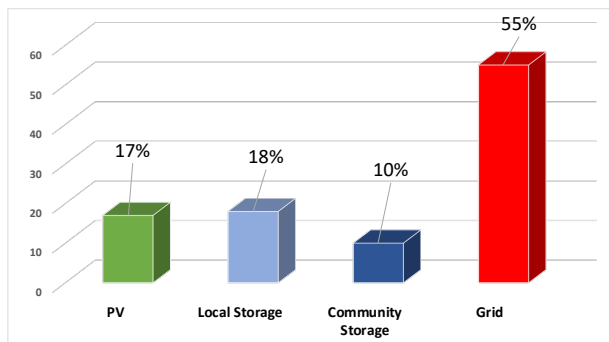


Figure 5.26 — Case 2b: results for 50% consumers 50% prosumers with “sharing enabled.”

Regarding Case 3 in Table 5.7 of this scenario, Figures 5.27 and 5.28 illustrate the model's outcome. This example examines a population composed of 10% prosumers and 90% consumers. As shown in Figures 5.27 and 5.28, when CHDTs are delegated to share energy, grid usage drops from 97% to 93%. Additionally, when sharing autonomy is enabled, community storage usage increases from 0% to 3%. Compared to Case 1 and Case 2, the share of photovoltaic and local storage decreased in this scenario as well. In this instance, the population of prosumers is rather small, thus 80% less than in Case 1 and 40% less than in Case 2. In addition, the contribution from the grid grows dramatically relative to Cases 1 and 2. This is due to the fact that the consumer population increased from 50% in Case 2 to 90% in Case 3, and from 10% to 90% in Case 1. From the above scenarios, it can be concluded that CHDTs can leverage "delegated autonomy" to alter the proportions and contributions of energy from varied sources. Therefore, this may be utilized as a technique to increase consumption from renewable sources in such environments.

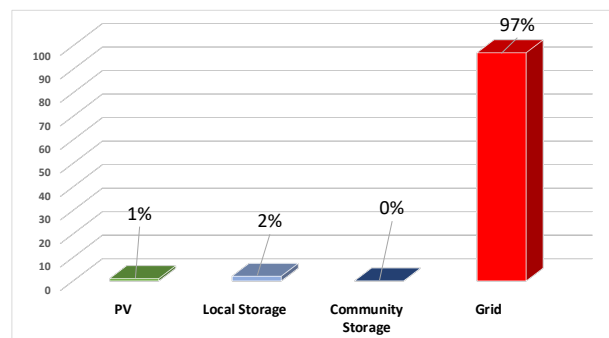


Figure 5.27— Case 3a: results for 10% of prosumers and 90% of consumers “sharing disabled.”

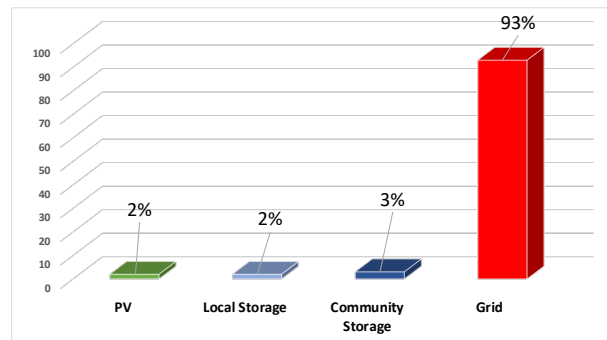


Figure 5.28— Results for 10% of prosumers and 90% of consumers with “sharing enabled.”

The partial conclusion that can be drawn from this simulation scenario suggests that the outcome of the model is consistent with the expected results in the following ways:

5. The notion of resource sharing in the CEE is plausible. In this particular scenario, the resource that has been shown to be sharable involves a centralized battery storage system. It was further shown that sharing in this sense can be achieved at two levels. The first level involves prosumer CHDTs sharing their surplus energy with the community storage system while the second level involves the community storage sharing stored energy back with the community.
6. Using the technique of delegation, CHDTs can share their own energy resources with other external system such as a community storage system. CHDTs can also share in the resources that are owned by other systems such as a community energy storage system.
7. Having a high population of prosumers with the ability to share their energy resource can result in a low dependency on the grid. Conversely, having a high population of consumers may still result in high dependency on the grid even when they share their resources.

5.1.5.2 Scenario 5B: Demonstrating Level 1 and Level 2 Resource Sharing

For this scenario, we also consider a CHDT population of 100. However, for illustration purposes, Table 5.9 is used to show a total of 10 CHDTs, constituting 5 prosumers and 5 consumers out of the total population. The model is run for a simulated period of 7 simulation days with resource sharing enabled. First, it can be observed from Table 5.9 that all prosumers were assigned PV systems of varying capacities. It can further be observed that all prosumers shared some quantity of energy (their surplus energy) at varying percentages with the community storage (level 1 sharing). For instance, prosumer CHDT 3 shared the most energy, contributing 52.46% of the total energy to the community storage, while prosumer CHDT 5 shared the least, contributing 9%. Perhaps CHDT 3 was able to share more because of the capacity of the PV system that was assigned (Brainsystem, which has a capacity of 6.930 KW). Concerning level 2 sharing, thus consuming energy back from the community storage, all prosumers, except prosumer CHDT 6, also participated in level 2 sharing, although in fewer quantities as compared to the consumer CHDTs.

On the contrary, none of the consumer CHDTs was assigned a PV system. Furthermore, none of the consumer CHDTs were involved in level 1 sharing. However, all consumer CHDTs participated in level 2 sharing, thus consuming energy from the community storage. It can further be observed that consumer CHDTs benefited more from level 2 sharing than prosumer CHDTs. For instance, consumer CHDTs 0, 1, and 7 consumed the most from the community storage, thus 14.46%, 32.34%, and 16.89%, respectively. This is because, during the periods that PV is unavailable, usually in the evening, the community storage may be fully charged and ready to share its contents, however, at that time of the day, most prosumer CHDTs may still have sufficient charge available in their local storage systems concurrently. In this case, the consumers' CHDTs will most often be the ones to benefit from or utilize energy from the community storage. In practice, energy from renewable sources will be cheaper than energy from fossil sources because energy prices (from the grid) are usually higher during peak periods of the day, which often coincide with evening demands. In the prototype model, consumer CHDTs have access to only two energy sources, i.e., (a) the grid and (b) the community storage system. The energy consumption rule in the ecosystem is framed to promote sustainable consumption. The rule mandates both prosumer and consumer CHDTs to consume from the grid as the last option. Therefore, consumer CHDTs first option will be to consume from the community storage and will only consider the grid when the community storage is unavailable. On the other hand, the priority for prosumer CHDTs is in this order: first, to consume directly from the PV source, then from the local storage, then from the community storage, and finally from the grid as the last option. This kind of arrangement ensures the maximization of renewable energy consumption in the community while minimizing consumption from the grid.

Table 5.9 — Results of scenario 4b demonstrating level 1 and 2 sharing

Prosumer CHDTs	Consumer CHDTs	Level 1 Sharing (%)	Level 2 Sharing (%)	Type of PV System Assigned
-	CHDT 0	125.67	14.46	Nil
-	CHDT 1	-	32.34	Nil
-	CHDT 2	-	11.32	Nil
CHDT 3	-	52.46	1.63	Brainsystem (6.930KW)
CHDT 4	-	9.18	5.46	Helius (3.99KW)
CHDT 5	-	9	6.51	Dass (3.22KW)
CHDT 6	-	18.46	0	Helius (3.99KW)
-	CHDT 7	0	16.89	Nil
-	CHDT 8	0	8.59	Nil
CHDT 9	-	10.90	2.81	Dass (3.22KW)

This shows that without resource sharing, dependence on the grid could be high within such an ecosystem. In this particular case, an example is discussed in (Daryan et al., 2022). In this example, a peer-to-peer energy sharing scheme for energy trading among Smart Energy Hubs, which can trade in both electrical and thermal energies, is discussed. The study shows that sharing helps reduce costs and dependency on gas/electricity utility companies. In a practical sense, a similar peer-to-peer energy sharing scenario (Kusakana, 2019) was

conducted in South Africa. The study's outcome revealed that sharing can substantially reduce the prosumers' operational costs by maximizing the use of locally generated renewable energy and storage while minimizing their reliance on the grid. The results observed thus far from the simulations are, however, consistent with this claim and also help to buttress the point that the credibility of the model is reasonably sufficient to be accepted.

5.2 Validation by Potential Users and Interest Groups

In the context of the design science research, after an artifact is created and used to study the proposed system or phenomenon, feedback can be collected from a focus groups, such as potential users of the system to help validate the model (Slettebø, 2021). As such, we adopted this approach to solicit potential users' confidence and also to attempt to measure or quantify their perceived practicability and suitability of the proposed CEE/CHDT concepts for their intended purposes. Thus, data was collected from three different focus groups, consisting of (a) potential users, (b) professional interest group 1, and (c) professional interest group 2. Three separate events were organized at three different locations on three different dates in Ghana to help validate the model from the perspective of potential users. Details of the various groups and the corresponding events are provided below.

5.2.1 The Potential User Group

This group constituted of representatives from nine households that have installed photovoltaic systems of different capacities on their respective residences. They were selected on a random basis. Invitation letters were sent to a total of 15 households, of which 9 responded and successfully made it to the validating event. This group showed great interest in the CEE/CHDT concepts because they had practically experienced the benefits of renewable energy and were interested in learning more about a system that could enhance their user experience and benefits. This group, for the most part, did not have any technical knowledge of energy management. They happened to invest in photovoltaic systems to overcome the unreliable nature of the power supply and also to help curb the rising cost of energy. The following are excerpts from the questions that were asked by this group.

1. *How much such a system may cost if they wanted to invest?*
2. *Concerns about the notion of "community" as they perceived that the penetration of photovoltaic systems in Ghana is very low and sparsely distributed.*
3. *Ease of use and support.*
4. *Internet connectivity and reliability.*



Figure 5.29—Potential user group validating event.

5.2.2 The Professional Interest Group 1

This group is made up of professionals from Ghana's energy sector. The group was mainly composed of employees from the Volta River Authority of Ghana (VRA Ghana, 2012), the Electricity Company of Ghana (ECG Ghana, 2022), and the Bui Power Authority (BPA Ghana, 2023). This was the largest focus group and consisted of 14 members. This group is considered an interest group because their work ethics and social responsibility mandate them to promote sustainable energy consumption in households and within their local communities. They also showed immense interest in the CEE/CHDT concepts. The contributions of this group were skewed towards the technical aspects of the study, particularly from an energy point of view. They also showed great interest in the concept of collaboration mechanisms as an energy management technique. Some questions/concerns that emerged from this group include:

1. Can the software/model be made available to be used on a pilot basis?
2. Concerns about internet connectivity and the reliability of the system in the local context.
3. How tariffs are going to be managed?
4. Power quality issues
5. Grid stabilization concerns
6. Illiteracy and general concern about the lack of ICT infrastructure
7. Grid connected versus Islanded communities, etc.



Figure 5.30— Professional interest group 1

5.2.3 The professional Interest Group 2

This group constituted academic staff from the Regional Centre of Energy and Environmental Sustainability (RCEES, 2021), which is a leading internationally accredited Centre of Excellence providing research and postgraduate education in energy and environmental sustainability. Present at the event were two professors, two PhD holders, and four young PhD researchers. The contribution from this group was rich, with several constructive suggestions. Some concerns were raised regarding technical validation. However, it was agreed that for such novel ideas, finding the right data for benchmarking purposes was difficult, and therefore other alternative validation approaches, such as the adopted ones, should be acceptable. They also showed great interest in agent-based simulation and the possibility of future collaboration. For this group, the focus of the discussion was based on the following key areas:

1. Technical validation of the energy aspects (physical layer) of the model.
2. Validation of the collaborative aspects of the model.
3. Future works.
4. Sources of data for the PV model.
5. Collaboration as a management technique.
6. Potential for collaborative research in multimethod modelling.
7. Potential to train young researchers in the use of Anylogic and agent-based modelling.



Figure 5.31— Professional user group 2

5.2.4 The Validation Processes

The validation process with focus groups comprised three phases. The first part consisted of a 20-minute presentation that described the overview and background concepts and knowledge. The second part involved a 30-minute demonstration of the CEE/CHDT model. The demonstration covered the various components of the model and the modelling techniques that were adopted. A few selected collaborative scenarios were also demonstrated. The third part consisted of a 30-minute question and discussion period, which in all three events exceeded 30 minutes due to the interest that the ideas generated among the participants. After the discussion, questionnaires were distributed, one per participant. The questionnaires were based on a 5-point Likert scale that ranged from “strongly disagree,” having a weight of “1,” to “strongly agree,” having a weight of “5”. As shown in Table 5.10, the questionnaires sought to measure eight major constructs. Each construct was further broken down into a few dimensions, totalling 28 dimensions. The definition of each construct and the related dimensions are provided in Table 5.10. A modified version of the Unified Theory of Acceptance and Use of Technology model (UTAUT) (Venkatesh et al., 2003) was adopted as a guide in developing these constructs and dimensions.

Table 5.10 — Definition of the various constructs and their related dimensions

General Definition of Constructs	Dimensions of the construct to be measured.
PE: Performance Expectancy The degree to which users perceive that the CEE/CHDT System can help them improve their sustainable energy consumption efforts.	PE1- Facilitating energy use decisions: To measure potential users’ perception that CEE/ CHDT can help them to make the right decision in their sustainable energy consumption effort.
	PE2- Facilitating efficient energy use: To measure potential users’ perception that the CEE/CHDT can help to increase the level of efficiency regarding their energy use choices and behaviours.
	PE3- Reduce human interference: To measure potential users’ perception that their CHDT can act on their behalf to make sustainable energy consumption efforts easier.
	PE4- Efficient energy management technique: To measure potential users’ perception that managing energy consumption using CEE/CHDT techniques may yield a more efficient outcome as compared to other known systems.

General Definition of Constructs	Dimensions of the construct to be measured.
EE: Effort Expectancy The degree of ease associated with the use of CEE/CHDT System.	EE1- Ease of use: To measure potential users' perception that using CHDT to manage their household energy consumption may be an easy task.
	EE2- Ease of comprehension: To measure potential users' perception that delegating a CHDT is a clear and easy process to understand.
	EE3- Ease of adaptation: To measure potential users' perception that if a person can use simple technologies like a computer or a cell phone, then the person can easily learn how to use the CEE/CHDT System.
	EE4- Ease of effort: To measure potential users' perception that it may require very little effort to use the CHDT.
SI: Social Influence. The degree to which users perceive that the acceptance of the CEE/CHDT can be affected by the kind of people surrounding them.	SI1- Influence of peers: If people have their close associates using the CEE/CHDT system, they may be influenced try and use it.
	SI2- Influence of a superior: If superiors recommend the use of the CEE/CHDT system to their subordinates, it may influence their intention or decision to use it.
	SI3- Influenced by social status: Using the CEE/CHDT system could increase a person's social status for example as a "sustainable energy advocate".
FC: Facilitating Conditions. The degree to which users perceive that the knowledge and skills required to use the CEE/CHDT can easily be obtained.	FC1- Pro-sustainable behaviours by close associates: The people around me are interested in perusing behaviours that could enhance the sustainable energy consumption in their homes.
	FC2- Environmental conditions: People's environments (workplace/community/close associates etc.) that promote sustainable energy consumption behaviours are more likely to endorse the CEE/CHDT System.
	FC3- The condition influenced by people's interest in technology: People who have basic technological interest may be interested in the CEE/CHDT and may like to utilize it to complement their sustainable energy consumption efforts.
	FC4- Availability of helpful materials and resources: If potential users encounter any difficulty in using the CEE/CHDT, they are most likely to get help from colleagues.
	FC5- Willingness to adopt new technology: People's willingness to adopt a system such as the CEE/CHDT to help them manage my household's energy consumption.
UI: Use Intentions: The degree to which users perceive that they intend to experiment/use with CEE/CHD system.	UI1- Having passion for new technology: I am a person who likes new things and trying new technologies.
	UI2- Being an early technology adopter: I often encounter new products, services, and technologies earlier than the people around me.
	UI3- Technology discoverability: One of my key strengths is the discovery of new technologies.
GA: Goal Alignment. The degree to which users are willing to flexibly contribute to community goals that are in line with their personal goals.	GA1- Flexible contribution: Willing to flexibly align own goals (voluntarily and regularly).
	GA2- Offer of Incentives: Willing to align own goals when incentivized.
	GA3- Joining a VO/Coalition: Willing to join a short-term VO, proposed by the community in line with own value system.
Co: Collaborations. The degree to which users perceive collaboration as a useful management technique or mechanism to adopt in managing energy consumption in the context of a community.	Co1- Willingness to participate in collaborative endeavours: I am willing to participate in collaborative endeavours.
	Co2- Willingness to know more about collaboration: I am willing to learn how collaboration in the CEE/CHDT system works.
	Co3- Willing to align my value system: I am willing to join a coalition when the goal is in line with my value system.
DG: Delegation/Delegated autonomy The degree to which users are willing to delegate their value system to their CHDTs.	Dg1- Willing to delegate my value system to a CHDT: I am willing to delegate my value system to my CHDT to carry out for me.
	Dg2- Willing to trust the decision of my CHDT: I am willing to trust that the decision my CHDT.
	Dg3- Delegated autonomy: I am willing to give full autonomy to my CHDT if I can trust it.

5.2.4.1 The Unified Theory of Acceptance and use of Technology Model

Consideration is given to the adaptation of the Unified Theory of Acceptance and Use of Technology (UTAUT) model when evaluating the CEE/CHDT concept from the perspective of potential users and interest groups. UTAUT is a technology adoption model that describes

the extent to which the use of information technology is accepted (Venkatesh et al., 2003). Venkatesh et al. founded the UTAUT model by combining eight prior technology adoption models, namely: (a) the innovation diffusion theory (IDT), (b) the technology acceptance model (TAM), (c) the theory of reasoned action (TRA), (d) the theory of planned behaviour (TPB), (e) the social cognitive theory (SCT), (f) the motivational model (MM), the combined (g) TAM and TPB (C-TAM-TPB), and (h) the model of personal computer utilization (MPCU).

According to (Sarfraz, 2017), the UTAUT model is the most comprehensive model of technology adoption and acceptance. Initially, the UTAUT model was comprised of seven constructs: (a) performance expectation (PE), (b) effort expectation (EE), (c) social influence (SI), (d) facilitating conditions (FC), (e) computer self-efficacy, (f) anxiety, and (vii) attitude toward using technology (Venkatesh et al., 2003).

Some examples of recent applications that adopted this validation mode include (a) understanding the use of learning management systems by undergraduate university students in Saudi Arabia (Al-Mamary, 2022), (b) online shopping adoption during COVID-19 and social isolation (Erjavec & Manfreda, 2022), (c) investigating mobile acceptance in academic library services (Parhamnia, 2022), (d) understanding intention to adopt AI and related technologies among librarians (Andrews et al., 2021), (e) understanding acceptance of “eHealthcare” by IoT natives and IoT immigrants (Arfi et al., 2021), and (f) adoption intention of electric vehicles in India (Jain et al., 2022).

The UTAUT model is widely used to predict the intention and behaviour of potential users, of a proposed information technology (IT) based system (Venkatesh et al., 2003). Referring to Figure 5.32, the UTAUT model considers the effect of four factors on behavioural intention. These are: performance expectancy (PE), effort expectancy (EE), social influence (SI), and facilitative conditions (FC). The three fundamental perspectives of UTAUT are as follows: First, behavioural intention is directly influenced by performance expectancy, effort expectancy, and social influence. Second, use behaviour is directly influenced by facilitating conditions and behavioural intention; and third, age, gender, experience, and voluntariness of use mediate the influence of performance expectancy, effort expectancy, and facilitating conditions on behavioural intention (Venkatesh et al., 2003).

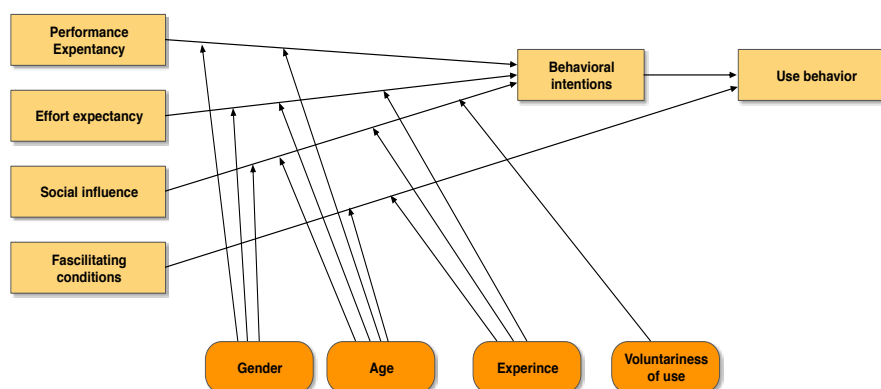


Figure 5.32— The Unified Theory of Acceptance and Use of Technology (UTAUT) model. Adopted from (Venkatesh et al., 2003).

5.2.4.2 Measuring the Validation Constructs and Dimensions

A total of 31 responses were collected from the participants at all three validation events. The data from the respondents and the corresponding analysis are described in the following paragraphs. The Cronbach alpha technique (Taber, 2018) is used to test the internal consistency/reliability of the collected data. The SPSS statistical tool (IBM, 2016) is used for the data analysis. The overall Cronbach alpha for all eight construct is found to be 0.866. This value represents acceptable internal consistency and is an indication that the measuring instrument (questionnaire) is reliable, and its outcome can be trusted.

After a careful analysis of the data, that was collected from the respondents, the overall conclusion drawn from the validation is shown in Table 5.11. In the table, the average scores were either rounded up or down to correspond to one of the points on the Likert scale. For instance, the average score for PE1 is 4.55. This is rounded up to 5.0, which corresponds to “strongly agree” on the Likert scale. Similarly, PE2 is rounded down to 4.0, which corresponds to “agree” on the Likert scale. The general conclusion for the validation is that the respondents agreed to all eight construct and 28 dimensions of the CEE/CHDT model. This can be interpreted as a unanimous acceptance of the fact that the developed model/artifact is fit for its intended purpose.

Table 5.11— Conclusion drawn from the data which was collected from the respondents

Construct	Dimensions	Average score (Based on 31 respondents)	Concluding Remarks (Based on the Likert scale)
PE	PE1	4.55	Strongly agree
	PE2	4.48	Agree
	PE3	4.45	Agree
	PE4	4.26	Agree
EE	EE1	4.29	Agree
	EE2	4.32	Agree
	EE3	4.39	Agree
	EE4	4.26	Agree
SI	SI1	4.03	Agree
	SI2	3.97	Agree
	SI3	4.16	Agree
FC	FC1	4.48	Agree
	FC2	4.10	Agree
	FC3	4.58	Strongly Agree
	FC4	4.13	Agree
	FC5	4.39	Agree
UI	UI1	4.58	Strongly Agree
	UI2	4.55	Strongly Agree
	UI3	4.48	Agree
GA	GA1	4.52	Strongly Agree
	GA2	4.32	Agree
	GA3	4.16	Agree
Co	Co1	4.23	Agree
	Co2	4.35	Agree

Construct	Dimensions	Average score (Based on 31 respondents)	Concluding Remarks (Based on the Likert scale)
	Co3	4.26	Agree
DG	Dg1	4.23	Agree
	Dg2	4.35	Agree
	Dg3	4.35	Agree

In Figures 5.33 to 5.40, we use the Radar graph to compare the results of all the eight constructs. For instance, in Figure 5.33, Performance Expectancy 1 (PE1) which is the measure of potential users' perception that CEE/CHDT can help them to manage their household energy consumption more effectively, obtained the highest score of 4.55 out of 5. In Figure 5.34, effort expectancy 3 (EE3) which is the measure of ease of adaptation, obtained the highest score under effort expectancy. In Figure 5.40, Co2 which is the measure of potential users' willingness to try collaborative mechanism as a management technique for sustainable energy consumption had the highest score of 4.35.

