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Economic Analysis of Rooftop Solar Panels in Bonn, Germany

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Summary of rooftop solar analysis

Location: Bonn, Germany **Date of analysis**: September 2022

Recommendation*: install 10 monosilicon modules, for a net present value of 5535.93 EUR, with a payback period of 11.22 years.*

Main economic results

Financing	NPV (EUR)	Payback (years)	IRR (%/year)	LCOE (EUR/kWh)
[Gov. subsidies and] 75% debt	5535.93	11.22	15.35	0.1395
[Gov. subsidies and] 100% equity	5342.83	10.18	8.32	0.1418
[No gov. subsidies and] 100% equity	2426.09	14.04	5.30	0.1464

(All rows are for the same number of kWp)

Additional results

The optimal year for setting up a 10 module monosilicon rooftop PV-system is 2022. An electricity price cap at 0.40 EUR/kWh with a maturity of one year reduces the NPV for the 01/01/2023 by 707.38 EUR.

Main inputs and assumptions

Household and Economics

Electricity Consumption	3519.4	kWh/year	Inflation	[1.8, 5.5]%	per year
Electricity Buy Price	[0.42,0.85]	EUR/kWh	Bank loan interest rate	2.23%	per year
Electricity Sell Price	[0.025,0.082]	EUR/kWh	Bank loan maturity	10	years
			Equity cost of capital	2.77%	per year

PV panels

Peak power	395	W/panel	System losses	15.02%	of output
Panel Area	1.9	m^2/panel	Degradation w/ age	0.7%	per year
Useful life	25	years	Maintenance costs	26	EUR/kWp
			Total cost of optimal installation size (without subsidies)	9356.34	EUR
			Total cost of optimal installation size (after subsidies)	8961.34	EUR
			Deinstallation Costs (not discounted)	1729.22	EUR

Government subsidies

Refund of 100 EUR for each installed Kilowatt-Peak up to 30 kWp (Bundesstadt Bonn). Feed-in tariff of 0.082 EUR/kWh for the first 20 years (*EEG*) and an 2.23% interest rate on a 10-year loan (*KfW Standard 270*).

1 Introduction

Since autumn 2021, EU countries have been pressured by rising energy prices, supply chain bottlenecks and complicating geopolitical factors. Additionally, the Russian invasion of the Ukraine accelerated difficulties and aggravated Germany's energy situation. The German dependency on Russian imports (55% of gas imports, 35% of oil imports and 45% of coal imports in 2021) represents a serious situation and requires massive changes (Gagnebin, Bouacida, & Rüdinger, 2022). Here matters the question of what kind of energy dependency is a country willing to enter. The Russian strategy of using energy supply as political leverage forces Germany to search for alternative sources. Those urgent problems require German households to turn down the heating, shower for shorter durations or take other energy-saving steps. Under the current time pressure, large-scale solutions on the governmental level may take too long. In order to relieve this situation, residential rooftop PV-systems embody the solution of reducing energy dependency by increasing supply. Photovoltaic systems represent a solution to turn down the demand for conventional electricity sources and reduce the pressure on the energy dependent industry. This technology enables households to consume power without provoking shortages in the wholesale market. In order to prove the value of residential PV-systems as microgenerators, which support the household electricity consumption and ease the electricity demand, the economic value under various determinants on the residential level has to be evaluated.

This analysis will show that residential PV-systems with a size between 2 and 30 modules generate a positive Net Present Value (NPV). In addition, the current price environment provides the optimal stimulus. Furthermore, a price cap of 0.40 EUR/kWh reduces the incentives for installing a PV-system.

2 Model Overview

This economic analysis of a rooftop PV-system under the assumption of different financial, economic and political situations for the German area is currently of immense importance. This work aims at examining different scenarios and highlighting the main factors. Several sources explored the economic viability by assuming static input factors or solely including inflationary patterns. The extension of non-static inputs is especially important due to the current situation of high volatility and uncertainty. Compared to rigid assumptions, a moving inflation rate and electricity prices inter alia extend the scope of this analysis. Those valuable extensions are applied to the optimization model of a household using a rooftop PV-system to determine the optimal solution in a volatile environment. This model identifies the optimal size of the PV-system by maximizing the NPV. For the optimal case, further indicators are calculated. Those indicators are besides the NPV, the Internal Rate of Return (IRR), the Payback Period (PP), and the Levelized Cost of Electricity (LCOE).

The analysis is constructed in three steps. First, each input is viewed on itself, and if necessary, assumptions and forecasts are made. If the variable is strongly influenced by the government and no obvious market prices are available, the forecast is as conservative as possible. Second, a technical simulation of the PV-system is conducted. Through this procedure, cash flows can be constructed for the chosen period and the optimum is found. To increase applicability, this process is implemented in an excel model. The model can adapt to different initial conditions, simulate different scenarios and apply various environments to those. Therefore, the performed project is made for the individual use-case and thus fulfills a long-term purpose in solving previously mentioned issues.

3 Data & Assumptions

3.1 Technical Parameters

3.1.1 PV-System

The main parts of the PV-system are modules, inverter, smart meter and further installation parts like cables. All those parts impact the efficiency of the system. Throughout the 25 years of the expected lifespan of the system, the power output decreases (Kost, 2021). The analysis is focused on monosilicon modules. The module efficiency decreases in the first year by 3% and in the following years by 0.7% (Wirth, 2022). This is called degradation. Both degradation values are the median degradation of the panels offered by the suppliers (photovoltaik4all.de, 2022). Further system losses stay constant each year. Those losses are, for example, inverter losses, AC/DC cables losses and temperature losses. It is important to include a tailored performance ratio for each year since the generated amount of power decreases annually and the relationship between prices and performance ratio can have a significant influence on profitability. If polysilicon modules are used, all system losses, despite the degradation of the panels, do not change. For the base case of monosilicon modules, the power output of the system is 84.98% of the irradiation on the panels in the first year and 71.29% in the last year (Reise, Müller, Armbruster, Reich, & Kiefer, 2012). Those results are in line with the German standard of initial system losses of 16% (Fraunhofer ISE, 2022).