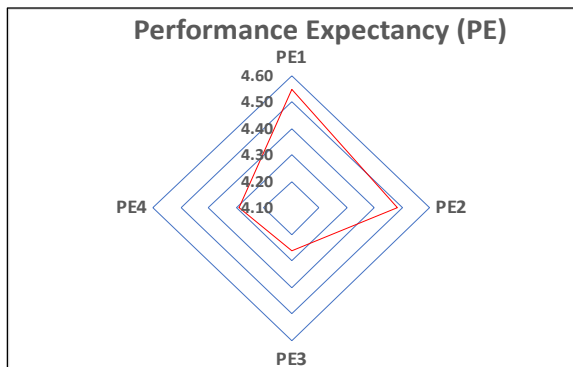


Figure 5.33—Performance expectancy.

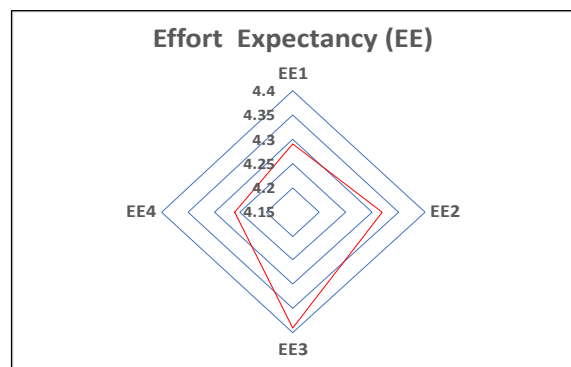


Figure 5.34—Effort expectancy.

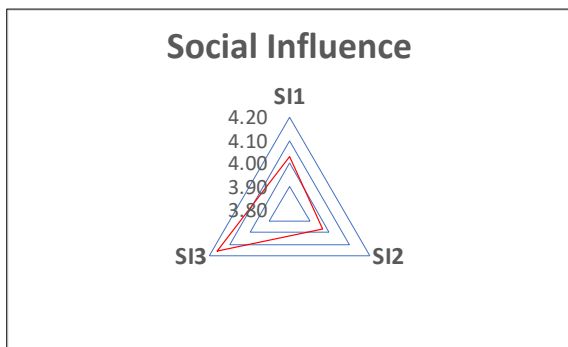


Figure 5.35—Social influence.

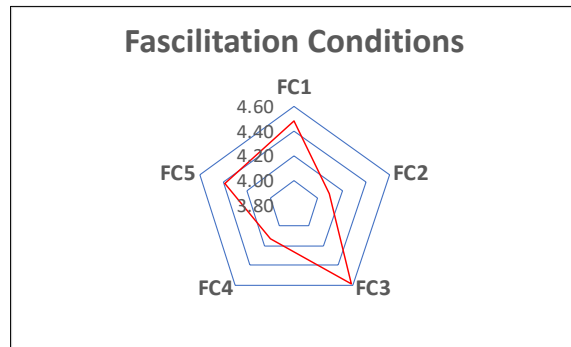


Figure 5.36—Facilitating conditions.

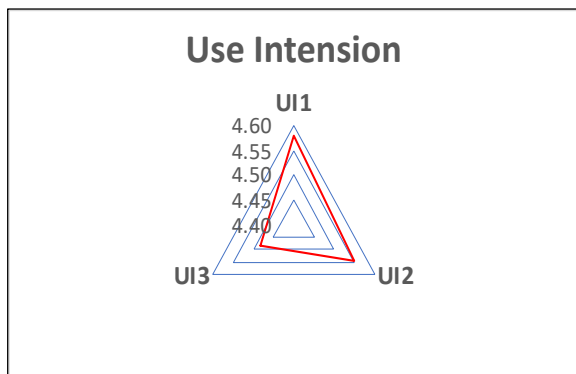


Figure 5.37—Use intension.

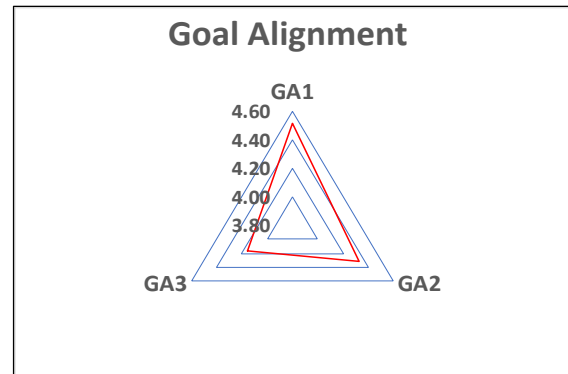


Figure 5.38—Goal alignment.

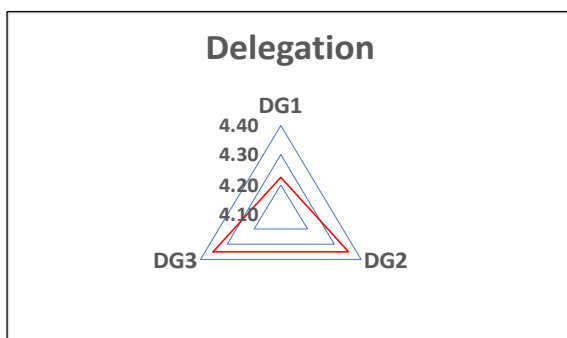


Figure 5.39—Delegation.

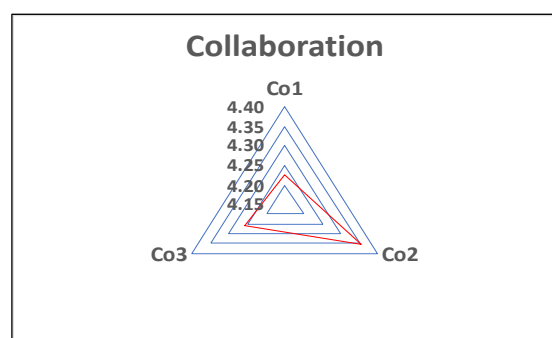


Figure 5.40—Collaboration.

In conclusion, this validation method has helped to measure each of the 28 dimensions relating to the 8 constructs of the CEE model. The measuring instrument is designed in the form of a questionnaire that is based on a 5-point Likert scale, using the Unified Theory of Acceptance and Use of Technology (UTAUT) model as a guide. In all, a total of 31 respondents participated in the measuring process. The outcome of this validation approach has shown that the respondents unanimously accepted the CEE concept and its related principles as fit for their intended purposes. Furthermore, although the general outcome suggests a unanimous acceptance, it can be observed from Figures 5.33 to 5.40 that each dimension relating to a particular construct has different levels of acceptance and that some dimensions were more acceptable to the respondents than others.

5.3 Validation by the Research Community

A number of publications in peer-reviewed conference proceedings and scientific journals are also made with the goal of getting qualitative peer validation and disseminating the thesis results, in addition to the routes of validation indicated above. The list of publications is shown in Table 5.12, and their respective contributions to various sections of the thesis are also shown in Table 5.13. In total, there are 5 publications in international journals and 11 articles in the

proceedings of international conferences that have undergone peer review. One paper (number 11, Table 5.12) was awarded the best paper in a conference.

Table 5.12— List of publications related to CEE

Item	List of Related Publications
	Publication in Journals
1	Adu-Kankam, K. O., & Camarinha-Matos, L. M., 2018. Towards Collaborative Virtual Power Plants: Trends and convergence. <i>Sustainable Energy, Grids and Networks</i> , 626, 217-230. https://doi.org/10.1016/j.segan.2018.08.003
2	Adu-Kankam, K. O., & Camarinha-Matos, L. M., 2022. Renewable Energy Communities or Ecosystems: An Analysis of Selected Cases. <i>Heliyon</i> , July 2022. https://doi.org/10.2139/ssrn.4112124
3	Adu-Kankam, K. O., & Camarinha-Matos, L. M., 2022. Delegating Autonomy on Digital Twins in Energy Ecosystems, <i>Int. J. SMART GRID</i> , vol. 6, no. 4, December 2022, doi: https://doi.org/10.20508/ijsmartgrid.v6i4.257.g253
4	Adu-Kankam, K. O., & Camarinha-Matos, L. M., 2023. "Modelling Collaborative Behaviors in Energy Ecosystems", <i>Computers</i> 12, no. 2: 39. February 2023 https://doi.org/10.3390/computers12020039
5	Adu-Kankam, K. O., & Camarinha-Matos, L.M., 2023. Collaborative Digital Twins: The Case of the Energy Communities. <i>SN COMPUT. SCI.</i> 4, 664 (2023). August 2023, https://doi.org/10.1007/s42979-023-02050-2
Conference Proceedings	
1	Adu-Kankam, K. O., & Camarinha-Matos, L. M. 2018. Towards Collaborative Virtual Power Plants. In Camarinha-Matos L. M, Adu-Kankam K. O., (Ed.), <i>Technological Innovation for Resilient Systems DoCEIS 2018</i> (pp. 28–39). Springer, Cham. https://doi.org/10.1007/978-3-319-78574-5_3
2	Adu-Kankam, K. O., & Camarinha-Matos, L. M. 2019. Emerging Community Energy Ecosystems: Analysis of Organizational and Governance Structures of Selected Representative Cases. In <i>IFIP Advances in Information and Communication Technology, Technological Innovation for Industry and Service Systems. Doctoral Conference on Computing, Electrical and Industrial Systems 2019</i> . (Vol. 553, pp. 24–40). Springer chem. https://doi.org/10.1007/978-3-030-17771-3_3
3	Adu-Kankam, K. O., & Camarinha-Matos, L. M. 2020. A Framework for Behavioural Change Through Incentivization in a Collaborative Virtual Power Plant Ecosystem. <i>Technological Innovation for Life Improvement. DoCEIS 2020. IFIP AICT</i> , 577, 31–40, DOI: https://doi.org/10.1007/978-3-030-4512 . April 2020, https://doi.org/10.1007/978-3-030-45124-0_3
	<i>This paper received the best paper award.</i>
4	Adu-Kankam, K. O., & Camarinha-Matos, L. M. 2020. A Collaborative Approach to Demand Side Energy Management. In <i>Working Conference on Virtual Enterprises, PRO-VE 2020, Boosting Collaborative Networks 4.0. IFIP Advances in ICT</i> (Vol. 598, pp. 393–405). Springer chem. November 2020, https://doi.org/10.1007/978-3-030-62412-5_32
5	Adu-Kankam, K. O., & Camarinha-Matos, L.M., 2021. Towards a Hybrid Model for the Diffusion of Innovation in Energy Communities. <i>IFIP Advances in ICT, Technological Innovation for Applied Artificial Intelligent Systems. Doctoral Conference on Computing, Electrical and Industrial Systems.</i> , 626, 175–188. June 2021, https://doi.org/10.1007/978-3-030-78288-7
6	Adu-Kankam, K.O., Camarinha-Matos, L.M. (2022). Modelling “Cognitive Households Digital Twins” in an Energy Community. In: Bendaoud, M., Wolfgang, B., Chikh, K. (eds) <i>The Proceedings of the International Conference on Electrical Systems & Automation. ICESA 2021</i> . Springer, Singapore. March 2022, https://doi.org/10.1007/978-981-19-0039-6_6

Item	List of Related Publications
	Publication in Journals
7	Adu-Kankam, K. O., & Camarinha-Matos, L. M. 2022b. Modelling Mutual Influence Towards Sustainable Energy Consumption. In Camarinha-Matos L, M., (Ed.), Technological Innovation for Digitalization and Virtualization (pp. 3–15, June 2022, DOI: https://doi.org/10.1007/978-3-031-07520). Springer, Cham. https://doi.org/10.1007/978-3-031-07520-9_1
8	Adu-Kankam, K. O., & Camarinha-Matos, L. M. 2022a. A Framework for Collaborative Virtual Power Plant Ecosystem. In Camarinha-Matos, L. M., Ortiz, A., Boucher, X., Osório (Ed.), Collaborative Networks in Digitalization and Society 5.0. PRO-VE 2022. IFIP Advances in Information and Communication Technology, (pp. 151–166). Springer, Cham. September 2022, https://doi.org/10.1007/978-3-031-14844-6_13
9	Adu-Kankam, K. O., & Camarinha-Matos, L. M., “Modelling ‘Delegated Autonomy’ in Cognitive Household Digital Twins,” in 2022 11th International Conference on Renewable Energy Research and Application (ICRERA), October 2022, pp. 192–199, doi: 10.1109/ICRERA55966.2022.9922673.
10	Adu-Kankam, K.O., Camarinha-Matos, L.M. (2022). A Framework for the Integration of IoT Components into the Household Digital Twins for Energy Communities. In: Camarinha-Matos, L.M., Ribeiro, L., Strous, L. (eds) Internet of Things. IoT through a Multi-disciplinary Perspective. IFIPIoT 2022. IFIP Advances in Information and Communication Technology, vol 665. Springer, Cham. October 2022, https://doi.org/10.1007/978-3-031-18872-5_12
11	Adu-Kankam, K. O., Camarinha-Matos, L. M. 2023. A Collaborative Dimension for Renewable Energy Communities. In: Camarinha-Matos, L.M., Ferrada, F. (eds) Technological Innovation for Connected Cyber Physical Spaces. DoCEIS 2023. IFIP Advances in Information and Communication Technology, vol 678. Springer, Cham. https://doi.org/10.1007/978-3-031-36007-7_2

Table 5.13 — Publications and their related contributions to the thesis

Association of Related Publications with Thesis Chapters and Research Questions	
1. Towards Collaborative Virtual Power Plants: Trends and convergence.	
Contributes to: a. Theoretical background b. Literature review	Key RQs considered: a. Which collaborative organizations are emerging in the domain of VPPs? [Organizational forms] b. Which collaboration principles are being applied in the emerging collaboration forms? [CN principles] c. Which technological elements support collaboration in VPPs? [Technology]
2. Delegating Autonomy on Digital Twins in Energy Ecosystems	
Contributes to: a. Theoretical background b. Prototype demonstration	Key RQs considered: a. Using a multi-method simulation approach, how can the cognitive intelligence of CHDTs be modelled? b. In case the ecosystem has a specific goal, such as minimizing consumption from the grid while maximizing consumption from renewable energy sources, how can “delegated autonomy” be used to achieve this goal?
3. Modelling Collaborative Behaviours in Energy Ecosystems	
Contributes to: a. Theoretical background b. Prototype demonstration	Key RQs considered: a. Using multimethod simulation techniques, how can the following collaborative behaviours within the CEE be demonstrated?

Association of Related Publications with Thesis Chapters and Research Questions	
1. Towards Collaborative Virtual Power Plants: Trends and convergence.	
	<ul style="list-style-type: none"> i. Collaborative roles/behaviours played by the CEE-manager such as <ul style="list-style-type: none"> - opportunity-seeking and goal-formulation. -goal proposition/invitation to form a coalition or virtual organization. - formation and dissolution of coalitions. ii. Collaborative roles/behaviours played by CHDTs. These may include acceptance or decline of invitation based on: <ul style="list-style-type: none"> - delegation or non-delegation, - value system compatibility or non-compatibility. <p>b. How can the sharing of a common resource like a community energy storage system be demonstrated in the CEE?</p>
4. A Collaborative Dimension for Renewable Energy Communities	
<p>Contributes to:</p> <ul style="list-style-type: none"> a. Theoretical background b. Conceptual background 	<p>Key RQs considered:</p> <ul style="list-style-type: none"> a. What are RECs? <ul style="list-style-type: none"> i. What are the motivations for RECs? ii. What are some of the existing cases of RECs? iii. What are the obstacles / barriers to the advancement of RECs? iv. What role can collaborative networks play to help overcome (some of) the mentioned barriers? b. What are Collaborative Renewable Energy Communities (CRECs)? What are the main aspects of CRECs? (Namely in terms of structure and organization, governance, involving mechanisms of collaboration etc. c. What are some potential use cases of the CREC concept?
5. Renewable Energy Communities or Ecosystems: An Analysis of Selected Cases	
<p>Contributes to:</p> <ul style="list-style-type: none"> a. Theoretical background b. Literature review 	<p>Key RQs considered:</p> <ul style="list-style-type: none"> a. How can the interaction between members of the selected energy ecosystems be described? b. What technological enablers and trends underlie the establishment, operation, and service provision of these ecosystems? c. How do the characteristics and functions of virtual power plants (VPPs) compare to those of renewable energy ecosystems?
6. A Framework for the Integration of IoT Components into the Household Digital Twins for Energy Communities	
<p>Contributes to:</p> <ul style="list-style-type: none"> a. Theoretical background b. Conceptual background 	<p>Key RQs considered:</p> <ul style="list-style-type: none"> a. How can the integration of IoT components in household appliances enable the feasibility and functionality of the Cognitive Household Digital Twin (CHDT) concept? b. How can the integration of IoT components facilitate the cognitive and decision-making capabilities of the CHDTs?
7. Modelling Cognitive Households Digital Twins in an Energy Community	

Association of Related Publications with Thesis Chapters and Research Questions	
1. Towards Collaborative Virtual Power Plants: Trends and convergence.	
Contributes to: a. Theoretical background b. Conceptual background c. Collaborative behaviours d. Prototype demonstration	Key RQs considered: a. How can the cognitive capabilities of CHDTs be modelled? b. How can CHDTs utilize these cognitive capabilities to make decisions that facilitate collaborations?
8. Modelling 'Delegated Autonomy' in Cognitive Household Digital Twins.	
Contributes to: a. Theoretical background b. Conceptual background c. Collaborative behaviours d. Prototype demonstration	Key RQs considered: a. In the context of collaboration, where excess energy produced by prosumer CHDTs can be shared with the community (CEE), how can the use of "delegated autonomy" be used to enhance sustainable consumption? b. In the case that CHDTs have access to multiple sources of energy and can therefore choose from any preferred source, even if that source demands that the CHDT wait until the preferred source is evaluable, how can "delegated autonomy" be used to enhance sustainable consumption?
9. Towards Collaborative Virtual Power Plants.	
Contributes to: a. Theoretical background	Key RQs considered: a. What are the key drivers or motivation for collaboration in the domain of VPPs? [Seeking to identify motivation for collaborations] b. Which collaborative organizations are emerging in the domain of VPPs? [Seeking to identify organizational forms] c. Which collaborative principles are being applied in the emerging collaboration forms? [Seeking to identify CN principles] d. Which technological elements support collaboration in VPPs? [Seeking to identify collaborative technological] e. Who are the key players, agents or systems that participate in these collaborations? [Seeking to identify key players in the collaborations]
10. Towards a Hybrid Model for the Diffusion of Innovation in Energy Communities.	
Contributes to: a. Conceptual background	Key RQs considered: a. How do DIT and TTM models compare from both the contextual and structural perspectives? b. Based on the observed contextual and structural similarities or differences, how can these models be hybridized into a single model?
11. A Collaborative Approach to Demand Side Energy Management.	
Contributes to: a. Theoretical background b. Conceptual background	Key RQs considered: a. How can collaborations and antecedent interventions enhance the behaviour of consumers towards the delegation of deferrable loads within an energy ecosystem? b. How can collaboration through the sharing of experience and knowledge (technical and professional) enhance membership fluidity in an energy ecosystem We
12. Emerging Community Energy Ecosystems: Analysis of Organizational and Governance Structures of Selected Representative Cases	

Association of Related Publications with Thesis Chapters and Research Questions	
1. Towards Collaborative Virtual Power Plants: Trends and convergence.	
Contributes to: a. Theoretical background b. Conceptual background c. Literature review	Key RQs considered: a. How are these RECs organised? (Which can include as sub-questions: i. What are the roles and responsibilities? ii. How are these RECs governed? iii. What relationship exists between roles? b. How do these RECs interact with the power grid? and c. What role does collaborations play in these RECs?
13. A Framework for Collaborative Virtual Power Plant Ecosystem.	
Contributes to: a. Theoretical background b. Conceptual background c. Collaborative behaviours	Key RQs considered: a. What framework can support the modelling of each collaborative behaviour by a population of CHDTs within a CEE? i. Communication and information exchange towards coalition formation (Joining a Virtual Organization (VO)) ii. Communication and information exchange towards the execution of a specific goal: iii. Sharing common resources: In this context we consider the scenario were CHDTs share energy that is stored in a common community storage. iv. Collective actions. The behaviour exhibited by members when they all act in the same way in order to achieve a collective objective.
14. Modelling Mutual Influence Towards Sustainable Energy Consumption.	
Contributes to: a. Conceptual background b. Collaborative behaviours c. Prototype demonstration	Key RQs considered: a. In the context that “influencer” CHDTs could convey either positive or negative influence on “influencee” CHDTs in a CEE, how can the aggregation of these influences over time be used to determine the overall behaviour of a CHDT? b. How can the overall behaviour of a CHDT be used in decision-making? c. Considering that CHDTs could be influenced to alter their decisions, how can “mutual influence” be used to alter the decisions of CHDTs towards sustainable energy consumption.
15. A Framework for Behavioral Change Through Incentivization in a Collaborative Virtual Power Plant Ecosystem.	
Contributes to: a. Theoretical background b. Conceptual background	Key RQs considered: What kind of incentives can suitably be used in a REC environment The model tests effectiveness of a. one-size-fits-all and b. customized incentives”
16. Collaborative Digital Twins: The Case of the Energy Communities	
Contributes to: a. Theoretical background b. Conceptual background	Key RQs considered: a. What architectural framework is suitable to support the conceptualization of a Collaborative Digital Twin (CDT)? b. How can the CDT concept be demonstrated and assessed in renewable energy communities?

5.4 Limitations of the Validation Process

The following are some observed limitations to the validation process:

1. **Limited number of photovoltaic system users:** Although nine of the respondents had practical experience using photovoltaic systems, the researchers would have preferred to have a much higher number than this. This could have helped by providing more diverse and practical feedback from the potential user group.
2. **Validation from the Collaborative Networks Community:** The validation from this community was primarily based on feedback from peer-reviewed journal publications and international conferences. Although this feedback was very constructive and useful, it addressed different sections of the model at different times. We believe the experience could have been richer if the community had had the opportunity to experience the practical demonstration of the complete model. This could have helped generate interesting discussions concerning the collaborative aspects of the model.
3. **Geographical distribution:** Sustainability and issues concerning sustainable energy consumption, although "universal," may be perceived and approached differently by different people from different geographical regions. We have the view that having the demonstration in different geographic regions (countries) could have also enriched the outcome, although we do not expect a significant variation in the final outcome.
4. **Data sources:** The data that was used to model the various households in the model was sourced from the United Kingdom (UK). We share the view that perhaps the system should also be verified using other data sources since the use-behaviours of households in Ghana, for instance, may be different from that of the UK. However, It was not possible to get such data during the realization of this work.

5.5 Limitations of the CEE and CHDT Models

1. **Assessment of the energy aspects:** Since Anylogic is not a dedicated tool for the simulation of energy consumption and generation, the results in relation to the energy aspects may not be accurate. However, since the focus of the work is to show that the mentioned collaborative behaviours can have some impact on the energy infrastructure, the obtained results can have a reasonable level of acceptance on these grounds.
2. **Assumptions:** Several assumptions were made in the design of the model and also during the simulation runs. For instance:
 - a. All households were embedded with the same number of appliances, although this may not be the case in a physical community.
 - b. Additionally, these households were assumed to have two value systems at a time, which may not be the case in a real household.

- c. Regarding the preconditions for the formation of community goals, it is also assumed that 3 preconditions are needed, although in a real-world implementation, the actual preconditions may involve several factors such as technical, economic, environmental, and financial.
- d. The “decision constant” is a tentative value on which the CHDTs make decisions. This number can be altered upwards or downwards, and, in each case, it can affect the outcome of the model. This makes it a subjective quantity, that depends on the modeller. The current literature has limited information in this area.

These limitations however open opportunities for future work.

5.6 Addressing Ethical Concerns Relating to the CEE Concept

The CEE concept is designed to be less intrusive and would not require users to submit sensitive personal data besides their digital profiles, which reside in the users' CHDT memory and will not be shared with any third party inside or outside the community. Furthermore, the notion of influence will be designed in conformance with only the principles of “reward” and “punishment,” which are popular concepts that are used mainly for behaviour modifications. This technique helps to keep the behaviour of subjects on the expected path and make the maximum use of their capabilities. No other forms of influence would be permitted. In this way, it is possible to prevent the scenario where CHDTs are influenced in a manner that could be inimical to the community objectives. Again, the proposed influence is targeted mostly at free-rider and other non-conforming CHDTs who are part of the community but have not defined their digital profiles, and therefore their behaviours are inimical to the collective interest of the community. This is a common phenomenon in communities where some members do not conform to community norms. A typical example is the notion of the “tragedy of the commons,” where some members abuse or overexploit a shared community resource for their personal or parochial gains. Furthermore, since this is a closed community, it could be easier to integrate security mechanisms that could help to minimize the possibility of CHDTs encountering external and malicious influences.

5.7 Addressing Some Potential Conflicts in RECs

Renewable energy communities can bring about various benefits, but they can also encounter conflicts arising from different factors. Some possible conflicts in renewable energy communities include:

1. **Resource Allocation:** In communities where renewable energy resources are shared, conflicts may arise over how resources are shared/allocated. Some members might feel they are not receiving their fair share of the energy generated or the economic benefits. Collaboration can play a crucial role in resolving these problems. It can bring together diverse stakeholders, expertise, and resources to help develop a comprehensive solution that addresses this challenge effectively and holistically. These may include:

- a. **Community Engagement:** Engaging with the local community through collaborative workshops, town hall meetings, and educational programs can foster a sense of ownership and participation. Involving community members in the decision-making process ensures that their needs and preferences are considered in resource allocation strategies. In the CEE, this can be achieved when human users or delegators assign their preferences by way of their value systems to their CHDTs to be considered during collective decision-making processes, including resource sharing and allocation. Moreso, the CEE manager can engage the community through invitations that are tailored towards a specific goal. Community members, through their CHDTs, can also engage through the various responses (acceptance or decline) to invitations.
 - b. **Sharing Knowledge and Expertise:** Collaboration allows different parties, including researchers, engineers, policymakers, and community members, to pool their knowledge and expertise together. This cross-disciplinary approach can lead to innovative solutions that consider various perspectives and insights. Knowledge sharing can help members to share their resources more flexibly.
 - c. **Scale and Impact:** Collaboration enables the scaling up of solutions. When multiple entities, communities or regions work together, they can collectively achieve larger-scale projects that have a greater impact on the community. With respect to the CEE, it is possible to scale up by integrating entities, such as security services, municipalities, and emergency response service providers, to help provide prompt and decisive emergency response services in emergency situations.
2. **Decision-Making:** Renewable energy community decisions, such as where to place renewable energy infrastructure or how to manage the generated energy, might not be universally agreed upon due to individual preferences. Conflicts may arise if decision-making processes are not transparent and inclusive. Collaboration can significantly contribute to resolving the problem of decision-making in renewable energy communities by bringing together diverse perspectives, expertise, and resources to make well-informed and effective choices. Here's how collaboration can help address decision-making challenges:
- a. **Collective Intelligence:** Collaboration involves the pooling of knowledge and insights from various stakeholders, including community members, experts, policymakers, and industry professionals. This collective intelligence enhances the quality of decision-making by considering a wide range of perspectives. Regarding the CEE, the decision to form a virtual organization (VO) to either pursue or decline a particular business opportunity is dependent on the collective feedback that is received from all the involved CHDTs, in relation to that opportunity. In such instances, the final decision is mostly based on the input of diverse community members (via their CHDTs), with different objectives and preferences, which are usually in line with their value system.

- b. ***Informed Decision-Making:*** Collaborative discussions and information sharing lead to more informed decisions. Different stakeholders can provide data, analysis, and viewpoints that might otherwise be overlooked, leading to better-rounded and comprehensive choices. For instance, the CEE manager can often make informed decisions based on the data that it collects from its members (CHDTs). This data may include information such as which CHDT is delegated or not, the degree of autonomy for delegated CHDTs, the type of resources available for sharing, etc. These pieces of information help the manager make informed decisions.
- c. ***Risk Management:*** Collaborative decision-making allows for the identification and mitigation of potential risks. When a group is involved in decision-making, it typically brings together individuals with different backgrounds, experiences, and expertise. This diversity of perspectives can help identify and assess risks that might not be apparent to a single decision-maker. By considering a broader range of viewpoints, the group can better anticipate potential pitfalls and challenges. For instance, renewable energy investment cooperatives are cooperatives that are formed by community members who pool their resources to invest in renewable energy projects, such as solar or wind farms. By making investment decisions collectively, community members can share financial risks, making it more accessible for individuals to participate in clean energy initiatives.
- d. ***Balancing Trade-offs:*** Many decisions in renewable energy communities involve trade-offs between economic, environmental, and social factors. Collaboration helps find a balance among these aspects by considering diverse stakeholder interests and values. For example, choosing the location of renewable energy projects can be a trade-off between maximizing energy generation and minimizing environmental impact. Again, communities can strike a balance by conducting thorough environmental impact assessments and selecting sites that minimize harm to ecosystems, wildlife, and local communities while still generating a significant amount of clean energy.
- e. ***Stakeholder Engagement:*** Collaboration engages all relevant stakeholders in the decision-making process. This fosters transparency, accountability, and inclusivity, ensuring that decisions align with the needs and aspirations of the community. For instance, in the CEE, decisions are made in alignment with community goals, which are often the key objectives of the community. Furthermore, aspects of inclusivity are achieved when members are given equal opportunity to participate in community goals or business opportunities via invitations, which leads to coalition formation. In such cases, each stakeholder is given the opportunity to contribute to the overall decision-making and value co-creation process.

- f. **Consensus Building:** Collaborative processes encourage consensus building. When multiple stakeholders are involved in decision-making, the resulting choices are more likely to be accepted and supported by the community. For instance, in community-owned renewable energy projects, building consensus on financial models and ownership structures is essential. This might involve discussions on financing, profit-sharing, and the governance of the community. Consensus building is a typical decision-making process in the CEE. The CEE manager builds consensus by collecting feedback from CHDTs in the community, regarding every specific goal. The principle of “quorum formation” is also mimicked in the CEE using the principle of “minimum threshold” just as is the case in consensus decision-making.
 - g. **Shared Vision and Goals:** Collaborative discussions help align stakeholders around a shared vision and common goals. This shared understanding provides a foundation for making decisions that are consistent with the community's overall objectives. Some examples of shared vision and goals may involve the goal of becoming energy-independent, reducing reliance on fossil fuels and external energy sources. In this example, the community members envision generating and using locally sourced renewable energy, contributing to energy security and self-sufficiency. Again, the community may have a shared goal, such as trying to significantly reduce greenhouse gas emissions within the community. This may include commitments to achieve specific emission reduction targets, aligning with national or global climate agreements, etc. Generally, the CEE concept is based on the core values of “shared vision” or “common goals,” as it has been mentioned severally in the thesis. Membership in the CEE is based on these common or shared interests. Additionally, all collaborative endeavours or business opportunities are driven by these common goals.
 - h. **Flexibility and Adaptation:** Renewable energy communities often face dynamic and evolving challenges. Collaborative decision-making allows for flexibility and adaptation in response to changing circumstances, ensuring that decisions remain relevant and effective. For example, flexible contributions by members’ towards community goals in the CEE can contribute to the management of dynamic and evolving circumstances. Through the concepts of “value system,” “value system compatibility,” and coalition formation, the CEE manager can make quick and informed decisions in response to dynamic situations like demand response etc. Furthermore, resource diversification can help communities diversify and adapt renewable energy sources to include not only solar and wind but also biomass, geothermal, and hydroelectric power, ensuring a more adaptable and reliable energy mix.
3. **Economic Benefits:** If the community generates surplus energy, disagreements might arise regarding how the economic benefits, such as revenue from selling excess energy back to the grid, should be distributed among members.

- a. ***Cost Sharing and Resource Pooling:*** Collaborative efforts allow communities to share the costs of renewable energy infrastructure and resources. By pooling financial resources, communities can collectively invest in larger and more efficient projects, leading to economies of scale. For instance, residents and businesses within a community can co-invest in a common resource, such as energy storage systems like batteries. This pooled resource allows for the efficient storage of excess renewable energy generated during peak periods, reducing the need to rely on the grid during low-production times and resulting in cost reduction.
- b. ***Shared Financing Models:*** Collaborative financing models, such as community solar or crowdfunding campaigns such as Solar Bankers (Solar Bankers, 2018), can enable community members to collectively invest in renewable energy projects. This spreads financial risks and rewards among participants. Some typical examples include green bonds. These are shared financing models in renewable energy communities. In this example, communities, local governments, or renewable energy developers issue green bonds to raise capital for sustainable energy projects. Investors purchase these bonds, and the funds are used for projects like wind farms, energy-efficient buildings, or grid enhancements. Interest is paid to bondholders, and the capital is repaid over time from project revenues. Furthermore, governments and private sector entities can enter into public-private partnerships (PPP) to finance and develop renewable energy projects. These partnerships combine public funds with private investment to support infrastructure development, such as renewable energy facilities or grid enhancements. These financing models can also be applied to the CEE concepts. For instance, the burden of acquiring a centralized storage system, which is capital-intensive, can be eased through the issuance of green bonds or PPP agreements. If bondholders happen to be members of the ecosystem, it may be possible to modify the intelligence of their CHDTs so that they can be used to monitor their investments and related dividend payments and schedules.
- c. ***Partnerships with Industry:*** Collaborating with renewable energy companies, technology providers, and financial institutions can bring expertise and investment capital into the community. These partnerships can help develop and implement projects with a stronger economic impact. For example, communities can partner with electric vehicle charging station companies to install and maintain public charging infrastructure for electric vehicles. These partnerships encourage the adoption of clean transportation. In this sense, the CEE is suggested to involve industry partners such as energy service providers, and distribution service operators. Other relevant partners may include municipalities, the financial sector, and academic and research institutions.
- d. ***Local Job Creation:*** Collaborative renewable energy projects often require various skills and expertise. By involving local contractors, technicians, and

other professionals, communities can create job opportunities and boost the local economy. Some examples include local communities employing solar panel installers and technicians to set up, maintain, and repair solar PV systems on residential, commercial, and community buildings. These jobs include solar technicians, electricians, and roofing professionals. Additionally, communities near wind farms can create jobs in the manufacturing, assembly, and maintenance of wind turbines. Positions may include wind turbine technicians, engineers, and machinists. Relating this to the CEE concept, jobs like IT specialists who are knowledgeable in cloud computing, artificial intelligence, and cyber-physical systems would be needed to help manage the CHDTs and their related digital twin environments. In addition, technicians with knowledge of battery storage systems and PV installation will benefit from the job opportunities that will be created by the CEE.

4. **Inclusion and Equity:** Ensuring that all community members have equal access and benefits from renewable energy initiatives can be challenging. Conflicts may emerge if certain demographics feel marginalized or excluded from participating.
 - a. **Cultural Sensitivity:** Collaboration allows for the incorporation of cultural sensitivities into project design and implementation, avoiding actions that might disproportionately impact certain groups negatively. For instance, ensuring that community members from various cultural backgrounds are actively involved in the decision-making process for renewable energy projects. The need to seek input and feedback to address concerns and incorporate cultural values into project design. Also, indigenous communities usually have sacred sites that need to be respected. Before starting any renewable energy project, it's essential to engage with local indigenous groups, learn about their sacred sites, and adjust project plans to avoid encroachment or disruption. The CEE concepts can help address aspects of cultural sensitivity by way of common interests and open and voluntary participation. In this sense, it is expected that community members who have a common interest, such as protecting their communities and their related cultural values, can have free access to the ecosystem to contribute to decision-making that promotes the protection and sustainability of their communities.
 - b. **Inclusive Planning:** Collaboration allows for the consideration of various socioeconomic backgrounds, cultural perspectives, and needs when planning renewable energy projects. This ensures that solutions are tailored to the specific requirements of different community members. This can be achieved through collaboration with a wide range of stakeholders, including community members, local government officials, environmental organizations, and advocacy groups, to gather diverse perspectives and build consensus. In the area of inclusive planning, the CEE excels in the sense that the CEE manager consults all the CHDTs in the ecosystem for their inputs before finalizing plans or decisions relating to any community goal.

- c. ***Equitable Distribution:*** Collaborative resource allocation strategies can ensure that the benefits of renewable energy, such as reduced energy costs and improved air quality, are distributed equitably among community members, including low-income households. Equitable distribution can be achieved by ensuring that the cost of accessing renewable energy is affordable for all community members, including low-income households. This can be achieved through subsidies, low-cost financing, or community solar programs that allow individuals to benefit from renewable energy without high upfront costs. Equitable distribution is a key feature of the CEE. For instance, in the ecosystem, consumers can benefit from renewable energy that is generated by prosumers. Besides this, consumers can also contribute to value co-creation by engaging in the delegation of their deferrable loads. This simple and voluntary action can earn consumers some revenue or credit to help reduce their energy costs.
- 5. **Local Environmental Concerns:** Depending on the technology and location, there could be concerns about local environmental impacts, such as disruption to wildlife habitats or water usage for hydroelectric projects. These concerns might lead to conflicts among community members.
 - a. ***Holistic Planning:*** Collaborative efforts allow for comprehensive planning that considers not only energy generation but also environmental factors such as habitat preservation, water usage, and land management. For instance, to ensure the long-term success of the project, a holistic plan would include a financial analysis that takes into account initial investment costs, operational and maintenance expenses, potential revenue from energy sales, and the economic benefits to the community. Beyond the financial aspects, holistic planning considers the broader social benefits. This can include improvements in community well-being, reduced air pollution, and increased energy independence, which can positively impact residents' quality of life
 - b. ***Environmental Impact Assessment:*** Collaboration with environmental experts and organizations can lead to thorough environmental impact assessments that identify potential risks and mitigation measures before renewable energy projects are implemented. For instance, in a solar energy project, assessing the impact of land use change, habitat disruption, and potential water usage for cleaning solar panels. Evaluating the impact on local flora and fauna, including measures to protect or relocate endangered species, and analysing the visual impact of solar panels, and addressing concerns from local residents.
 - c. ***Stakeholder Engagement:*** Collaborative approaches engage local communities, environmental advocates, and regulatory bodies in the decision-making process, ensuring that environmental concerns are addressed from the outset. Organizing focus group discussions with representatives from various stakeholder groups, including local residents, environmental organizations,

and businesses, as well as facilitating in-depth conversations to explore specific issues and concerns, are some examples.

6. **External Stakeholders:** Conflicts can also arise when interacting with external stakeholders, such as regulatory agencies, utility companies, and neighbouring communities. Differences in goals and priorities might lead to tensions.
 - a. **Long-Term Relationships:** Collaboration fosters the development of long-term relationships. Resolving conflicts positively can set the stage for future collaboration and cooperation. Building lasting partnerships with local communities, residents, and community organizations to foster trust and cooperation is a good example of long-term relationship. From another perspective, maintaining positive, long-term relationships with landowners who lease their property for renewable energy installations, such as wind turbines or solar panels is another example.
 - b. **Inclusive Problem Solving:** Collaborative problem-solving involves all stakeholders in developing solutions. This inclusivity increases the likelihood of finding solutions that are fair and acceptable to all parties. For instance, utilizing mediation services or third-party facilitators to help resolve conflicts and disputes that may arise between different stakeholders, such as landowners and project developers.
 - c. **Win-Win Solutions:** Collaborative approaches aim to find win-win solutions that balance the interests of the renewable energy community and external stakeholders, minimizing negative impacts and maximizing benefits. Some examples include developing community solar projects that allow local residents and businesses to benefit from renewable energy without the need for rooftop solar panels. This creates a win-win situation by reducing electricity bills for community members while promoting renewable energy adoption.

In summary, the general conclusions that can be drawn from a validation process are usually centred around the assessment of the validity, accuracy, reliability, prospects, and compliance of the artifact under consideration. They guide decision-making depending on the outcome or results and could often be the basis for providing recommendations for improvement to ensure that the subject being validated meets its intended objectives, requirements, and purpose. Some critical decisions that can result from a validation process may involve the decision to proceed with implementation, make changes, or abandon the concept or method altogether. In this particular case, it is recommended that a real-world implementation of the principles, concepts, and methods discussed in this thesis be given critical consideration. This is because, by considering the outcome of all the validation processes, it can be concluded with a good level of certainty that the prospects of CEE and CHDT concepts are relatively high.

CONCLUSIONS AND FUTURE WORK

The conclusion of this research work and final observations on the originality of the study are provided in this chapter. It Includes an overview of the study's main topics and conclusions. It also provides a summary of the completed work, a description of the results obtained, and suggested avenues for further research.

6.1 Overview of the Work

The main research question that this thesis seeks is:

How can the application of collaborative networks principles and mechanisms enhance the response of renewable energy communities (RECs)s?

In this context, the following responses are considered:

-Response to demand and supply dynamics using collaborative energy consumption behaviours.

-Response to challenges in stakeholders' satisfaction and flexible participation in RECs

To address this research question, the design science research method is adopted. An artifact is created using multi-method simulation techniques. The artifact is composed of two complementary models, which include (a) a digital twin replica of a Renewable Energy Community, namely the Collaborative Energy Ecosystem, and (b) a population of digital twin replicas of the households within the CEE environment, namely CHDTs. The CHDTs are modelled to be endowed with cognitive intelligence so that they can make autonomous decisions based on their "value systems," which represent a set of the user's needs, preferences, priorities, objectives, and expectations. CHDTs can be delegated using the notion of "delegated autonomy" to carry out the value system of the user. Based on their cognitive intelligence, CHDTs can make autonomous decisions and engage in collective actions that can result in sustainable energy consumption within the ecosystem.

The creation of the artifact is preceded by a discussion of background knowledge and a comprehensive literature review. The thesis discusses the underlying background concepts

and theories that are borrowed as foundation principles for the thesis. Principles, mechanisms, and knowledge are borrowed from the disciplines of collaborative networks, virtual power plants, renewable energy communities, and digital twin technology to ground the work. The conceptual frameworks of the CEE and CHDT are also highlighted.

The conclusions that can be drawn from the work are that the CEE and CHDT concepts are plausible concepts that can help transform the way RECs approach sustainable energy generation and consumption. In this context, the work has shown that the CEE manager can aggregate resources within the community to be used in support of grid management activities. For instance, deferrable loads (DDL) can be utilized to achieve this purpose. In the CEE ecosystem, the manager could ensure a collective deferral of these loads to ensure that consumption within the ecosystem is significantly minimized. By adopting these concepts, several grid management techniques can be deployed. For instance, a grid management VO can be formed to provide ancillary services, such as helping to shift loads from peak periods to off-peak periods, using the concepts of “delegated autonomy” and “value system” compatibility. Similarly, a VO can be formed with the objective of minimizing consumption from the grid by ensuring that deferrable loads are delegated to make maximum use of renewable energy sources when available. Additionally, the ecosystem could use the VO formation techniques to aggregate and export surplus energy from within the community to the grid, particularly when the ecosystem generates surplus renewable energy. This could be accomplished through a collaboration effort between the CEE manager, a distribution service operator, the energy market, and the CHDTs themselves.

Besides the simulation outcomes as a means of validation, the model is also validated in the research community through peer-reviewed publication and presentation at several international conferences. The final aspect of the validation was conducted using two interest groups. The data from these groups is analysed using the SPS software. The conclusion revealed that the potential users and interest groups unanimously accepted the model as fit for its intended purpose.

6.2 Novel Contributions

The novelty of this work is shown in Figure 6.1 and discussed briefly below.

1. **Background work:** Helped to establish (a) a comprehensive understanding and overview of the current state of research on the subject matter of this thesis, (b) a summary and well-synthesized arguments about existing views, concepts, thoughts, and evidence known to this field of study, and (c) an identification of the major problems that require further investigation on the topic.
2. **Concepts:** A collection of Collaborative Energy Ecosystem, Cognitive Household Digital Twins, and Collaborating Digital Twins related concepts is suggested and defined. By providing a formal definition of these notions, we establish a foundation for the CEE/CHDT concepts and further provide clarification to their meanings. Other

concepts suggested include: CEE Virtual Breeding Environment (CEE VBE), and the CEE Virtual Organization (CEE VO).

3. **Models:** Two major models are proposed, namely: (a) the CEE Model, which is a computer-based software environment that is used to replicate the digital twin of the renewable energy community; (b) is the CHDT, which is also a software model that is used to simulate the intelligent digital twin of households that are located within the CEE environment. The conceptual models are presented using a multimethod simulation approach that integrates system dynamics, agent-based, and discrete event simulation techniques.
4. **Method:** The proposed methods of (a) opportunity seeking by the CEE manager, (b) community goals proposition, (c) individual household value systems, (d) value systems compatibility with community goals, (e) delegation of deferrable loads (DDL), (f) delegate autonomy are the key methods that are adopted to enable the proposed models achieve their goals. Additionally, mechanism like incentives and influence were also tested. The effect of these mechanisms on decision-making was also explored.
5. **Tools:** An artifact constituting a software prototype of the proposed ecosystem was designed to support the implementation and simulation of the proposed CEE and CHDT models and methods in an integrated manner.

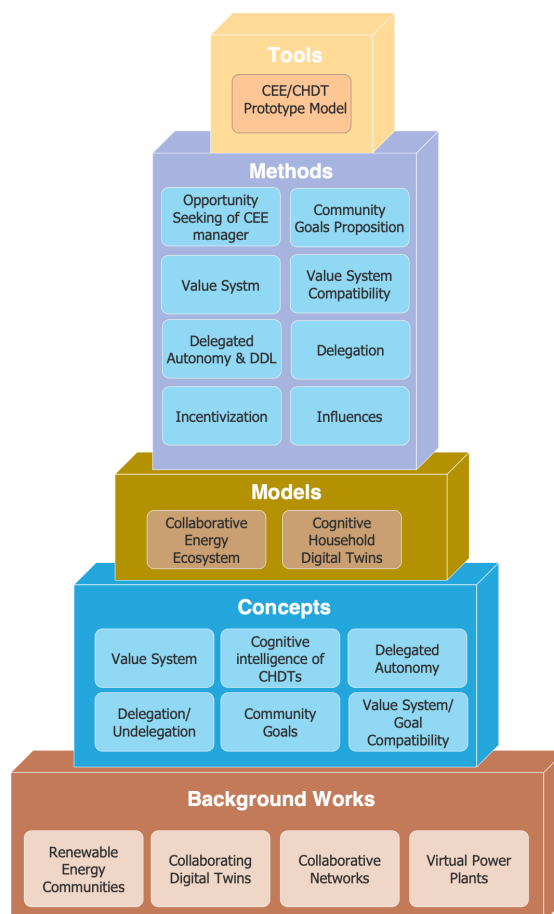


Figure 6.1 — The main contributions of this work.

6.3 Future Work

6.3.1 Real World Implementations:

In the current stage of the work, only simulation-based developments were performed. For a real-world implementation, the following strategy is devised:

1. Identification and Selection of Suitable Sensors and Actuators: Although the market is saturated with many of these devices, some preliminary studies need to be conducted to identify the most suitable and compatible units. Additionally, smart appliances will also be explored to determine how their integrated smart capabilities can be utilized in this sense.
2. Digital Twin Service Provider: The service of a suitable “digital twin as a service provider” needs to be identified, assessed, and procured. This provider may be expected to provide the digital twin environment (DTE) to host the digital twins. Further assessment needs to be carried out to determine if the implementation of intelligent and collaborative algorithms can be supported in their DTEs. Some service providers that have already been identified include: Ansis Twin Builder, Bosch IoT suit, IBMs Digital Twin Builder, and Azure Digital Twins.
3. Other smart home portals that are currently available may also be explored to determine if they could provide DTE services. Some portals that have already been identified include: openHAB, Home Assist, ioBroker, Ago Control, OpenMotics, and Domoticz.
4. After completing the first 3 milestones, thus steps (a), (b), and (c) a prototype CREC constituting a few households could be developed. This prototype can be used for further studies to advance these ideas.

6.3.2 Exploration of Other Collaborative Behaviours

The utility and applicability of the developed notions and mechanisms can be investigated further by considering different scenarios:

1. **Disaster response management:** For example, if a disruptive event or catastrophic failure occurs anywhere in the ecosystem or community, several potential Emergency Virtual Organizations (EVO) can be formed to assist emergency response teams in planning and carrying out necessary disaster response/recovery operations. In such circumstances, CHDTs can provide valuable data regarding the operational state of their physical twin, or in other words, the extent to which the event has affected their corresponding physical counterpart. Such data from CHDTs can be used to assess the impact of the disruptive event and aid in response planning. An ad-hoc emergency virtual organization (EVO) can also be formed in such circumstances to aggregate energy that can be used to support critical infrastructure or parts of the community that are in dire or critical need of energy. Additionally, with their cognitive intelligence and decision-making capabilities, CHDTs can take autonomous decisions, such as

isolating the physical twin from being susceptible to events or failures that have the potential to cascade across an entire community.

2. **Grid agility:** In addition to disaster management, the capabilities of CHDTs to aggregate surplus energy to support the grid will also be investigated in detail. The proposed CEE ecosystem could also be a useful base to explore novel concepts like “antifragility” and how it can help improve the resilience and agility of the power grid.
3. **Value co-creation and reward sharing:** Furthermore, the adoption of other collaborative behaviours such as co-creation of value, estimation of the individual contribution to goal achievement and value creation, sharing of rewards, and conflict resolution in such an ecosystem would be explored further. In future studies, data about the thermal comfort of rooms or the living environment in households may also be useful for CHDTs in their decision-making, particularly concerning the regulation of temperature in the living environment.

Bibliography

- Achuo, E. D., Wendji, C., & Nchofoung, T. N. (2022). Energy consumption and environmental sustainability: What lessons for posterity? *Energy Reports*, 8(October), 12491–12502. <https://doi.org/https://doi.org/10.1016/j.egy.2022.09.033>
- Adamopoulos, A., Davey, B., Bruno, V., & Dick, M. (2019). Blockchain Collaborative Network Development Framework. *SSRN Electronic Journal*, March 2021. <https://doi.org/10.2139/ssrn.3677671>
- Adly, B., & El-Khouly, T. (2022). Combining retrofitting techniques, renewable energy resources and regulations for residential buildings to achieve energy efficiency in gated communities. *Ain Shams Engineering Journal*, 13(6), 101772. <https://doi.org/10.1016/j.asej.2022.101772>
- Adu-Kankam, K. O., & Camarinha-Matos, L. M. (2022). Renewable Energy Communities or Ecosystems: An Analysis of Selected Cases. *SSRN Electronic Journal*, 8(July 2022). <https://doi.org/10.2139/ssrn.4112124>
- Adu-Kankam, K. O., & Camarinha-Matos, L. M. (2018). Towards collaborative Virtual Power Plants: Trends and convergence. *Sustainable Energy, Grids and Networks*, 16, 217–230. <https://doi.org/10.1016/j.segan.2018.08.003>
- Adu-Kankam, K. O., & Camarinha-Matos, L. M. (2022a). A Framework for the Integration of IoT Components into the Household Digital Twins for Energy Communities. In L. Camarinha-Matos, L.M., Ribeiro, L., Strous (Ed.), *IFIP Advances in Information and Communication Technology: Vol. 665 IFIP* (pp. 197–216). Springer, chem. https://doi.org/10.1007/978-3-031-18872-5_12
- Adu-Kankam, K. O., & Camarinha-Matos, L. M. (2022b). Modelling “Delegated Autonomy” in Cognitive Household Digital Twins. *2022 11th International Conference on Renewable Energy Research and Application (ICRERA)*, 192–199. <https://doi.org/10.1109/ICRERA55966.2022.9922673>
- Afsarmanesh, H., & Camarinha-matos, L. M. (2005). A Framework for Management of Virtual Organization Breeding Environments. *working conference on virtual enterprises, PRO-VE 2005*, 35–48.
- Ahmad, F., Adnane, A., Franqueira, V., Kurugollu, F., & Liu, L. (2018). Man-In-The-Middle Attacks in Vehicular Ad-Hoc Networks: Evaluating the Impact of Attackers’ Strategies. *Sensors*, 18(11), 4040. <https://doi.org/10.3390/s18114040>
- Ahmadian, A., Ponnambalam, K., Almansoori, A., & Elkamel, A. (2023). Optimal Management of a Virtual Power Plant Consisting of Renewable Energy Resources and Electric Vehicles Using Mixed-Integer Linear Programming and Deep Learning. *Energies*, 16(2), 1000. <https://doi.org/10.3390/en16021000>
- AI and the tech behind the Virtual Power Plant*. (2021). Origin. <https://www.originenergy.com.au/blog/virtual-power-plant/>
- Algarvio, H. (2021). The Role of Local Citizen Energy Communities in the Road to Carbon-Neutral Power Systems: Outcomes from a Case Study in Portugal. *Smart Cities*, 4(2), 840–863. <https://doi.org/10.3390/smartcities4020043>
- Al-Mamary, Y. H. S. (2022). Understanding the use of learning management systems by undergraduate university students using the UTAUT model: Credible evidence from Saudi Arabia. *International Journal of Information Management Data Insights*, 2(2), 100092. <https://doi.org/10.1016/j.ijime.2022.100092>
- Alonso, M., Turanzas, J., Amaris, H., & Ledo, A. T. (2021). Cyber-physical vulnerability assessment in smart grids based on multilayer complex networks. *Sensors*, 21(17). <https://doi.org/10.3390/s21175826>
- An, L., Grimm, V., Bai, Y., Sullivan, A., Turner, B. L., Malleson, N., Heppenstall, A., Vincenot, C., Robinson, D., Ye, X., Liu, J., Lindkvist, E., & Tang, W. (2023). Modeling agent decision and behavior in the light of data science and artificial intelligence. *Environmental Modelling & Software*, 166(May 2022), 105713. <https://doi.org/10.1016/j.envsoft.2023.105713>

- Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., McCallum, P., & Peacock, A. (2019). Blockchain technology in the energy sector: A systematic review of challenges and opportunities. In *Renewable and Sustainable Energy Reviews* (Vol. 100, pp. 143–174). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2018.10.014>
- Andrews, J. E., Ward, H., & Yoon, J. W. (2021). UTAUT as a Model for Understanding Intention to Adopt AI and Related Technologies among Librarians. *Journal of Academic Librarianship*, 47(6), 102437. <https://doi.org/10.1016/j.acalib.2021.102437>
- Anylogic (2018). *Multimethod Simulation Modelling for Business Applications – AnyLogic Simulation Software*. White Paper. Retrieved February 10, 2023, from <https://www.anylogic.com/resources/white-papers/multimethod-simulation-modeling-for-business-applications/>
- AnyLogic Simulation Software. (2017). *AnyLogic: Simulation Modelling Software Tools & Solutions for Business*. <https://www.anylogic.com/>
- Astarloa, B., Anas Kaakeh, Lombardi, M., & Joseph Scalise. (2017). *The Future of Electricity: New Technologies Transforming the Grid Edge*. World Economic Forum. http://www3.weforum.org/docs/WEF_Future_of_Electricity_2017.pdf
- Aversa, P., Donatelli, A., Piccoli, G., & Luprano, V. A. M. (2016). Improved Thermal Transmittance Measurement with HFM Technique on Building Envelopes in the Mediterranean Area. *Selected Scientific Papers - Journal of Civil Engineering*, 11(2), 39–52. <https://doi.org/10.1515/sspjce-2016-0017>
- Axon, S. (2020). The socio-cultural dimensions of community-based sustainability: Implications for transformational change. *Journal of Cleaner Production*, 266, 121933. <https://doi.org/10.1016/j.jclepro.2020.121933>
- Aydeger, A., Akkaya, K., Cintuglu, M. H., Uluagac, A. S., & Mohammed, O. (2016). Software Defined Networking for Resilient Communications in Smart Grid Active Distribution Networks. *2016 IEEE International Conference on Communications (ICC)*, 1–6. <https://doi.org/10.1109/ICC.2016.7511049>
- Baeyens, E., Bitar, E. Y., Khargonekar, P. P., & Poolla, K. (2011). Wind energy aggregation: A coalitional game approach. *Proceedings of 50th IEEE Conference on Decision and Control and European Control Conference*, 3000–3007. <https://doi.org/10.1109/CDC.2011.6160785>
- Bahloul, M., Breathnach, L., Cotter, J., Daoud, M., Saif, A., & Khadem, S. (2022). Role of Aggregator in Coordinating Residential Virtual Power Plant in “StoreNet”: A Pilot Project Case Study. *IEEE Transactions on Sustainable Energy*, 13(4), 2148–2158. <https://doi.org/10.1109/TSTE.2022.3187217>
- Bakari, K. E., & Kling, W. L. (2012). Fitting distributed generation in future power markets through virtual power plants. *2012 9th International Conference on the European Energy Market*, 1–7. <https://doi.org/10.1109/eem.2012.6254692>
- Baldini, G. (2022). Detection of cybersecurity spoofing attacks in vehicular networks with recurrence quantification analysis. *Computer Communications*, 191(April), 486–499. <https://doi.org/https://doi.org/10.1016/j.comcom.2022.05.021>
- Bannavikarn, S., & Hoonchareon, N. (2021). Solar Power Aggregation Framework for Virtual Power Plant’s Energy Trading. *2021 International Conference on Power, Energy and Innovations (ICPEI)*, 45–48. <https://doi.org/10.1109/ICPEI52436.2021.9690673>
- Bao, Y., Cheng, X., Pi, J., Zhang, Y., Hou, C., & Guo, Y. (2021). Selection Strategy of Virtual Power Plant Members Considering Power Grid Security and Economics of Virtual Power Plant. *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*, 1314–1319. <https://doi.org/10.1109/EI252483.2021.9713381>
- Barbiroglio, E. (2022). *Energy communities bring renewable power to the people | Research and Innovation*. Horizon: The EU Research and Innovation Magazine. <https://ec.europa.eu/research-and-innovation/en/horizon-magazine/energy-communities-bring-renewable-power-people>
- Behi, B., Arefi, A., Jennings, P., Gorjy, A., & Pivrikas, A. (2021). Advanced Monitoring and Control System for Virtual Power Plants for Enabling Customer Engagement and Market Participation. *Energies*, 14(4), 1113. <https://doi.org/10.3390/en14041113>

- Belmar, F., Baptista, P., & Neves, D. (2023). Modelling renewable energy communities: assessing the impact of different configurations, technologies and types of participants. *Energy, Sustainability and Society*, 13(1), 18. <https://doi.org/10.1186/s13705-023-00397-1>
- Ben Arfi, W., Ben Nasr, I., Khvatova, T., & Ben Zaied, Y. (2021). Understanding acceptance of eHealthcare by IoT natives and IoT immigrants: An integrated model of UTAUT, perceived risk, and financial cost. In *Technological Forecasting and Social Change* (Vol. 163). <https://doi.org/10.1016/j.techfore.2020.120437>
- Bianca, A. (2019). *How Does a Common Goal in an Organization Help Employees Shape Culture?* <https://yourbusiness.azcentral.com/common-goal-organization-employees-shape-culture-3311.html>
- Bianchi, S., De Filippo, A., Magnani, S., Mosaico, G., & Silvestro, F. (2021). VIRTUS Project: A Scalable Aggregation Platform for the Intelligent Virtual Management of Distributed Energy Resources. *Energies*, 14(12), 3663. <https://doi.org/10.3390/en14123663>
- Biswas, S., Bagchi, D., & Narahari, Y. (2014). Mechanism Design for Sustainable Virtual Power Plant Formation. *IEEE International Conference on Automation Science and Engineering*, 67–72. <https://doi.org/10.1109/CoASE.2014.6899306>
- BittWatt. (2018). BittWatt Whitepaper. In *Whitepaper Version 1.0* (pp. 1–31).
- Blok, K., & Cihlar, J. (2018). *Energy cloud 4.0: Capturing Business Value Through Disruptive Energy Platforms*. Guidehouse. <https://guidehouse.com/-/media/www/site/insights/energy/2018/energy-cloud-4-capturing-business-value.pdf>
- Bloomberg. (2022). *European Energy Bills Hit Record Despite Government Support - Bloomberg*. https://www.bloomberg.com/news/articles/2022-11-07/european-energy-bills-hit-record-despite-government-support?in_source=embedded-checkout-banner
- Borshchev, A. (2013). *Multi-method Modeling* (R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill, & M. E. Kuhl, Eds.). Proceedings of the 2013 Winter Simulation Conference. <https://informatics.org/wsc13papers/includes/files/410.pdf>
- Borshchev, A., & Filippov, A. (2004). From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. *22nd International Conference of the System Dynamics Society*, 66(11), 1–23.
- Bose, A., & Overbye, T. J. (2021). *Electricity Transmission System Research and Development: Grid Operations* (Issue April).
- Botsis, V., Doulamis, N., Doulamis, A., Makris, P., & Varvarigos, E. (2015). Efficient clustering of DERs in a virtual association for profit optimization. *Proceedings - 18th Euromicro Conference on Digital System Design, DSD*, 494–501. <https://doi.org/10.1109/DSD.2015.47>
- BPA. (2023). *Bui Power Authority*. <https://buipower.com/>
- Brailsford, S. C., Eldabi, T., Kunc, M., Mustafee, N., & Osorio, A. F. (2019). Hybrid simulation modelling in operational research: A state-of-the-art review. *European Journal of Operational Research*, 278(3), 721–737. <https://doi.org/10.1016/j.ejor.2018.10.025>
- Brock, S. (2018). *Can Grid+ Disintermediate Utilities?* Stina.Io. <https://www.stina.io/blog/2018/01/can-grid-actually-disrupt-energy.html>
- Bronski, P., Creyts, J., Gao, S., Hambridge, S., Hartnett, S., Hesse, E., Morris, J., Nanavatty, R., & Pennington, N. (2018). *The Decentralized Autonomous Area Agent (D3A) Market Model*. <https://www.energyweb.org/insights/reports/>
- Buterin, V. (2015). *On public and private blockchains (2015)*. Ethereum Blog Crypto Renaissance Salon. <https://blog.ethereum.org/2015/08/07/on-public-and-private-blockchains/>
- Cai, M., Hu, S., Wang, Y., & Xiao, J. (2022). A Dynamic Social Network Matching Model for Virtual Power Plants and Distributed Energy Resources with Probabilistic Linguistic Information. *Sustainability*, 14(22), 14920. <https://doi.org/10.3390/su142214920>
- Calvo-Bascones, P., Voisin, A., Do Van, P., & Sanz-Bobi, M. A. (2022). A collaborative network of digital twins for anomaly detection applications of complex systems. Snitch Digital Twin concept. *Computers in Industry*, 144, 103767. <https://doi.org/10.1016/j.compind.2022.103767>
- Camarinha-Matos, L. M. (2009). Collaborative networked organizations: Status and trends in manufacturing. *Annual Reviews in Control*, 33(2), 199–208. <https://doi.org/10.1016/j.arcontrol.2009.05.006>

- Camarinha-Matos, L. M. (2016). Collaborative smart grids – A survey on trends. *Renewable and Sustainable Energy Reviews*, 65, 283–294. <https://doi.org/https://doi.org/10.1016/j.rser.2016.06.093>
- Camarinha-Matos, L. M., & Afsarmanesh, H. (2005). Collaborative Networks: a new scientific discipline. *Journal of Intelligent Manufacturing*, 16(4-5), 439–452. <https://doi.org/10.1007/s10845-005-1656-3>
- Camarinha-Matos, L. M., & Afsarmanesh, H. (2008). *Collaborative Networks: Reference Modeling* (L. M. Camarinha-Matos and H. Afsarmanesh, Ed.; pp. 1–334). Springer Science+Business Media, LLC.
- Camarinha-Matos, L. M., & Afsarmanesh, H. (2021a). The Evolution Path to Collaborative Networks 4.0. In *IFIP Advances in Information and Communication Technology* (Vol. 600, pp. 170–193). Springer, Cham. https://doi.org/10.1007/978-3-030-81701-5_7
- Camarinha-Matos, L. M., & Afsarmanesh, H. (2021b). The Evolution Path to Collaborative Networks 4.0. In *IFIP Advances in Information and Communication Technology* (Vol. 600, pp. 170–193). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-030-81701-5_7
- Camarinha-Matos, L. M., Afsarmanesh, H., Galeano, N., & Molina, A. (2009). Collaborative networked organizations – Concepts and practice in manufacturing enterprises. *Computers & Industrial Engineering*, 57(1), 46–60. <https://doi.org/10.1016/j.cie.2008.11.024>
- Camarinha-Matos, L. M., Afsarmanesh, H., & Ollus, M. (2005). Ecolead: A holistic approach to creation and management of dynamic virtual organizations. *Sixth IFIP Working Collaborative Networks and Their Breeding Environments*, 3–16.
- Camarinha-Matos, L. M., Fornasiero, R., & Afsarmanesh, H. (2017). Collaborative Networks as a Core Enabler of Industry 4.0. In L. M. Camarinha-Matos, H. Afsarmanesh, & R. Fornasiero (Eds.), *18th IFIP WG 5.5 Working Conference on Virtual Enterprises, PRO-VE 2017* (Vol. 506, pp. 3–17). https://doi.org/10.1007/978-3-319-65151-4_1
- Camarinha-Matos, L. M., Oliveira, A. I., Ferrada, F., & Thamburaj, V. (2017). Collaborative services provision for solar power plants. *Industrial Management and Data Systems*, 117(5), 946–966. <https://doi.org/10.1108/IMDS-06-2016-0246>
- Camarinha-Matos, L. M., Ortiz, A., Boucher, X., & Osório, A. L. (2022). Collaborative Networks in Digitalization and Society 5.0: Proceedings of PRO-VE 2022. In L. M. Camarinha-Matos, A. Ortiz, X. Boucher, & A. L. Osório (Eds.), *IFIP Advances in Information and Communication Technology* (Vol. 662). Springer International Publishing. <https://doi.org/10.1007/978-3-031-14844-6>
- Cao, L., Hu, P., Li, X., Sun, H., Zhang, J., & Zhang, C. (2023). Digital technologies for net-zero energy transition: a preliminary study. *Carbon Neutrality*, 2(1), 7. <https://doi.org/10.1007/s43979-023-00047-7>
- Capodiecì, N., & Cabri, G. (2013). Managing deregulated energy markets: An adaptive and autonomous multi-agent system application. *SMC '13 Proceedings of the 2013 IEEE International Conference on Systems, Man, and Cybernetics*, 758–763. <https://doi.org/10.1109/SMC.2013.134>
- Carrera-Rivera, A., Ochoa, W., Larrinaga, F., & Lasa, G. (2022). How-to conduct a systematic literature review: A quick guide for computer science research. *MethodsX*, 9, 101895. <https://doi.org/10.1016/j.mex.2022.101895>
- Carstensen, A.-K., & Bernhard, J. (2019). Design science research – a powerful tool for improving methods in engineering education research. *European Journal of Engineering Education*, 44(1–2), 85–102. <https://doi.org/10.1080/03043797.2018.1498459>
- Carvalho, J. A. (2012). *Validation Criteria for the Outcomes of Design Research*. IT Artefact Design & Workpractice Intervention, a Pre-ECIS and AIS SIG Prag Workshop. <https://repositorium.sdum.uminho.pt/bitstream/1822/21713/1/ITADWlarticleJACvf r.pdf>
- Causam-eXchange. (2018). Catalyzing a Cleaner Power Grid, One Financial Transaction at a Time. In *whitepaper* (pp. 1–45).

- Chantrel, S. P. M., Surmann, A., Erge, T., & Thomsen, J. (2021). Participative Renewable Energy Community—How Blockchain-Based Governance Enables a German Interpretation of RED II. *Electricity*, 2(4), 471–486. <https://doi.org/10.3390/electricity2040028>
- Chen., Liu, Y., He, Y., Pei, X., & Li, J. (2018). A Comprehensive Valuation of Virtual Power Plant in Multiple Electricity Markets. *2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2)*, 1–6. <https://doi.org/10.1109/EI2.2018.8582575>
- Chen, W., Lakshmanan, L. V. S., & Castillo, C. (2013). Information and Influence Propagation in Social Networks. In M. T. Özsu (Ed.), *Synthesis Lectures on Data Management* (Vol. 5, Issue 4, pp. 1–177). Morgan & Claypool Publishers series. <https://doi.org/10.2200/S00527ED1V01Y201308DTM037>
- Chigbu, U. E., Atiku, S. O., & Du Plessis, C. C. (2023). The Science of Literature Reviews: Searching, Identifying, Selecting, and Synthesising. *Publications*, 11(1), 2. <https://doi.org/10.3390/publications11010002>
- Choi, B. K., & Kang, D. (Eds.). (2013). *Modeling and Simulation of Discrete-Event Systems*. John Wiley & Sons, Inc. <https://doi.org/10.1002/9781118732793>
- Cicceri, G., Tricomi, G., D'Agati, L., Longo, F., Merlino, G., & Puliafito, A. (2023). A Deep Learning-Driven Self-Conscious Distributed Cyber-Physical System for Renewable Energy Communities. *Sensors*, 23(9), 4549. <https://doi.org/10.3390/s23094549>
- Cleantechnica. (2017). *Energo Labs: Building a Decentralized Autonomous Energy Community*. <https://cleantechnica.com/2017/07/03/energo-labs-building-decentralized-autonomous-energy-community/>
- Cobigo, V., Martin, L., & Mcheimech, R. (2016). Understanding Community. *Canadian Journal of Disability Studies*, 5(4), 181. <https://doi.org/10.15353/cjds.v5i4.318>
- Committee on Industry Research and Energy (ITRE). (2017). Energy Poverty - Study for the ITRE Committee. *European Parliament*, PE 607.350, 1–58.
- Consensys. (2017). GridPlus: Welcome to the future of energy. In *Grid+ Whitepaper version 2.0* (pp. 1–65). <https://cryptorating.eu/whitepapers/Grid+/Gridwhitepaper.pdf>
- ConsenSys. (2022). *Blockchain in the Energy Sector | Real World Blockchain Use Cases | ConsenSys*. <https://consensys.net/blockchain-use-cases/energy-and-sustainability/>
- Conte, F., D'Antoni, F., Natrella, G., & Merone, M. (2022). A new hybrid AI optimal management method for renewable energy communities. *Energy and AI*, 10, 100197. <https://doi.org/10.1016/j.egyai.2022.100197>
- Cosic, A., Stadler, M., Mansoor, M., & Zellinger, M. (2021). Mixed-integer linear programming based optimization strategies for renewable energy communities. *Energy*, 237, 121559. <https://doi.org/10.1016/j.energy.2021.121559>
- Cuenca, J. J., Daly, H. E., & Hayes, B. P. (2023). Sharing the grid: The key to equitable access for small-scale energy generation. *Applied Energy*, 349(July), 121641. <https://doi.org/10.1016/j.apenergy.2023.121641>
- Daftlogic, (2018), List of the Power Consumption of Typical Household Appliances. <https://www.daftlogic.com/information-appliance-power-consumption.htm>
- Danish, M. S. S., & Senjyu, T. (2023). Shaping the future of sustainable energy through AI-enabled circular economy policies. *Circular Economy*, 2(2), 100040. <https://doi.org/10.1016/j.cec.2023.100040>
- Daryan, A. G., Sheikhi, A., & Zadeh, A. A. (2022). Peer-to-Peer Energy sharing Among Smart Energy Hubs in an integrated Heat-Electricity Network. *Electric Power Systems Research*, 206(February), 107726. <https://doi.org/10.1016/j.epsr.2021.107726>
- Das, A., Peu, S. D., Akanda, M. A. M., & Islam, A. R. M. T. (2023). Peer-to-Peer Energy Trading Pricing Mechanisms: Towards a Comprehensive Analysis of Energy and Network Service Pricing (NSP) Mechanisms to Get Sustainable Enviro-Economical Energy Sector. *Energies*, 16(5), 2198. <https://doi.org/10.3390/en16052198>
- De, K., & Badar, A. Q. H. (2022). Virtual Power Plant Profit Maximization in Day Ahead Market using Different Evolutionary Optimization Techniques. *2022 4th International Conference on Energy, Power and Environment (ICEPE)*, 1–6. <https://doi.org/10.1109/ICEPE55035.2022.9797939>
- Delbeke, J., & Vis, P. (2019). *Towards a Climate-Neutral Europe* (J. Delbeke & P. Vis, Eds.). Routledge. <https://doi.org/10.4324/9789276082569>

- Dethlefs, T., Preisler, T., Renz, W., Hamburg, H. A. W., & Tor, B. (2015). A DER Registry System as an Infrastructural Component for future Smart Grid Applications. *International ETG Congress, Die Energiewende - Blueprints for the New Energy Age; Proceedings Of*, 93–99.
- Digital Substation. (2018). *WePower to Tokenise Estonia's Energy Grid*. <http://digitalsubstation.com/en/2018/10/31/wepower-to-tokenise-estonia-s-energy-grid/>
- Dobravec, V., Matak, N., Sakulin, C., & Krajačić, G. (2021). Multilevel governance energy planning and policy: a view on local energy initiatives. *Energy, Sustainability and Society*, 11(2), 1–17, DOI:<https://doi.org/10.1186/s13705-020-00277>. <https://doi.org/10.1186/s13705-020-00277-y>
- Donaghy, T., & Jiang, C. (2021). Fossil Fuel Racism: How Phasing Out Oil, Gas, and Coal Can Protect Communities. In *Greenpeace* (pp. 1–46). <https://empowerourfuture.org/fossil-fuel-racism-how-phasing-out-oil-gas-and-coal-can-protect-communities/>
- Doroudchi, E., Khajeh, H., & Laaksonen, H. (2022). Increasing Self-Sufficiency of Energy Community by Common Thermal Energy Storage. *IEEE Access*, 10, 85106–85113. <https://doi.org/10.1109/ACCESS.2022.3195242>
- Dragomir, O. E., & Dragomir, F. (2023). Application of Scheduling Techniques for Load-Shifting in Smart Homes with Renewable-Energy-Sources Integration. *Buildings*, 13(1), 134. <https://doi.org/10.3390/buildings13010134>
- Dumitrașcu, D.-G., Coroiu, M., Tărău, R., & Covaci, R. (2023). Smart Energy Communities - A Backbone for the Internet of Energy. *2023 10th International Conference on Modern Power Systems (MPS)*, 01–06. <https://doi.org/10.1109/MPS58874.2023.10187537>
- ECG Ghana. (2022). *Electricity Company of Ghana Ltd*. <https://ecg.com.gh/index.php/en/>
- Economics Online. (2020). *Definition of the division of labour -Economics Online*. [https://www.economicsonline.co.uk/Definitions/Division_of_labour.html#:~:text=The division of labour is the positive effects of specialisation.](https://www.economicsonline.co.uk/Definitions/Division_of_labour.html#:~:text=The%20division%20of%20labour%20is%20the%20positive%20effects%20of%20specialisation.)
- Egbue, O., Naidu, D., & Peterson, P. (2016). The Role of Microgrids in Enhancing Macrogrid Resilience. *2016 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)*, 125–129. <https://doi.org/10.1109/ICSGCE.2016.7876038>
- El Bakari, K., & Kling, W. L. (2011). Development and operation of virtual power plant system. *Innovative Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition On*, 1–5. <https://doi.org/10.1109/ISGTEurope.2011.6162710>
- El Bakari, K., Myrzik, J. M. A., & Kling, W. L. (2009). Prospects of a virtual power plant to control a cluster of distributed generation and renewable energy sources. *Proceedings of the Universities Power Engineering Conference, September 2014*.
- Electrify-Network. (2018). *Electrify Network: Bright Side of Power*. Whitepaper Rev 3.8.
- Electron. (2018). *Electron | Blockchain Systems for The Energy Sector*. Whitepaper. <http://www.electron.org.uk/index.html#top>
- EnergiMine. (2018). EnergiMine White paper version 5.0: Decentralizing global energy markets by rewarding energy efficient behaviour. In *whitepaper* (Issue 5.0).
- Energy Web. (2022). *Energy Web Foundation. Energy web foundation*. <https://www.energyweb.org/>. <https://energyweb.org/>
- Enose, N. (2014). Implementing an integrated security management framework to ensure a secure smart grid. *Proceedings of the 2014 International Conference on Advances in Computing, Communications and Informatics, ICACCI*, 778–784. <https://doi.org/10.1109/ICACCI.2014.6968521>
- Enosi. (2018). *A Distributed Energy Protocol: Connecting and automating energy markets with distributed ledger technology*. (pp. 1–37). <https://enosi.io/images/file/whitepaper.pdf>
- Erjavec, J., & Manfreda, A. (2022). Online shopping adoption during COVID-19 and social isolation: Extending the UTAUT model with herd behavior. *Journal of Retailing and Consumer Services*, 65(December 2021), 102867. <https://doi.org/10.1016/j.jretconser.2021.102867>
- Etainpower. (2017). A Blockchain-based Energy Ecosystem Powered by AI. In *whitepaper version 1.0.0* (pp. 1–64). <https://medium.com/@mutiarafarma82/etain-power-a-blockchain-based-energy-ecosystem-powered-by-ai-45ec1cafe7f7>

- Ethereum. (2023). *The History of Ethereum: Its Origin and Upgrades*. <https://worldcoin.org/articles/history-of-ethereum>
- European Commission. (2019). *Energy performance of buildings directive*. https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en
- European Commission. (2021). *State of the Energy Union 2021 – Contributing to the European Green Deal and the Union's recovery*. European Commission. <https://iea.blob.core.windows.net/assets/beceb956-0dcf-4d73-89fe-1310e3046d68/NetZeroby2050->
- European Council of the European Union. (2023). *Energy price rise since 2021*. <https://www.consilium.europa.eu/en/infographics/energy-prices-2021/>
- European Parliament. (2018). Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018. *Official Journal of the European Union*, 328(1), 1–77. <https://doi.org/https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1999&from=EN>
- European Parliament, & Council of the European Union. (2019). *Directive (EU) 2019/944 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU*. Official Journal of the European Union. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944>
- European Union. (2019). *Directive (eu) 2019/ 944 of the European Parliament and of the Council - of 5 June 2019 - on Common Rules for the Internal Market for Electricity and Amending Directive 2012/ 27/ EU*. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944>
- Fan, X., Zhang, L., Sun, H., Hu, S., Sun, C., & Zhu, B. (2022). The Day-Ahead Bidding Strategy of Virtual Power Plant for Participating in Electric Energy Market and Peak Regulation Market. *2022 4th Asia Energy and Electrical Engineering Symposium (AEEES)*, 242–247. <https://doi.org/10.1109/AEEES54426.2022.9759804>
- Farag, M. M., Azab, M., & Mokhtar, B. (2014). Cross-layer security framework for smart grid: Physical security layer. In IEEE (Ed.), *IEEE PES Innovative Smart Grid Technologies, Europe* (pp. 1–7). <https://doi.org/10.1109/ISGTEurope.2014.7028963>
- Farhangi, H. (2010). *The Path of the Smart Grid*. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=5357331&casa_token=sh9KQMWYfigAAAAA:zy8OTXQLsHADuspITG3yOk9wokzewV8hgkCZQuo8Jz0S2hPIQpzWHeQVYG_ADRS5jvWvlk44hX0&tag=1
- Faria, P., Spinola, J., & Vale, Z. (2016). Aggregation and Remuneration of Electricity Consumers and Producers for the Definition of Demand-Response Programs. *IEEE Transactions on Industrial Informatics*, 12(3), 952–961. <https://doi.org/10.1109/TII.2016.2541542>
- Feldman, D., Ramasamy, V., Fu, R., Ramdas, A., Desai, J., & Margolis, R. (2021). *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020*. National Renewable Energy Laboratory. <https://www.nrel.gov/research/publications.html>
- Ferrada, & Camarinha-Matos. (2019). Simulation Model to Estimate Emotions in Collaborative Networks. *Applied Sciences*, 9(23), 5202. <https://doi.org/10.3390/app9235202>
- Figgenger, J., Stenzel, P., Kairies, K. P., Linßen, J., Haberschusz, D., Wessels, O., Robinius, M., Stolten, D., & Sauer, D. U. (2021). The development of stationary battery storage systems in Germany – status 2020. *Journal of Energy Storage*, 33(101982), 1–14, DOI:<https://doi.org/10.1016/j.est.2020.101982>
- Gährs, S., & Knoefel, J. (2020). Stakeholder demands and regulatory framework for community energy storage with a focus on Germany. *Energy Policy*, 144(111678), 1–11, DOI:<https://doi.org/10.1016/j.enpol.2020.111678>
- Gan, H., Zhang, J., Wang, J., Hou, D., Jiang, Y., & Gao, D. W. (2021). Cyber Physical Grid-Interactive Distributed Energy Resources Control for VPP Dispatch and Regulation. *2021*

- IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, 1–5. <https://doi.org/10.1109/ISGTEurope52324.2021.9640131>
- Gandiglio, M., Marocco, P., Bianco, I., Lovera, D., Blengini, G. A., & Santarelli, M. (2022). Life cycle assessment of a renewable energy system with hydrogen-battery storage for a remote off-grid community. *International Journal of Hydrogen Energy*, 47(77), 32822–32834. <https://doi.org/10.1016/j.ijhydene.2022.07.199>
- Gao, X., Li, X., & Yang, X. (2021). Robustness assessment of the cyber-physical system against cascading failure in a virtual power plant based on complex network theory. *International Transactions on Electrical Energy Systems*, 31(11), e13039. <https://doi.org/10.1002/2050-7038.13039>
- Geysler, W. (2022). *What is an Influencer? - Social Media Influencers Defined*. Influencer Marketing Hub. <https://influencermarketinghub.com/what-is-an-influencer/>
- Giordano, A., Mastroianni, C., & Scarcello, L. (2020). Optimization Model for IoT-Aware Energy Exchange in Energy Communities for Residential Users. *Electronics*, 9(6), 1003. <https://doi.org/10.3390/electronics9061003>
- Gohn, B., & Wheelock, C. (2010). *Smart Grid: Ten Trends to Watch in 2011 and Beyond*. Pike Research. <https://www.pikeresearch.com/wordpress/wp-content/uploads/2010/10/SG10T-10-Pike-Research.pdf>
- Gov.uk. (2015). *Community Energy - GOV.UK*. GOV UK. <https://www.gov.uk/guidance/community-energy>
- Graça, P., & Camarinha-Matos, L. M. (2021). Assessment of Sustainable Collaboration in Collaborative Business Ecosystems. *Computers*, 10(12). <https://doi.org/10.3390/computers10120167>
- Greeneum. (2018). Greeneum network green paper. In *Whitepaper* (pp. 1–48). <https://www.greeneum.net/greeneum-blog-media-overview/2017/11/10/greeneum-whitepaper-released>
- GridLAB. (2023). *GridLAB-D Simulation Software*. <https://www.gridlabd.org/>
- GridX. (2017). *GridX*. Company Profile. <https://www.gridx.com/>
- Gross, C., Siepermann, M., & Lackes, R. (2020). The Acceptance of Smart Home Technology. In *Lecture Notes in Business Information Processing: Vol. 398 LNBIIP* (pp. 3–18). https://doi.org/10.1007/978-3-030-61140-8_1
- Gunal, M. M. (2012). A guide for building hospital simulation models. *Health Systems*, 1(1), 17–25. <https://doi.org/10.1057/hs.2012.8>
- Guo, X., Liang, C., Umar, M., & Mirza, N. (2022). The impact of fossil fuel divestments and energy transitions on mutual funds performance. *Technological Forecasting and Social Change*, 176(December 2021), 121429. <https://doi.org/10.1016/j.techfore.2021.121429>
- Gupta, M. (2020). *Blockchain for dummies* (3rd ed.). John Wiley & Son, Inc.
- Hanke, F., Guyet, R., & Feenstra, M. (2021). Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases. *Energy Research & Social Science*, 80(August), 102244. <https://doi.org/10.1016/j.erss.2021.102244>
- Hansen, A. H., Jensen, R. H., Stausgaard Jensen, L., Guldager, E. K., Sigsgaard, A. W., Moroder, F., Raptis, D., Siksnyys, L., Pedersen, T., & Skov, M. B. (2020). Lumen: A Case Study of Designing for Sustainable Energy Communities through Ambient Feedback. *32nd Australian Conference on Human-Computer Interaction*, 724–729. <https://doi.org/10.1145/3441000.3441001>
- Harbo, S., Nault, A., & Rhee, A. (2016). *Community - Based Resource Sharing in Southeastern Michigan*. <https://graham.umich.edu/media/files/dow/Dow-Masters-2015-Sharing-Communities.pdf>
- Hargroves, K., James, B., Lane, J., & Newman, P. (2023). The Role of Distributed Energy Resources and Associated Business Models in the Decentralised Energy Transition: A Review. *Energies*, 16(10), 4231. <https://doi.org/10.3390/en16104231>
- Harrison, K., Sumic, Z., Cohen, E., & Foust, N. (2018). *Top 10 Trends in 2018 Driving the Utility Industry Toward a Decarbonized, Distributed, Digital and Democratized Future*. Gartner Research. <https://www.gartner.com/en/documents/3870486/top-10-trends-in-2018-driving-the-utility-industry-toward0>

- Hertwich, E. G., & Peters, G. P. (2009). Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science and Technology*, 43(16), 6414–6420. <https://doi.org/10.1021/es803496a>
- Hielscher, S., Seyfang, G., & Smith, A. (2013). Grassroots innovations for sustainable energy: exploring niche-development processes among community- energy initiatives. In M. J. Cohen, H. S. Brown, & P. J. Vergragt (Eds.), *Innovations in Sustainable Consumption* (pp. 133–156). Edward Elgar Publishing. <https://doi.org/10.4337/9781781001349.00017>
- Hittini, H., Abdrabou, A., & Zhang, L. (2016). SADS: Security aware distribution system architecture for smart grid applications. *Proceedings of the 2016 12th International Conference on Innovations in Information Technology, IIT*, 1–6. <https://doi.org/10.1109/INNOVATIONS.2016.7880028>
- Hoicka, C. E., Lowitzsch, J., Brisbois, M. C., Kumar, A., & Ramirez Camargo, L. (2021). Implementing a just renewable energy transition: Policy advice for transposing the new European rules for renewable energy communities. *Energy Policy*, 156. <https://doi.org/10.1016/j.enpol.2021.112435>
- Homer Energy. (2016). HOMER - Hybrid Renewable and Distributed Generation System Design Software. In [Http://Www.Homerenergy.Com](http://www.Homerenergy.Com).
- Huang, D., Zhang, C., Li, Q., Han, H., Huang, D., Li, T., & Wang, C. (2020). Consortium Blockchain-based Decentralized Energy Trading Mechanism for Virtual Power Plant. *2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2)*, 3084–3089. <https://doi.org/10.1109/EI250167.2020.9346653>
- Huang, Y., Warnier, M., Brazier, F., & Miorandi, D. (2015). Social Networking for Smart Grid Users. A Preliminary Modeling and Simulation Study. *IEEE 12th International Conference on Networking, Sensing and Control*, 438–443. <https://doi.org/10.1109/ICNSC.2015.7116077>
- Hugo, O., & Garnsey, E. (2002). The emergence of electronic messaging and the growth of four entrepreneurial entrants. *New Technology Based Firms in the New Millenium*, 2(February 2014), 97–123.
- Hyperledger Project. (2020). *Fabric whitepaper*. <https://www.hyperledger.org/>
- IANOS. (2020). *Virtual Power Plant Design*. IntegrAted SolutionNs for DecarbOnisation and Smartification of Islands. <https://ianos.eu/newsevents/ivpp-design/>
- IBM. (n.d.). *IBM SPSS Statistics for Academic Institutions* | IBM. Retrieved January 19, 2023, from <https://www.ibm.com/products/spss-statistics-campus-editions>.
- Intergovernmental Panel on climate change. (2023). *FIFTY-EIGHTH SESSION OF THE IPCC. Interlaken, Switzerland. IPCC SIXTH ASSESSMENT REPORT*. https://www.ipcc.ch/site/assets/uploads/2023/03/Doc5_Adopted_AR6_SYR_Longer_Report.pdf
- Interreg Europe. (2022). *Empowering Citizens for Energy Communities: A Policy Brief from the Policy Learning Platform on Low Carbon Economy* (Issue November, pp. 1–24). https://www.interregeurope.eu/sites/default/files/good_practices/PolicyBrief_RECommunities_final.pdf
- Ioannis, K., Raimondo, G., Dimitrios, G., Gioia Rosanna, D., Georgios, K., Gary, S., Ricardo, N., & Igor, N.-F. (2017). *Blockchain in Energy Communities A proof of concept*. <https://doi.org/10.2760/121912>
- IRENA. (2019). *Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper)*. International Renewable Energy Agency. https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf
- IRENA. (2021). *Energy Transition - Towards the achievement of SDG 7 and Net-zero emissions*. United Nations Department of Economic and Social Affairs. https://www.un.org/sites/un2.un.org/files/2021-twg_2-062321.pdf
- Jain, N. K., Bhaskar, K., & Jain, S. (2022). What drives adoption intention of electric vehicles in India? An integrated UTAUT model with environmental concerns, perceived risk and government support. *Research in Transportation Business and Management*, 42(May 2021), 100730. <https://doi.org/10.1016/j.rtbm.2021.100730>

- Jamil, N., Qassim, Q. S., Bohani, F. A., Mansor, M., & Ramachandaramurthy, V. K. (2021). Cybersecurity of Microgrid: State-of-the-Art Review and Possible Directions of Future Research. *Applied Sciences*, 11(21), 9812. <https://doi.org/10.3390/app11219812>
- Jazaeri, J. (2021). Application of 5G Technology in Orchestration of Virtual Power Plants and Demand Response. *2021 4th International Symposium on Advanced Electrical and Communication Technologies (ISAECT)*, 1–4. <https://doi.org/10.1109/ISAECT53699.2021.9668601>
- Jha, A. V., Appasani, B., Ghazali, A. N., Pattanayak, P., Gurjar, D. S., Kabalci, E., & Mohanta, D. K. (2021). Smart grid cyber-physical systems: communication technologies, standards and challenges. *Wireless Networks*, 27(4), 2595–2613. <https://doi.org/10.1007/s11276-021-02579-1>
- Jiang, G., Xie, Z., Han, T., Du, H., Feng, R., Luo, S., Wu, X., & Zhang, J. (2021). Virtual Power Plant Platform for Demand Response Based on Microservice Architecture. In *Frontiers in Artificial Intelligence and Applications* (Vol. 345, pp. 102–117). <https://doi.org/10.3233/FAIA210395>
- Jin, L., Duan, K., & Tang, X. (2018). What Is the Relationship between Technological Innovation and Energy Consumption? Empirical Analysis Based on Provincial Panel Data from China. *Sustainability*, 10(2), 145. <https://doi.org/10.3390/su10010145>
- Johannesson, P., & Perjons, E. (2014). *An Introduction to Design Science* (1st ed.). Springer, Cham Heidelberg New York. [https://doi.org/DOI 10.1007/978-3-319-10632-8](https://doi.org/DOI%2010.1007/978-3-319-10632-8)
- Junker, R. G., Azar, G. A., Lopes, R. A., Lindberg K. B., Reynders G., Relan R., Madsen, H., (2018). Characterizing the energy flexibility of buildings and districts. *Applied Energy*, 225, 175–182. <https://doi.org/10.1016/j.apenergy.2018.05.037>
- Karitpower. (2023). *How Virtual Power Plants Use AI for Smarter Energy Forecasting & Management | Karit VPP Energy Services*. <https://karitpower.com/news/how-virtual-power-plants-use-artificial-intelligence/>
- Karunathilake, H., Hewage, K., Mérida, W., & Sadiq, R. (2019). Renewable energy selection for net-zero energy communities: Life cycle based decision making under uncertainty. *Renewable Energy*, 130, 558–573. <https://doi.org/10.1016/j.renene.2018.06.086>
- Kazimierczuk, K., Henderson, C., Duffy, K., Hanif, S., Bhattacharya, S., Biswas, S., Jacroux, E., Preziuso, D., Wu, D., Bhatnagar, D., & Tarekegne, B. (2023). A socio-technical assessment of marine renewable energy potential in coastal communities. *Energy Research & Social Science*, 100, 103098. <https://doi.org/10.1016/j.erss.2023.103098>
- King, P., Martin-Ortega, J., Armstrong, J., Ferré, M., & Bark, R. H. (2023). Mainstreaming nature-based solutions: What role do Communities of Practice play in delivering a paradigm shift? *Environmental Science & Policy*, 144(March), 53–63. <https://doi.org/10.1016/j.envsci.2023.03.003>
- Klenergy Tech. (2017). *The Pylon Network Whitepaper*. Whitepaper. <https://pylon-network.org/es/>
- Kobou Ngani, P., & Hadji-Minaglou, J.-R. (2023). Model Predictive Control for Residential Battery Storage System: Profitability Analysis. *Batteries*, 9(6), 316. <https://doi.org/10.3390/batteries9060316>
- Kotcher, J., Maibach, E., & Choi, W. T. (2019). Fossil fuels are harming our brains: Identifying key messages about the health effects of air pollution from fossil fuels. *BMC Public Health*, 19(1), 1–13. <https://doi.org/10.1186/s12889-019-7373-1>
- Krishna, R., & Hemamalini, S. (2022). Optimal Energy Management of Virtual Power Plants with Storage Devices Using Teaching-and-Learning-Based Optimization Algorithm. *International Transactions on Electrical Energy Systems*, 2022, 1–17. <https://doi.org/10.1155/2022/1727524>
- Kusakana, K. (2019). Modeling an Optimal Peer-to-Peer Energy Sharing Between Prosumers in a South African Context. *2019 IEEE Milan PowerTech*, 1–6. <https://doi.org/10.1109/PTC.2019.8810861>
- KWHcoin. (2016). *KWHCoin Whitepaper*. In *Whitepaper* (pp. 1–25). <https://coinpaprka.com/storage/cdn/whitepapers/6395703.pdf>
- Lai, B.-C., Chiu, W.-Y., & Tsai, Y.-P. (2022). Multiagent Reinforcement Learning for Community Energy Management to Mitigate Peak Rebounds Under Renewable Energy

- Uncertainty. *IEEE Transactions on Emerging Topics in Computational Intelligence*, 6(3), 568–579. <https://doi.org/10.1109/TETCI.2022.3157026>
- Lancel, S., Chapurlat, V., Dray, G., & Martin, S. (2023). Emergency evacuation in a supermarket during a terrorist attack: towards a possible modelling of the influence of affordances on the evacuation behavior of agents in a complex virtual environment. *Journal of Safety Science and Resilience*, 4(2), 139–150. <https://doi.org/10.1016/j.jnlssr.2022.10.006>
- Landry, L. (2021). *How to Delegate Effectively: 9 Tips for Managers* | HBS Online. Harvard Business School. <https://online.hbs.edu/blog/post/how-to-delegate-effectively>
- Laoharojanaphand, V., & Ongsakul, W. (2021). Virtual battery storage service using hydropower plant with co-located floating solar and wind generation. *Sustainable Energy Technologies and Assessments*, 47(July), 101531. <https://doi.org/10.1016/j.seta.2021.101531>
- Lazzari, F., Mor, G., Cipriano, J., Solsona, F., Chemisana, D., & Guericke, D. (2023). Optimizing planning and operation of renewable energy communities with genetic algorithms. *Applied Energy*, 338, 120906. <https://doi.org/10.1016/j.apenergy.2023.120906>
- Le, V. T., & Pitts, A. (2019). A survey on electrical appliance use and energy consumption in Vietnamese households: Case study of Tuy Hoa city. *Energy and Buildings*, 197(2019), 229–241. <https://doi.org/10.1016/j.enbuild.2019.05.051>
- Lee, T.-C., Anser, M. K., Nassani, A. A., Haffar, M., Zaman, K., & Abro, M. M. Q. (2021). Managing Natural Resources through Sustainable Environmental Actions: A Cross-Sectional Study of 138 Countries. *Sustainability*, 13(22), 1–19. <https://doi.org/10.3390/su132212475>
- Li, T., An, J., Zhang, D., Diao, X., Liu, C., & Liu, W. (2022). Research on Interval Optimal Scheduling Strategy of Virtual Power Plants with Electric Vehicles. *World Electric Vehicle Journal*, 13(12), 235. <https://doi.org/10.3390/wevj13120235>
- Li, W., Hu, Y., Jiang, C., Wu, S., Bai, Q., & Lai, E. (2023). ABEM: An adaptive agent-based evolutionary approach for influence maximization in dynamic social networks. *Applied Soft Computing*, 136, 110062. <https://doi.org/10.1016/j.asoc.2023.110062>
- Liang, Y., Zhou, Q., Pan, Y., & Liu, L. (2022). Risk Stabilization and Market Bidding Strategy of Virtual Power Plant Alliance Based on Multi-stage Robust Optimization. *2022 7th Asia Conference on Power and Electrical Engineering (ACPEE)*, 351–356. <https://doi.org/10.1109/ACPEE53904.2022.9783960>
- Linnenberg, T., & Fay, A. (2018). Software engineering for agent-based energy systems. *2018 IEEE 14th International Conference on Automation Science and Engineering (CASE)*, 2018-August, 174–180. <https://doi.org/10.1109/COASE.2018.8560487>
- Lition. (2018). The blockchain infrastructure for all regulated markets built on the world's first P2P energy trading solution commercially live on a mass market. In *Whitepaper version 1.10.0* (pp. 1–56).
- Liu, J., Hu, H., Yu, S. S., & Trinh, H. (2023). Virtual Power Plant with Renewable Energy Sources and Energy Storage Systems for Sustainable Power Grid-Formation, Control Techniques and Demand Response. *Energies*, 16(9), 3705. <https://doi.org/10.3390/en16093705>
- Liu, Y., Xin, H., Qu, Z., & Gan, D. (2016). An Attack-Resilient Cooperative Control Strategy of Multiple Distributed Generators in Distribution Networks. *IEEE Transactions on Smart Grid*, 7(6), 2923–2932. <https://doi.org/10.1109/TSG.2016.2542111>
- Lo, C. H., & Ansari, N. (2012). The progressive smart grid system from both power and communications aspects. *IEEE Communications Surveys and Tutorials*, 14(3), 799–821. <https://doi.org/10.1109/SURV.2011.072811.00089>
- LO3 Energy. (2017). Exergy Token: The first energy marketplace for the new energy consumer. In *Whitepaper* (pp. 1–9). <https://www.truevaluemetrics.org/DBpdfs/Initiatives/Exergy/Exergy-2018-Executive-Summary.pdf>
- LO3 Energy. (2020). *Brooklyn Microgrid - Community Powered Energy*. <https://www.brooklyn.energy/>
- Lord, M. (2022). *What is a Digital Service?* <https://www.ibm.com/topics/what-is-a-digital-twin>

- Louisiana Community Network. (2004). Introduction to Community Development. In *Louisiana Community Network.org*.
- Lukumba, P., & Simon, T. (2023). Detection of False Data Injection Attacks in Smart-Grid Systems: Benchmarking Deep Learning Techniques. *Journal of Electrical Electronics Engineering*, 2(1), 41–49. <https://doi.org/10.1109/MCOM.2015.7045410>
- Luo, F., Dorri, A., Ranzi, G., Zhao, J., & Jurdak, R. (2022). Aggregating buildings as a virtual power plant: Architectural design, supporting technologies, and case studies. *IET Energy Systems Integration*, 4(4), 423–435. <https://doi.org/10.1049/esi2.12047>
- Ma, R., Zhou, H., Qian, W., Zhang, C., Sun, G., & Zang, H. (2020). Study on the Transaction Management Mode of Virtual Power Plants Based on Blockchain Technology. *2020 12th IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2020-Septe*, 1–5. <https://doi.org/10.1109/APPEEC48164.2020.9220580>
- Mackinnon Lawrence, J. V. (2018). Energy cloud. *Navigant Research*, 48.
- Mahdiraji, S. A., Holmgren, J., Alshaban, A., Mihailescu, R.-C., Petersson, J., & Fatah, J. Al. (2022). A Framework for Constructing Discrete Event Simulation Models for Emergency Medical Service Policy Analysis. *Procedia Computer Science*, 210(C), 133–140. <https://doi.org/10.1016/j.procs.2022.10.129>
- Maheshwari, Z., & Ramakumar, R. (2016). Smart Integrated Renewable Energy Systems (SIREs) for rural communities. *2016 IEEE Power and Energy Society General Meeting (PESGM)*, 1–5. <https://doi.org/10.1109/PESGM.2016.7741874>
- Mallett, R., Hagen-Zanker, J., Slater, R., & Duvendack, M. (2012). The benefits and challenges of using systematic reviews in international development research. *Journal of Development Effectiveness*, 4(3), 445–455. <https://doi.org/10.1080/19439342.2012.711342>
- Mao, T., Guo, X., Xie, P., Zhou, J., Zhou, B., Han, S., Wu, W., & Sun, L. (2020). Virtual Power Plant Platforms and Their Applications in Practice: a Brief Review. *2020 IEEE Sustainable Power and Energy Conference (ISPEC), 202006300000033*, 2071–2076. <https://doi.org/10.1109/iSPEC50848.2020.9351147>
- Mark, J., & Hufnagel, P. (1996). *The IEEE 1451. 4 Standard for Smart Transducers*. IEEE Standard Association. <https://standards.ieee.org/wp-content/uploads/import/documents/tutorials/1451d4.pdf>
- Martins, F., Felgueiras, C., Smitkova, M., & Caetano, N. (2019). Analysis of Fossil Fuel Energy Consumption and Environmental Impacts in European Countries. *Energies*, 12(6), 1–11. <https://doi.org/10.3390/en12060964>
- Melnyk, A., Cox, H., Ghorbani, A., & Hoppe, T. (2023). Value dynamics in energy democracy: An exploration of community energy initiatives. *Energy Research & Social Science*, 102(October 2021), 103163. <https://doi.org/10.1016/j.erss.2023.103163>
- Menniti, D., Sorrentino, N., Pinnarelli, A., Vizza, P., Brusco, G., & Barone, G. (2020). Sharing energy management model for renewable community self-consumption. *2020 17th International Conference on the European Energy Market (EEM)*, 1–6. <https://doi.org/10.1109/EEM49802.2020.9221969>
- MIT Technology Review insights, & Shell Inc; (2022). *Digital technology: The backbone of a net-zero emissions future*. MIT Technology Review Insights. https://www.shell.com/energy-and-innovation/digitalisation/digitalisation-accelerating-the-energy-transition/digitalisation-and-decarbonisation-mit-report/_jcr_content/root/main/section/call_to_action/links/item0.stream/1678207879539/34a35ef0e6176ff3eb255
- Mnatsakanyan, A., Albeshr, H., Almarzooqi, A., Iraklis, C., & Bilbao, E. (2022). Blockchain mediated virtual power plant: From concept to demonstration. *The Journal of Engineering*, 2022(7), 732–738. <https://doi.org/10.1049/tje2.12158>
- Mohajan, H. K. (2017). TWO CRITERIA FOR GOOD MEASUREMENTS IN RESEARCH: VALIDITY AND RELIABILITY. *Annals of Spiru Haret University. Economic Series*, 17(4), 59–82. <https://doi.org/10.26458/1746>
- Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2021). A Collaborative Approach on Energy-based Offered Services: Energy 4.0 Ecosystems. *Procedia CIRP*, 104, 1638–1643. <https://doi.org/10.1016/j.procir.2021.11.276>

- Multimethod Modeling – AnyLogic Simulation Software*. (2017). Retrieved September 2, 2022, from <https://www.anylogic.com/use-of-simulation/multimethod-modeling/>
- Nadeem, T. Bin, Siddiqui, M., Khalid, M., & Asif, M. (2023). Distributed energy systems: A review of classification, technologies, applications, and policies. *Energy Strategy Reviews*, 48(April), 101096. <https://doi.org/10.1016/j.esr.2023.101096>
- NADGrid. (2018). NAD Grid. In *Whitepaper* (pp. 1–30). <https://www.crunchbase.com/organization/nad-grid>
- Nafees, L., Cook, C. M., Nikolov, A. N., & Stoddard, J. E. (2021). Can social media influencer (SMI) power influence consumer brand attitudes? The mediating role of perceived SMI credibility. *Digital Business*, 1(2), 100008. <https://doi.org/10.1016/j.digbus.2021.100008>
- Nair, K. B. L., & Shereef, R. M. (2022). Voltage Stability Assessment of Transmission System with Electric Vehicles as Virtual Power Plants. *2022 IEEE International Power and Renewable Energy Conference (IPRECON)*, 1–6. <https://doi.org/10.1109/IPRECON55716.2022.10059549>
- Nanda, P., & Patnaik, S. (2023). A multi-agent coalition-based approach for order fulfilment in e-commerce. *Decision Analytics Journal*, 7(April), 100227. <https://doi.org/10.1016/j.dajour.2023.100227>
- Nastasi, B., & Mazzoni, S. (2023). Renewable Hydrogen Energy Communities layouts towards off-grid operation. *Energy Conversion and Management*, 291, 117293. <https://doi.org/10.1016/j.enconman.2023.117293>
- Nathaniel, S., Anyanwu, O., & Shah, M. (2020). Renewable energy, urbanization, and ecological footprint in the Middle East and North Africa region. *Environmental Science and Pollution Research*, 27(13), 14601–14613, <https://doi.org/10.1007/s11356-020-08>. <https://doi.org/10.1007/s11356-020-08017-7>
- Nazarenko, A. A., & Camarinha-Matos, L. M. (2020). The Role of Digital Twins in Collaborative Cyber-Physical Systems. *Technological Innovation for Life Improvement, DoCEIS 2020*, 191–205. https://doi.org/10.1007/978-3-030-45124-0_18
- Nazarenko, A. A., & Camarinha-Matos, L. M. (2021). Collaborative Cyber-Physical Systems Design Approach: Smart Home Use Case. In *IFIP Advances in Information and Communication Technology* (Vol. 626, Issue June, pp. 92–101). https://doi.org/10.1007/978-3-030-78288-7_9
- Neves, S. A., & Marques, A. C. (2021). The substitution of fossil fuels in the US transportation energy mix: Are emissions decoupling from economic growth? *Research in Transportation Economics*, 90(September 2020), 1–14. <https://doi.org/10.1016/j.retrec.2021.101036>
- Next Kraftwerke. (2021). *VPP explained: What is a Virtual Power Plant?* <https://www.next-kraftwerke.com/vpp/virtual-power-plant>
- Nguyen, L. K. N., Howick, S., & Megiddo, I. (2021). A Hybrid Simulation Modelling Framework for Combining System Dynamics and Agent-Based Models. *Proceedings of SW21 The OR Society Simulation Workshop, March*, 385–394. <https://doi.org/10.36819/SW21.042>
- Nikonowicz, Ł. B., & Milewski, J. (2012). Virtual Power Plants - general review: structure, application and optimization. *Journal of Power Technologies*, 92(3), 135–149.
- Nikonowicz, Ł., & Milewski, J. (2012). Virtual Power Plants-general review: structure, application and optimization. *Journal of Power Technologies*, 92(3), 135–149.
- Nowack, D., & Schoderer, S. (2020). The Role of Values for Social Cohesion: Theoretical Explication and Empirical Exploration. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.3553340>
- Nyasapoh, M. A., Elorm, M. D., & Derkyi, N. S. A. (2022). The role of renewable energies in the sustainable development of Ghana. *Scientific African*, 16(e01199), 1–16. <https://doi.org/10.1016/j.sciaf.2022.e01199>
- Obermaier, C., Riebl, R., Facchi, C., Al-Bayatti, A. H., & Khan, S. (2021). COSIDIA: An Approach for Real-Time Parallel Discrete Event Simulations Tailored for Wireless Networks. *Proceedings of the 2021 ACM SIGSIM Conference on Principles of Advanced Discrete Simulation*, 165–171. <https://doi.org/10.1145/3437959.3459250>

- Oest, F., Radtke, M., Blank-Babazadeh, M., Holly, S., & Lehnhoff, S. (2021). Evaluation of Communication Infrastructures for Distributed Optimization of Virtual Power Plant Schedules. *Energies*, 14(5), 1226. <https://doi.org/10.3390/en14051226>
- Opportunity Definition & Meaning | Dictionary.com. (n.d.). Retrieved September 9, 2022, from <https://www.dictionary.com/browse/opportunity>
- Ortega-Fernandez, I., & Liberati, F. (2023). A Review of Denial of Service Attack and Mitigation in the Smart Grid Using Reinforcement Learning. *Energies*, 16(2), 1–15. <https://doi.org/10.3390/en16020635>
- Parhamnia, F. (2022). *The Journal of Academic Librarianship Investigating mobile acceptance in academic library services based on Unified Theory of Acceptance and Use of Technology Model (UTAUT-2)*. 48(102570), 1–12. <https://doi.org/https://doi.org/10.1016/j.acalib.2022.102570>
- Park, H., & Shin, K. (2015). Membership Fluidity and Knowledge Collaboration in Virtual Communities: A Multilateral Approach to Membership Fluidity. *Journal of Intelligence and Information Systems*, 21(2), 19–47. <https://doi.org/10.13088/jiis.2015.21.2.19>
- Pasten, C., & Santamarina, J. C. (2012). Energy and quality of life. *Energy Policy*, 49(july 2012), 468–476. <https://doi.org/10.1016/j.enpol.2012.06.051>
- Pastore, L. M., Lo Basso, G., Ricciardi, G., & de Santoli, L. (2023). Smart energy systems for renewable energy communities: A comparative analysis of power-to-X strategies for improving energy self-consumption. *Energy*, 280, 128205. <https://doi.org/10.1016/j.energy.2023.128205>
- Peer to Peer Energy Blockchain Protocol. (2017). Peer to Peer Energy Blockchain Protocol - P2PEP. In *Whitepaper*. <https://icobench.com/ico/https-p2pep-com/whitepaper>
- Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of Management Information Systems*, 24(3), 45–77. <https://doi.org/10.2753/MIS0742-1222240302>
- Platt, R., Williams, J., Pardoe, A., & Straw, W. (2014). A New Approach to Electricity Markets: How new, disruptive technologies change everything. In *Institute for Public Policy Research*.
- Plewnia, F., & Guenther, E. (2021). The Transition Value of Business Models for a Sustainable Energy System: The Case of Virtual Peer-to-Peer Energy Communities. *Organization & Environment*, 34(3), 479–503. <https://doi.org/10.1177/1086026620932630>
- Pontes Luz, G., & Amaro e Silva, R. (2021). Modeling Energy Communities with Collective Photovoltaic Self-Consumption: Synergies between a Small City and a Winery in Portugal. *Energies*, 14(2), 323. <https://doi.org/10.3390/en14020323>
- PowerLedger. (2018). *POWER LEDGER*. Whitepaper. <https://www.powerledger.io/company/power-ledger-whitepaper>
- Prosume. (2017). Prosume: Decentralizing power. In *whitepaper* (pp. 1–16).
- PVOutput. (2018). Retrieved October 8, 2021, from <https://pvoutput.org/>
- Qi, J., Hahn, A., Lu, X., Wang, J., & Liu, C. (2016). Cybersecurity for distributed energy resources and smart inverters. *IET Cyber-Physical Systems: Theory & Applications*, 1(1), 28–39. <https://doi.org/10.1049/iet-cps.2016.0018>
- Qtum Chain Foundation. (2021). *Blockchain Platform QTUM Announces Partnership*. <https://www.globenewswire.com/news-release/2021/04/07/2205919/0/en/Blockchain-Platform-QTUM-Announces-Partnership-with-Indacoin-Limited.html>
- Que, L., Jiang, X., Wang, B., Jin, X., Cai, Z., Shi, L., & Lyn, Q. (2021). Virtual Power Plant Adjustable Resource Aggregation Adjustment Optimization Strategy Based on Multi-agent Game. *2021 International Conference on Networking, Communications and Information Technology (NetCIT)*, 285–290. <https://doi.org/10.1109/NetCIT54147.2021.00064>
- Rädle, S., Mast, J., Gerlach, J., & Bringmann, O. (2021). Computational intelligence based optimization of hierarchical virtual power plants. *Energy Systems*, 12(2), 517–544. <https://doi.org/10.1007/s12667-020-00382-z>
- Rahimiyan, M., & Baringo, L. M. (2016). Strategic Bidding for a Virtual Power Plant in the Day-Ahead and Real-Time Markets: A Price-Taker Robust Optimization Approach. *IEEE*

- Transactions on Power Systems*, 31(4), 2676–2687.
<https://doi.org/10.1109/TPWRS.2015.2483781>
- Rapier, R. (2020). *Fossil Fuels Still Supply 84 Percent Of World Energy – And Other Eye Openers From BP's Annual Review*. Forbes.
<https://www.forbes.com/sites/rrapier/2020/06/20/bp-review-new-highs-in-global-energy-consumption-and-carbon-emissions-in-2019/?sh=66828f4a66a1>
- Ravikumar, A., Deilami, S., & Taghizadeh, F. (2022). Advanced Dynamic Virtual Power Plants with Electric Vehicle Integration. *2022 IEEE Sustainable Power and Energy Conference (ISPEC)*, 1–6. <https://doi.org/10.1109/iSPEC54162.2022.10033028>
- RCEES. (n.d.). *Regional Centre for Energy and Environmental Sustainability*. 2023. Retrieved June 13, 2023, from <https://rcees.uenr.edu.gh/nebosh-training-in-uenr/>
- Rehman, A., Radulescu, M., Cismas, L. M., Alvarado, R., Secara, C. G., & Tolea, C. (2022). Urbanization, Economic Development, and Environmental Degradation: Investigating the Role of Renewable Energy Use. *Sustainability (Switzerland)*, 14(15). <https://doi.org/10.3390/su14159337>
- Reynders, G., Lopes, R. A., Marszal-Pomianowska, A., Aelenei, D., Martins, J., Saelens D. Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage. *Energy and Buildings*, 166, 2018, 372-390, <https://doi.org/10.1016/j.enbuild.2018.02.040>
- Ribeiro, C., Pinto, T., Morais, H., Vale, Z., & Santos, G. (2013). Intelligent remuneration and tariffs for virtual power players. *Towards Carbon Free Society through Smarter Grids, 2013 IEEE Grenoble Conference PowerTech, POWERTECH*, 308–312. <https://doi.org/10.1109/PTC.2013.6652157>
- Ribeiro, C., Pinto, T., & Vale, Z. (2012). Remuneration and tariffs in the context of virtual power players. *Proceedings - 23rd International Workshop on Database and Expert Systems Applications*, 308–312. <https://doi.org/10.1109/DEXA.2012.53>
- Rinaldi, S., Pasetti, M., Ferrari, P., Massa, G., Giustina, D. Della, & Unareti, S. A. (2016). Experimental Characterization of Communication Infrastructure for Virtual Power Plant Monitoring. In *Applied Measurements for Power Systems (AMPS), 2016 IEEE International Workshop On*, 1–6. <https://doi.org/10.1109/AMPS.2016.7602860>
- Ritchie, H., Roser, M., & Rosado, P. (2020). *Fossil Fuels - Our World in Data*. Published Online at OurWorldInData.Org. <https://ourworldindata.org/fossil-fuels>
- Rivola, D., Medici, V., Nespoli, L., Corbellini, G., & Strepparava, D. (2018). *Hive Power*. Whitepaper Version 1.3. <https://v.fastcdn.co/u/a25ac79a/29853262-0-Hive-Power-WP-1.3.pdf>
- Rocha, E. M., & Lopes, M. J. (2022). Bottleneck prediction and data-driven discrete-event simulation for a balanced manufacturing line. *Procedia Computer Science*, 200, 1145–1154. <https://doi.org/10.1016/j.procs.2022.01.314>
- Roozbehani, M. M., Heydarian-Forushani, E., Hasanzadeh, S., & Elghali, S. Ben. (2022). Virtual Power Plant Operational Strategies: Models, Markets, Optimization, Challenges, and Opportunities. *Sustainability*, 14(19), 12486. <https://doi.org/10.3390/su141912486>
- Rosa, L., Cruz, T., Simões, P., Monteiro, E., & Lev, L. (2017). Attacking SCADA systems: A practical perspective. *Proceedings of the IM 2017 - 2017 IFIP/IEEE International Symposium on Integrated Network and Service Management*, 741–746. <https://doi.org/10.23919/INM.2017.7987369>
- Rosin, A. ... Lebedev, D. (2012). Analysis of operation times and electrical storage dimensioning for energy consumption shifting and balancing in residential areas. *Elektronika Ir Elektrotehnika*, 4, 15–20. <https://doi.org/10.5755/j01.eee.120.4.1444>
- Rouzbahani, H. M., Karimipour, H., & Lei, L. (2021). A review on virtual power plant for energy management. In *Sustainable Energy Technologies and Assessments* (Vol. 47, Issue April, p. 101370). Elsevier Ltd. <https://doi.org/10.1016/j.seta.2021.101370>
- Ruhai, H., Zhiyi, Z., Junmin, L., & Guangqing, B. (2022). A Game Model of Virtual Power Plant Participating in Electric Power Market with Consumption Weight. *2022 IEEE International Conference on Power Systems and Electrical Technology (PSET)*, 421–429. <https://doi.org/10.1109/PSET56192.2022.10100469>

- Saboori, H., Mohammadi, M., & Taghe, R. (2011). Virtual Power Plant (VPP), Definition, Concept, Components and Types. *2011 Asia-Pacific Power and Energy Engineering Conference*, 1–4. <https://doi.org/10.1109/APPEEC.2011.5749026>
- Saxena, K., & Abhyankar, A. R. (2020). Agent-Based Distributed Computing for Power System State Estimation. *IEEE Transactions on Smart Grid*, 11(6), 5193–5202. <https://doi.org/10.1109/TSG.2020.3006932>
- Scarabaggio, P., Carli, R., Jantzen, J., & Dotoli, M. (2021). Stochastic Model Predictive Control of Community Energy Storage under High Renewable Penetration. *2021 29th Mediterranean Conference on Control and Automation (MED)*, 973–978. <https://doi.org/10.1109/MED51440.2021.9480353>
- Schleiger, E., Mason, C. M., Naughtin, C. K., & Reeson, A. F. (2023). *Collaborative Intelligence: A scoping review of current applications*. <https://doi.org/10.32388/RZGEPB>
- Sedjelmaci, H., & Senouci, S. M. (2016). Smart grid Security: A new Approach to Detect Intruders in a Smart Grid Neighborhood Area Network. *Wireless Networks and Mobile Communications (WINCOM), 2016 International Conference On*, 6–11. <https://doi.org/10.1109/WINCOM.2016.7777182>
- Seven, S., Yoldas, Y., Soran, A., Yalcin Alkan, G., Jung, J., Ustun, T. S., & Onen, A. (2022). Energy Trading on a Peer-to-Peer Basis between Virtual Power Plants Using Decentralized Finance Instruments. *Sustainability*, 14(20), 13286. <https://doi.org/10.3390/su142013286>
- Shafiul Alam, M., Al-Ismail, F. S., Salem, A., & Abido, M. A. (2020). High-level penetration of renewable energy sources into grid utility: Challenges and solutions. *IEEE Access*, 8, 190277–190299, DOI:10.1109/ACCESS.2020.3031481. <https://doi.org/10.1109/ACCESS.2020.3031481>
- Share&Charge. (2020). *Share&Charge - Enabling The Open EV-Economy of Tomorrow*. <https://shareandcharge.com/>
- Shepard, J. (2015). *sonnenCommunity Connects Households and Obsoletes Utilities - News*. EE Power. <https://eepower.com/news/sonnencommunity-connects-households-and-obsoletes-utilities/#>
- Shirado, H., Iosifidis, G., Tassioulas, L., & Christakis, N. A. (2019). Resource sharing in technologically defined social networks. *Nature Communications*, 10(1), 1079. <https://doi.org/10.1038/s41467-019-08935-2>
- Sidik, S. M. (2018). *Validation studies: Validating new tools and adapting old ones to new contexts*. How to Do Primary Care Research. <https://www.taylorfrancis.com/chapters/edit/10.1201/9781351014519-18/validation-studies-sherina-mohd-sidik>
- Siebert, N., Foggia, G., Lannez, S., Muscholl, M., Passelergue, J. C., Letendre, S., Moreau, A., & Bertone, Y. (2013). Reflexe: Managing commercial and industrial flexibilities in a market environment. *IEEE Grenoble Conference PowerTech, POWERTECH*, 1–6. <https://doi.org/10.1109/PTC.2013.6652315>
- Siemens. (2022). *PSS®E – transmission planning and analysis | PSS® power system simulation and modeling software | Siemens Global*.
- Sierla, S., Pourakbari-Kasmaei, M., & Vyatkin, V. (2022). A taxonomy of machine learning applications for virtual power plants and home/building energy management systems. *Automation in Construction*, 136(February), 104174. <https://doi.org/10.1016/j.autcon.2022.104174>
- Singh, K. N., Das, N., Maurya, M., Goswami, A. K., & Chudhury, N. B. D. (2022). An Intelligent Bidding Strategy based on Social Welfare of Virtual Power Plant considering Carbon Trading. *2022 IEEE International Conference on Power Electronics, Smart Grid, and Renewable Energy (PESGRE)*, 1–5. <https://doi.org/10.1109/PESGRE52268.2022.9715918>
- Slettebø, T. (2021). Participant validation: Exploring a contested tool in qualitative research. *Qualitative Social Work*, 20(5), 1223–1238. <https://doi.org/10.1177/1473325020968189>
- Solar Bankers. (2017). *Comprehensive guide to companies involved in blockchain and energy*. <http://ipci.io/wp-content/uploads/2017/12/Energy-Blockchain-Report.compressed.pdf>

- SolarBankers. (2018). Solar Bankers: The bright side of light. In *Whitepaper* (pp. 1–15). <https://solarbankers.com/>
- Solarriot - Home. (n.d.). Retrieved October 3, 2018, from <https://www.solariot.xyz/>
- Song, J., Guo, M., Lin, H., & Lv, R. (2021). Construction Scheme of Virtual Power Plant Centralized Control Platform Based on Information Interaction. *2021 13th International Conference on Wireless Communications and Signal Processing (WCSP)*, 1–5. <https://doi.org/10.1109/WCSP52459.2021.9613485>
- Sonnen. (n.d.). *sonnen Group | sonnen*. Retrieved February 28, 2022, from <https://sonnengroup.com/>
- Sosnina, E., Shalukho, A., & Erdili, N. (2022). Multi-agent Control of Distributed Generation Sources Based on the Environmental Friendliness Rating. *2022 International Russian Automation Conference (RusAutoCon)*, 20, 836–841. <https://doi.org/10.1109/RusAutoCon54946.2022.9896302>
- Sovacool, B. K., Burke, M., Baker, L., Kotikalapudi, C. K., & Wlokas, H. (2017). New frontiers and conceptual frameworks for energy justice. *Energy Policy*, 105, 677–691. <https://doi.org/10.1016/j.enpol.2017.03.005>
- Spectral. (2021). *Spectral - Joliette at De Ceuveel*. <https://spectral.energy/news-3/joliette-at-deceuveel/>
- SunContract. (2017). *SunContract Whitepaper*. <https://www.allcryptowhitepapers.com/suncontract-whitepaper/>
- Suncontract. (2020). *Electricity Marketplace for P2P energy trading - SunContract*. <https://suncontract.org/>
- SunExchange. (2018). *SunExchange Whitepaper: monetizing Sunshine*.
- Suuronen, S., Ukko, J., Eskola, R., Semken, R. S., & Rantanen, H. (2022). A systematic literature review for digital business ecosystems in the manufacturing industry: Prerequisites, challenges, and benefits. *CIRP Journal of Manufacturing Science and Technology*, 37, 414–426. <https://doi.org/10.1016/j.cirpj.2022.02.016>
- Svetec, E., Nad, L., Pasicko, R., & Pavlin, B. (2019). Blockchain application in renewable energy microgrids: an overview of existing technology towards creating climate - resilient and energy independent communities. *2019 16th International Conference on the European Energy Market (EEM)*, 1–7. <https://doi.org/10.1109/EEM.2019.8916292>
- Szulecki, K., & Overland, I. (2020). Energy democracy as a process, an outcome and a goal: A conceptual review. *Energy Research & Social Science*, 69(April), 101768. <https://doi.org/10.1016/j.erss.2020.101768>
- Taber, K. S. (2018). The Use of Cronbach’s Alpha When Developing and Reporting Research Instruments in Science Education. *Research in Science Education*, 48(6), 1273–1296. <https://doi.org/10.1007/s11165-016-9602-2>
- Tan, J. (2017). *Electrify.Asia Technical white paper 11.0*. Technical Whitepaper (Version 11.0). <https://cryptorating.eu/whitepapers/Electrify.Asia/Technical-Whitepaper-11-1.pdf>
- The European Union. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable Sources. *Official Journal of the European Union*, 82(L 328), 82–209.
- The sun exchange. (2018). Monetizing Sunshine. In *whitepaper* (pp. 1–48). https://dhqmkfjt3wud.cloudfront.net/documents/SUNEX+White+Paper_180416.pdf
- Thomas, M., DeCillia, B., Santos, J. B., & Thorlakson, L. (2022). Great expectations: Public opinion about energy transition. *Energy Policy*, 162(112777), 1–13, DOI:10.1016/j.enpol.2022.112777. <https://doi.org/10.1016/j.enpol.2022.112777>
- Thompson, S. (2022). Green Renewable Power and Policy in Canada: A Just Energy Transition to Net-Zero. *Journal of Geoscience and Environment Protection*, 10(03), 1–12. <https://doi.org/10.4236/gep.2022.103001>
- Tian, L., Cheng, L., Wan, Y., Yuan, K., Liu, R., & Wu, K. (2020). From Distributed Energy Resources to Virtual Power Plants: A Cyber-Physical System Solution for Integrating Demand-side in Smart Grid. *2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2)*, 3463–3467. <https://doi.org/10.1109/EI250167.2020.9346925>

- Tian, N., & Qiu, Y. (2022). Research on Network Slice Resource Scheduling in Virtual Power Plant. *2022 IEEE 5th International Conference on Computer and Communication Engineering Technology (CCET)*, 243–246. <https://doi.org/10.1109/CCET55412.2022.9906387>
- Ubelmesser, L., Klingert, S., & Becker, C. (2022). Modelling the Success of Renewable Energy Communities. *2022 IEEE International Conference on Pervasive Computing and Communications Workshops and Other Affiliated Events (PerCom Workshops)*, 445–450. <https://doi.org/10.1109/PerComWorkshops53856.2022.9767245>
- Ullah, Z., Arshad, & Hassanin, H. (2022). Modeling, Optimization, and Analysis of a Virtual Power Plant Demand Response Mechanism for the Internal Electricity Market Considering the Uncertainty of Renewable Energy Sources. *Energies*, 15(14), 5296. <https://doi.org/10.3390/en15145296>
- Ullah, Z., Arshad, Hassanin, H., Cugley, J., & Alawi, M. Al. (2022). Planning, Operation, and Design of Market-Based Virtual Power Plant Considering Uncertainty. *Energies*, 15(19), 7290. <https://doi.org/10.3390/en15197290>
- Unhelkar, B., & Arntzen, A. A. (2020). *A framework for intelligent collaborative enterprise systems. Concepts, opportunities and challenges*. Scandinavian Journal of Information Systems. <https://aisel.aisnet.org/cgi/viewcontent.cgi?article=1640&context=sjis>
- UNICEF. (2021). Defining social norms and related concepts. In *Unicef*. <https://www.unicef.org/media/111061/file/Social-norms-definitions-2021.pdf>
- United Nations. (2016). THE PARIS AGREEMENT. *United Nations Framework Convention on Climate Change (UNFCCC)*, 1(FCCC/CP/2015/10/Add.1), 1–41. <https://doi.org/10.1126/science.ns-1.2.41>
- United Nations. (2022). THE 17 GOALS - Sustainable Development. In *Sustainable Development*. <https://sdgs.un.org/goals>
- United Nations. (2023). *Global Sustainable Development Report*. United Nations. <https://doi.org/CAT/C/MAR/CO/4>
- United Nations Development Programme. (2016). *Sustainable Development Goals | United Nations Development Programme*. United Nations Development Programme. https://www.undp.org/sustainable-development-goals?gclid=CjwKCAjw29ymBhAKEiwAHJbJ8hNe6Y_iG1HnUs2bJjTZUPyq1hTuHMQjPseIW52PTv0K-_I7EOO9hoCcUEQAvD_BwE
- Usó-Doménech, J. L., & Nescolarde-Selva, J. (2016). What are Belief Systems? *Foundations of Science*, 21(1), 147–152. <https://doi.org/10.1007/s10699-015-9409-z>
- Vaishnavi, V. K., & Kuechler, W. (2007). *Design Science Research Methods and Patterns: Innovating Information and Communication Technology*. Auerbach Publications.
- Vasylichenko, A. (n.d.). *Bringing Fintech and Blockchain Technology into the Energy System*. Toomuch.Energy. Retrieved October 10, 2018, from <https://www.energik.be/activiteiten/documenten/DOC29.pdf>
- Veichtlbauer, A., Praschl, C., Gaisberger, L., Steinmaurer, G., & Strasser, T. I. (2022). Toward an Effective Community Energy Management by Using a Cluster Storage. *IEEE Access*, 10, 112286–112306. <https://doi.org/10.1109/ACCESS.2022.3216298>
- Venkatachary, S. K., Alagappan, A., & Andrews, L. J. B. (2021). Cybersecurity challenges in energy sector (virtual power plants) - can edge computing principles be applied to enhance security? *Energy Informatics*, 4(1), 5. <https://doi.org/10.1186/s42162-021-00139-7>
- Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User Acceptance of Information Technology: Toward a Unified View. *Management Information Systems Research Center, University of Minnesota*, 27(3), 425–478.
- Verde, S. F., & Rossetto, N. (2020). The Future of Renewable Energy Communities in the EU. An investigation at the time of the Clean Energy Package. In *The European University Institute, Technical Report* (Issue August). <https://doi.org/10.2870/754736>
- Vlux. (2018). *Vero VLUX Whitepaper Version 2.0: The evolution of Energy*. Whitepaper. https://vlux.io/media/VLUX_Whitepaper.pdf
- Voltmarkets. (2021). *Bitcoin Code - Automated trading platform on the crypto market*. Reliable Crypto Trading with Bitcoin Code. <https://voltmarkets.com/>
- VRA. (2012). *Volta River Authority*. October, 1–7. <https://www.vra.com/>

- Wainer, A., Petrovics, D., & van der Grijp, N. (2022). The grid access of energy communities a comparison of power grid governance in France and Germany. *Energy Policy*, 170(February), 113159. <https://doi.org/10.1016/j.enpol.2022.113159>
- Wang, J., Chen, S., Li, B., & Qi, B. (2022). Coordination and Optimization of Virtual Power Plant Based on Multi-agent System. *2022 5th International Conference on Circuits, Systems and Simulation (ICCSS)*, 187–191. <https://doi.org/10.1109/ICCSS55260.2022.9802186>
- Wang, N., Kong, X., Li, G., Li, X., Li, X., & Li, Z. (2022). Dynamic Aggregation Response Strategy of Adjustable Resources of Virtual Power Plants in Power Grid Balance Adjustment Scenario. *2022 25th International Conference on Electrical Machines and Systems (ICEMS)*, 1–6. <https://doi.org/10.1109/ICEMS56177.2022.9983257>
- Wang, X., Zhang, J., Jia, Z., Hu, A., Li, D., & Wu, X. (2021). A new energy trading model for virtual power plants based on blockchain. *2021 IEEE International Conference on Emergency Science and Information Technology (ICESIT)*, 93–99. <https://doi.org/10.1109/ICESIT53460.2021.9696896>
- Wang, X., Zhang, J., & Jiang, X. (2021). Research On Purchasing And Selling Energy Strategy Of Virtual Power Plant. *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*, 1507–1512. <https://doi.org/10.1109/EI252483.2021.9713066>
- Wang, Xuefeng, B., & Bin, L. (2022). Research on Consensus Algorithm of Hierarchical Partition Blockchain for Virtual Power Plant Transactions. *2022 2nd International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE)*, 1613–1617. <https://doi.org/10.1109/ICACITE53722.2022.9823468>
- WePower. (2017). WePower. In *Whitepaper (Version 0.81)* (pp. 1–45). <https://whitepaper.io/document/202/wepower-whitepaper>
- Widuto, A. (2022). Energy poverty in the EU. *European Parliament*, PE 733.583(July), 1–11.
- Wood, W., & Hayes, T. (2012). Social Influence on consumer decisions: Motives, modes, and consequences. *Journal of Consumer Psychology*, 22(3), 324–328. <https://doi.org/10.1016/j.jcps.2012.05.003>
- Xu, X., Zhang, Z., Yuan, J., & Shao, J. (2023). Design and multi-objective comprehensive evaluation analysis of PV-WT-BG-Battery hybrid renewable energy systems in urban communities. *Energy Conversion and Management: X*, 18, 100357. <https://doi.org/10.1016/j.ecmx.2023.100357>
- Yang, B., Lv, Z., & Wang, F. (2022). Digital Twins for Intelligent Green Buildings. *2022 7th International Conference on Smart and Sustainable Technologies (SpliTech)*, 12(6), 1–20. <https://doi.org/10.3390/buildings12060856>
- Yu, D., Zhao, X., Wang, Y., Jiang, L., & Liu, H. (2022). Research on Energy Management of a Virtual Power Plant Based on the Improved Cooperative Particle Swarm Optimization Algorithm. *Frontiers in Energy Research*, 10(February), 1–13. <https://doi.org/10.3389/fenrg.2022.785569>
- Zahedi, R., Ghodusinejad, M. hasan, Aslani, A., & Hachem-Vermette, C. (2022). Modelling community-scale renewable energy and electric vehicle management for cold-climate regions using machine learning. *Energy Strategy Reviews*, 43, 100930. <https://doi.org/10.1016/j.esr.2022.100930>
- Zhang, H. (2022). A Control System of Intelligent Building Air-Conditioning Load in Virtual Power Plant. *2022 IEEE 6th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*, 2022-Octob, 1418–1422. <https://doi.org/10.1109/IAEAC54830.2022.9929814>
- Zhang, J. (2022). The Concept, Project and Current Status of Virtual Power Plant: A Review. *Journal of Physics: Conference Series*, 2152(1), 012059. <https://doi.org/10.1088/1742-6596/2152/1/012059>
- Zhang, Y., Cassandras, C. G., Li, W., & Mosterman, P. J. (2018). A Discrete-Event and Hybrid Simulation Framework Based on SimEvents for Intelligent Transportation System Analysis. *IFAC-PapersOnLine*, 51(7), 323–328. <https://doi.org/10.1016/j.ifacol.2018.06.320>
- Zhang, Z., Yong, W., Yang, F., Wei, J., & Zhu, M. (2020). Real-Time Active Power Dispatch for Virtual Power Plant via a Multi-agent Leader-Follower Game Approach. *2020 IEEE 3rd*

- Student Conference on Electrical Machines and Systems (SCEMS)*, 875–880.
<https://doi.org/10.1109/SCEMS48876.2020.9352298>
- Zhang, & Zhao, D. (2021). Two-Stage Bidding Strategy of Virtual Power Plant in Electricity and Carbon Emissions Trading Markets. *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*, 3930–3935.
<https://doi.org/10.1109/EI252483.2021.9713152>
- Zhao, H., Wang, X., Wang, B., Ning, B., Sun, H., Liu, Z., & Pan, Z. (2022). A Multi Time-Scale Robust Aggregation Model for Virtual Power Plant Based on Rolling Correction. *2022 IEEE 6th Conference on Energy Internet and Energy System Integration (EI2)*, 2020, 2574–2579.
<https://doi.org/10.1109/EI256261.2022.10116634>
- Zhu, Y., Mao, T., Zhan, G., Ai, Q., & Yin, S. (2022). Optimal Scheduling Model for Virtual Power Plant Participating in Energy and Regulation Markets. *2022 7th Asia Conference on Power and Electrical Engineering (ACPEE)*, 447–453.
<https://doi.org/10.1109/ACPEE53904.2022.9784029>
- Zimmermann, Jean-Paul. Evans, Matt. Griggs, Jonathan. King, Nicola. Harding, Les., & Oberts, Penelope. Evans, C. (2012). *Household Electricity Survey: A study of domestic electrical product usage*. Intertek Report R66141.
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/208097/10043_R66141HouseholdElectricitySurveyFinalReportissue4.pdf
- Zishou, L., Tian, S., Xiong, Z., Ren, Y., Xie, X., & Ying, L. (2022). Study on the Participation of Virtual Power Plants with Demand Response in Peaking Auxiliary Services. *2022 Power System and Green Energy Conference (PSGEC)*, 716–721.
<https://doi.org/10.1109/PSGEC54663.2022.9881193>

Appendix 1

Sample Questionnaire

Thank you for agreeing to participate in this survey. The survey is being conducted by **Kankam Okatakyie Adu-Kankam**, a PhD researcher at the Nova University of Lisbon, Portugal. The purpose of the survey is to collect opinions from experts, professional and potential users of the **Collaborative Energy Ecosystem/Cognitive Household Digital Twin – (CEE/CHDT)**. I wish to assure participants that all the answers you provide in this survey will be kept confidential. No identifying information will be provided in the PhD thesis. The survey data will be reported in a summary form and will not identify any individual person.

1. What is your gender?
 - Male.
 - Female.

2. Which age category do you fall?
 - 18-29 years old.
 - 30-39 years old.
 - 40-49 years old.
 - 50-59 years old.
 - 60-69 years old.
 - 70 years old or older.

3. What is your level of education?
 - Below high school level.
 - High school level.
 - Bachelor’s degree.
 - Master’s degree.
 - PhD.

4. Which of the following category applies to you? (You may choose more than one option if applicable).
 - I am a PV system user/owner.
 - I am an energy expert.
 - I am a worker in the electricity/energy industry.
 - I am an academic staff, and my line of activities are around energy/electricity.

1. Performance Expectancy (PE)		
5	I think the CEE/CHDT could help me to manage my household energy consumption more effectively.	PE1

	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
6	I think CEE/CHDT could help me to increase the level of efficiency in the way I make energy-use choices and decisions. (personal expectation).	PE2
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
7	Using CHDT-DSS could make my sustainable energy consumption efforts more productive	PE3
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
8	I think managing energy consumption using CEE/CHDT could be efficient. (Comparing to other known systems).	PE4
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
2. Effort Expectancy (EE)		
9	Using CEE/CHDT to manage household energy consumption seems to be easy (Theoretically).	EE1
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
10	Delegation of CEE/CHDT is clear and easy to understand.	EE2
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
11	If I can use a computer/cell phone, I think I can easily learn how to use CEE/CHDT .	EE3
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
12	I may require very little effort to use the CEE/CHDT (Practical).	EE4
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
3. Social Influences (SI)		
13	If people around me such as family members, friends, colleagues, and neighbours, use the CEE/CHDT , I will also try to use it.	SI1
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
14	If opinion leaders in my community such as teachers, bosses, or role models recommend the use of the CEE/CHDT to me, it can influence my intention or decision to use it.	SI2
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
15	I think using the CEE/CHDT could increase my social status as a “sustainable energy advocate”.	SI3
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
4. Facilitating Condition (FC)		
16	I am interested in perusing behaviours that could enhance the sustainable energy consumption in my home.	FC1

	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
17	My environment (workplace/community/close associates etc.) promotes sustainable energy consumption behaviours and are likely to endorse the CEE/CHDT.	FC2
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
18	I am interested in technologies and systems such as the CEE/CHDT that can help to promote sustainable energy consumption and practices.	FC3
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
19	If I encounter any difficulty in using the CEE/CHDT, I think I can get help from colleagues.	FC4
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
20	I am happy to adopt a decision-support system such as the CEE/CHDT to help me manage my household's energy consumption.	FC5
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
5. Use Intention (UI)		
21	I interested and would like to know more about the usage of the CEE/CHDT.	UI1
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
22	I am willing to use the CEE/CHDT	UI2
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
23	I am willing to recommend the use of the CEE/CHDT to people around me.	UI3
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
6. Collaborations		
24	I think the use of collaborations as demonstrated in the CE-E is a more efficient technique to manage renewable energy communities.	CO1
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
25	I am happy to participate in any collaboration activities that is practiced in the CEE.	CO2
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
26	I think the notion of collaboration as demonstrated in the CEE can give me some flexibility in the way I contribute to or practice sustainable energy consumption.	CO3
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
7. Goal Alignment		

27	I am willing to modify my energy-use preferences (voluntarily and regularly) to help my community (CEE) achieve its goals.	GA1
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
28	I will modify my energy-use preferences only when the community (CEE) provides me with some incentives.	GA2
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
29	I am willing to join short-term coalitions in the CEE if it is in line with my goals.	GA3
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
8. Delegation		
30	I am willing to delegate my CHDT to carry-out my energy-use preferences on my behalf.	DG1
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
31	Decision making using CHDTs could be more convenient than in person.	DG2
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	
32	I think I can trust my CHDT to make the right decisions on my behalf.	DG3
	Strongly Disagree <input type="radio"/> Disagree <input type="radio"/> Neutral <input type="radio"/> Agree <input type="radio"/> Strongly Agree <input type="radio"/>	



Appendix 2

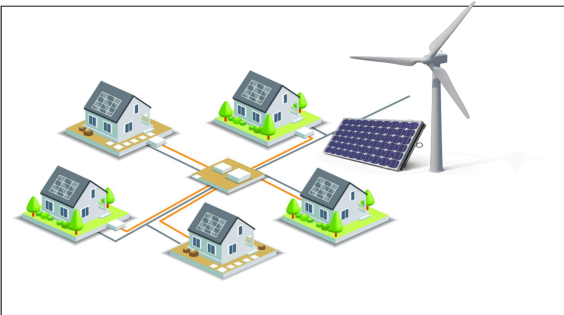
Data from the 31 Respondents

	PE1	PE2	PE3	PE4	EE1	EE2	EE3	EE4	SH	SI2	SI3	FC1	FC2	FC3	FC4	FC5	UI1	UI2	UI3	CO1	CO2	CO3	GA1	GA2	GA3	DG1	DG2	DG3
RESP-1	4	4	4	4	4	3	4	4	3	4	3	4	4	4	5	5	4	4	4	4	5	5	4	4	4	4	5	5
RESP-2	4	4	4	4	4	4	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	5	5
RESP-3	5	4	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	4	5	4	4	4	4	5	4	4	4	5
RESP-4	5	5	4	5	5	5	5	5	4	5	5	5	5	4	5	5	5	5	4	5	5	5	4	5	4	4	4	5
RESP-5	5	4	5	5	5	5	5	5	5	4	5	4	4	4	5	4	5	4	5	4	4	5	4	5	4	5	5	5
RESP-6	4	4	4	3	4	5	4	4	4	4	4	4	5	5	4	4	5	5	5	4	4	4	4	5	4	4	4	4
RESP-7	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	4	5	5	5	4	4	4	5	5
RESP-8	4	4	4	4	4	4	3	5	4	3	4	4	4	4	4	4	4	5	5	2	2	2	4	4	5	4	4	5
RESP-9	5	5	5	4	4	4	4	4	4	4	4	5	4	4	4	4	5	5	4	4	4	4	5	5	4	4	4	4
RESP-10	5	5	5	5	5	5	5	5	4	4	4	4	4	4	5	5	5	5	5	4	5	4	5	4	4	4	4	4
RESP-11	5	4	4	5	5	4	5	4	2	2	2	4	4	4	5	4	4	4	5	4	5	5	5	5	5	4	4	4
RESP-12	5	5	4	5	4	4	5	5	5	4	3	4	4	4	4	4	4	4	4	4	4	5	4	4	4	4	4	4
RESP-13	4	5	4	4	5	4	4	4	4	4	5	5	4	4	4	4	4	5	4	4	4	4	5	5	4	4	4	5
RESP-14	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5	4	4	4	5	4
RESP-15	5	5	5	5	5	5	4	5	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
RESP-16	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	4	5	4	4	4
RESP-17	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	4	4	5	5	4	4	4	4	4	4	4	4	4
RESP-18	4	4	5	4	5	4	5	4	4	5	4	4	4	4	5	3	4	5	4	4	4	4	4	4	4	4	4	4
RESP-19	4	4	4	4	4	4	4	3	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	5	4	4	5	4
RESP-20	5	5	5	4	5	5	5	4	4	4	4	4	5	4	5	5	5	5	5	5	4	4	4	4	4	4	4	5
RESP-21	5	5	5	5	4	4	4	4	5	4	4	4	5	5	5	5	4	4	4	4	4	4	5	4	4	4	5	4
RESP-22	5	5	5	5	5	4	4	5	3	4	4	4	4	4	4	4	4	5	5	5	5	4	5	4	4	4	5	4
RESP-23	5	5	5	4	5	5	5	5	4	4	4	5	4	5	4	4	5	5	5	5	4	4	4	5	4	4	4	5
RESP-24	5	4	4	4	4	4	4	4	4	3	5	5	4	5	4	5	5	5	5	5	5	4	5	4	4	4	5	4
RESP-25	4	4	4	3	4	4	4	4	3	3	3	4	3	4	3	4	3	3	3	3	4	4	5	4	4	3	3	3
RESP-26	5	5	5	5	5	4	5	4	4	4	4	5	4	5	4	5	5	5	5	5	4	4	5	5	4	3	3	3
RESP-27	5	5	4	4	4	4	4	4	5	5	5	5	3	5	4	4	5	5	5	4	4	4	4	3	4	4	5	5
RESP-28	5	5	5	5	4	4	5	5	4	3	5	5	4	3	5	4	4	5	4	4	5	5	5	5	5	4	5	5
RESP-29	4	4	4	4	5	5	5	5	4	4	4	5	4	5	3	4	4	4	4	4	4	4	4	4	4	4	5	5
RESP-30	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
RESP-31	4	5	4	3	4	4	4	4	4	3	3	3	5	3	4	3	4	5	4	5	4	4	4	4	4	5	4	4
Total	141	139	138	132	133	134	136	132	125	123	129	139	127	142	128	136	142	141	139	131	135	132	140	134	129	131	135	135
Average	4.55	4.48	4.45	4.26	4.29	4.32	4.39	4.26	4.03	3.97	4.16	4.48	4.10	4.58	4.13	4.39	4.58	4.55	4.48	4.23	4.35	4.26	4.52	4.32	4.16	4.23	4.35	4.35

Appendix 3

Some Selected Interfaces of the CEE and CHDT Models


The Collaborative Virtual Power Plant Ecosystem



The diagram illustrates a network of five houses, each equipped with solar panels, connected to a central power source consisting of a wind turbine and a solar panel. The houses are arranged in a circular pattern around the central power source, with lines representing the power distribution network.

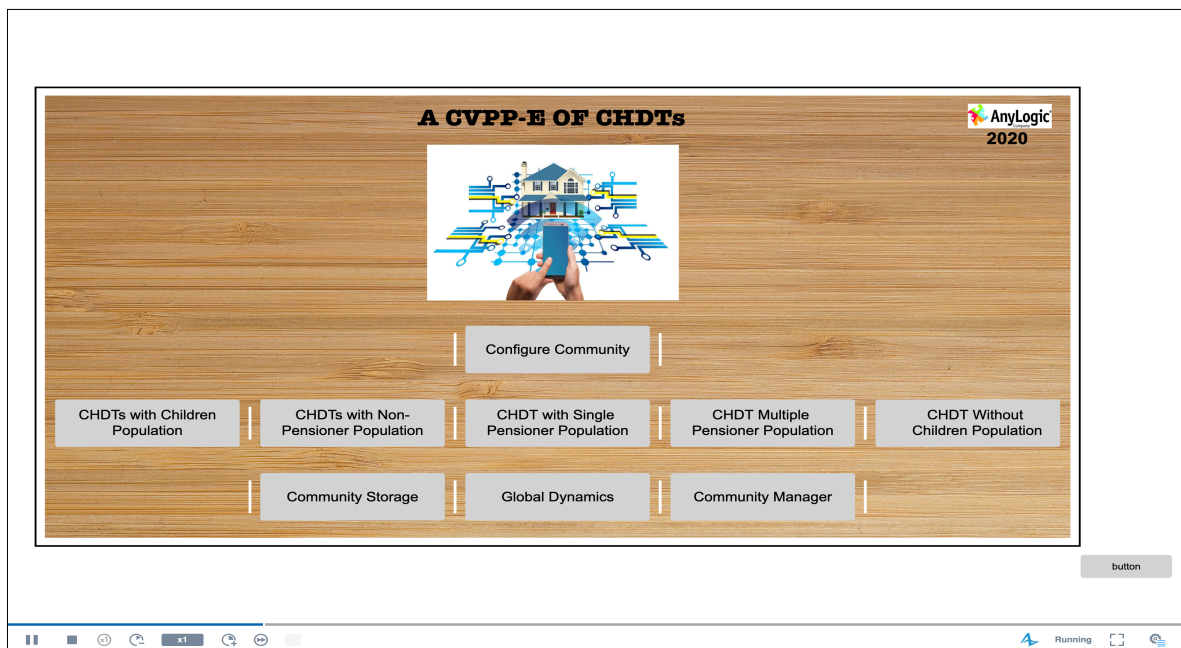
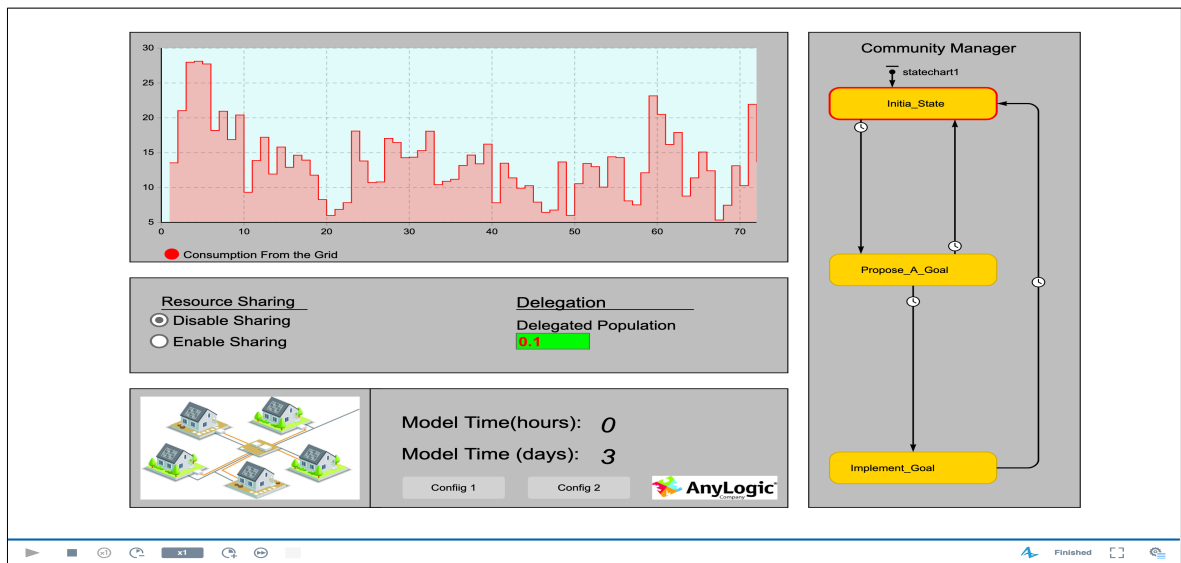
Discription of the scenario

1. Population of 100 households
2. The community manager proposed a goal
3. Acceptance or decline
4. Three kinds deffable loads (DL)
 - # Washing machine
 - # Dish washer
 - # Clothes dryer
3. Delegation DL
4. Collaborative decision-making

Powered by

(PLE Version)

▶■⌂⌂x1⌂⌂⌂

idle⌂⌂



Community configuration

CHDT of HH with no children

100

+1 CHDT	-1 CHDT
+5 CHDTs	-5 CHDTs
+10 CHDTs	-10 CHDTs
+50 CHDTs	-50 CHDTs

Total HHs of CHDT in Community

100

CHDT of HH with children

30

+1 CHDT	-1 CHDT
+5 CHDTs	-5 CHDTs
+10 CHDTs	-10 CHDTs
+50 CHDTs	-100 CHDT

Prosumer population **0.4**

Influencer population **0.5**

Positive Influencer Popul **0.9**

Cap. Of Community Storage **1000.0**

Undelegated
 Delegated

Enable Sustainability goals
 Disable Sustainability goals

Enable Social goals
 Disable Social goals

Enable Economic goals
 Disable Economic goals

Home

main root

newAgent null

connections

1 [root.cHDT_Household_with_single_pensioners[11]]

72:00 hours 11/04/2021 00:00

Time(hours): 0
Model days: 3

Appliance sub-model

Controller unit sub-model

PV sub-model

Process sub-model

Influencer / Influencee sub-model

Prosumer / Consumer sub-model

Appliance Behaviour sub-model

Aggregated consumption of the CHDT per energy source

Percentage consumption per energy source

- Community Storage 0 (0%)
- Local PV 19.16 (53%)
- Grid 7.86 (17%)
- Local Storage 14.42 (40%)

Home

Console

3,698 events scheduled by: T left

0 f@root.cHDT_with_non_pensi... 0.002

1 f@root.cHDT_Without_Childre... 0.002

2 f@root.cHDT_Without_Childre... 0.003

3 f@root.cHDT_Without_Childre... 0.01

4 f@root.cHDT_with_Childrens[... 0.013

5 f@root.cHDT_with_multiple_p... 0.02

6 f@root.cHDT_Without_Childre... 0.021

7 f@root.cHDT_with_multiple_p... 0.022

8 f@root.cHDT_with_multiple_p... 0.026

9 f@root.cHDT_Without_Childre... 0.039

10 f@root.cHDT_Without_Childre... 0.041

11 f@root.cHDT_Without_Childre... 0.043

12 f@root.cHDT_with_non_pensi... 0.059

13 f@root.cHDT_with_Childrens[... 0.069

14 f@root.cHDT_with_multiple_p... 0.076

15 f@root.cHDT_Without_Childre... 0.079

16 root.cHDT_with_Childrens[0].D... 0.083

17 root.cHDT_with_Childrens[0].B... ..

18 root.cHDT_with_Childrens[0].H... ..

19 root.cHDT_with_Childrens[0].H... ..

20 root.cHDT_with_Childrens[1].D... ..

21 root.cHDT_with_Childrens[1].B... ..

22 root.cHDT_with_Childrens[1].H... ..

23 root.cHDT_with_Childrens[1].H... ..

24 root.cHDT_with_Childrens[2].D... ..

25 root.cHDT_with_Childrens[2].B... ..

26 root.cHDT_with_Childrens[2].B... ..

27 root.cHDT_with_Childrens[2].H... ..

28 root.cHDT_with_Childrens[3].D... ..

29 root.cHDT_with_Childrens[3].B... ..

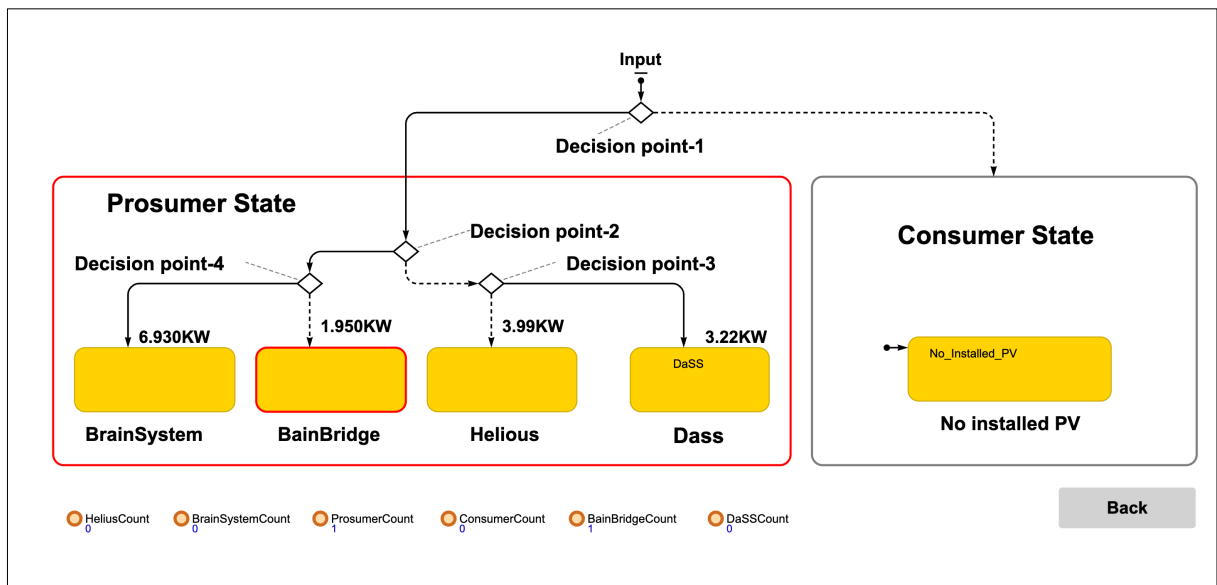
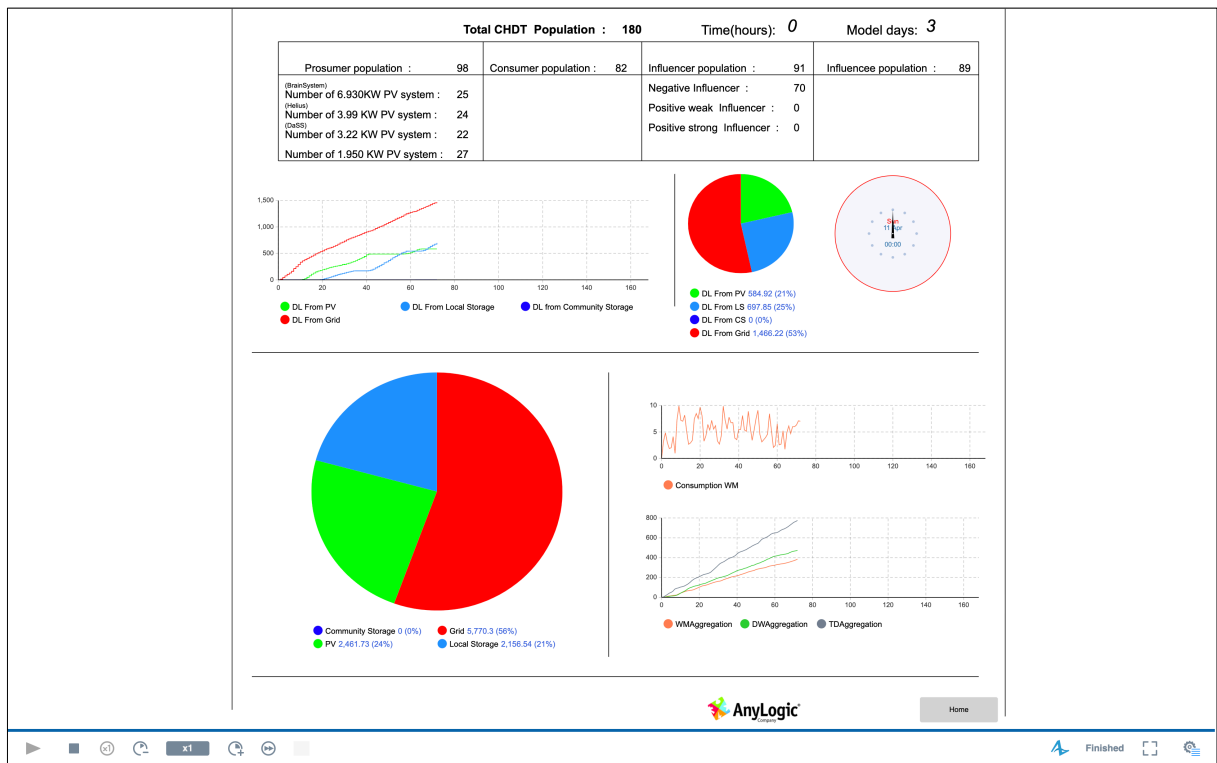
30 root.cHDT_with_Childrens[3].B... ..

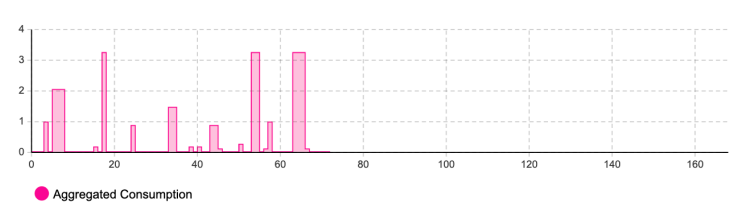
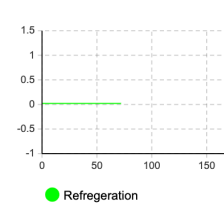
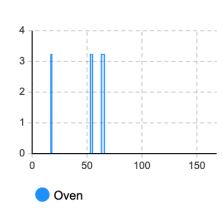
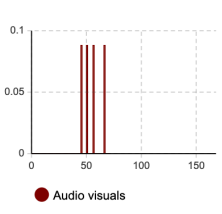
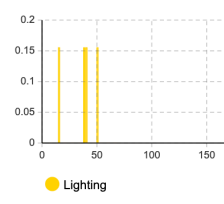
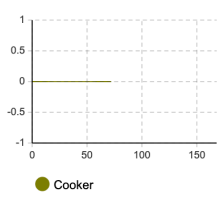
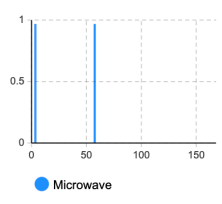
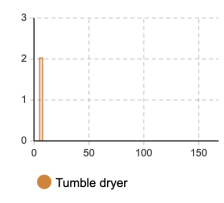
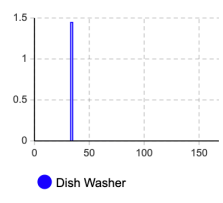
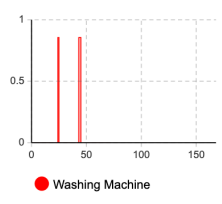
31 root.cHDT_with_Childrens[3].H... ..

0 hours/sec EPS: 0 FPS: 41 Step: 738,513

Running: 79.69 sec 76% of 512M

200





Back





A CONTRIBUTION TO COLLABORATIVE RENEWABLE ENERGY COMMUNITIES

KANKAM OKATAKYIE ADU-KANKAM

2023