3.1.2 Irradiance

The *EU Science Hub* provides the irradiance data for a 1 kWp PV-system for the city of Bonn (European Commission, 2022). The database *PVGIS-SARAH2* is used because it provides the most current data. The average irradiation of the years from 2016 to 2020 is considered and the 29th of February in leap years is excluded to increase accuracy. Overall, the average annual irradiance for

Bonn is 1223.08 kWh/m^{2}a for the adjusted panels. For comparison, the average solar irradiation on PV-modules in Central Germany is at about 1300 kWh/m^{2}a in 2021 (Kost, 2021). There are no initial system losses included when receiving the data because the respective performance ratio for each year is applied afterwards. The optimal slope and azimuth for the panels are utilized by the *EU Science Hub* and the assumption of the technical feasibility is applied (European Commission, 2022). In addition, the technology considered for irradiance data is crystalline silicon. Due to a time lag of 10 minutes in the irradiation series compared to the consumption series, the irradiation data had to be transformed. Therefore, it is shifted 10 minutes backward. As *Figure 10* in the *Appendix* shows, the transformation moves the power output curve further into the day. Due to the current price environment, it is preferable to consume the generated power than to sell. The share of consumed electricity increases with the transformation and therefore raises the NPV. The calculation for the transformation is shown by *Equation 4* in the *Appendix*.

3.1.3 Electricity Consumption

The considered household consists of two parents and two children. The base case assumes a family that lives in a house, uses gas for water and space heating and electricity for the stove. Air condition is not common in this part of Germany and therefore excluded. In addition, the excel tool can account for different sources of electricity consumption. For example, the tool user can choose between the type of power for stove, water, space heating, and the housing situation. The calculated annual consumption of the base case household is 3519.4 kWh per year. Further combinations of characteristics are for illustrative purposes presented in *Table 11* in the *Appendix*.

3.1.4 Load Profile

Figure 1: Standard load profile for different seasons (Y-Axis: kWh, X-Axis: Hour)

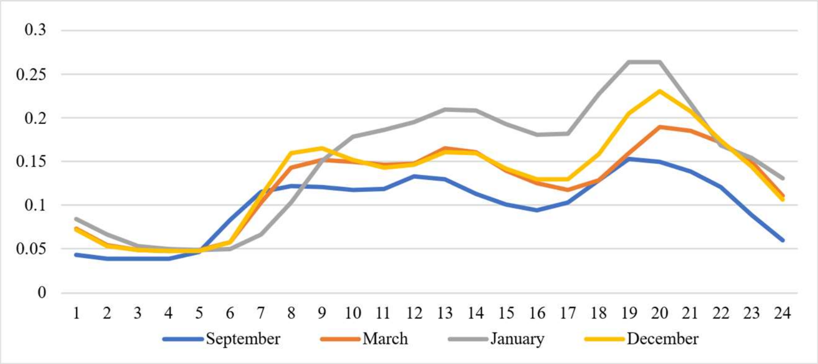


Figure 1 shows the electricity consumption of the household for each hour of the day for different seasons. Both parents are at work during the day and the kids are in school. The annual load profile is provided by the largest energy provider *Stadtwerke Bonn GmbH* for a household consuming 1000 kWh a year. This profile is used by the energy supplier for estimations of the hourly consumption if the household has no immediate measurement of electricity consumption. This profile is optimal because it is largely independent of the heterogeneity of the different household characteristics. If a consumption profile of a specific household is used, the result is biased. For example, a coffee machine biases significantly the energy consumption in the morning and particularly, when there is not sufficient energy generated by the system.

Fast load variations and prolonged periods without major electricity use are not captured. The time series is scaled to match the household annual consumption of the base case. The factor for the base case consumption is $\frac{3519.4}{1000}$. The assumption of linearity is applied here. That means, the consumption per hour increases linearly to the overall consumption.

3.2 Economic Variables

3.2.1 PV-System Price

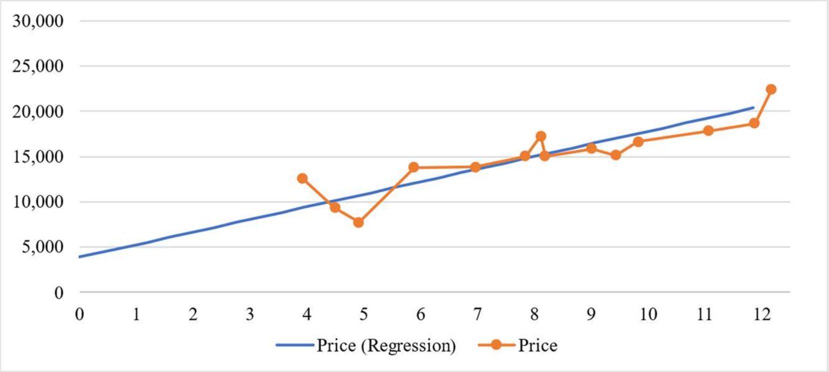
Each component of the system is separated from the bill. The average cost for an inverter is 1653 EUR, for a smart meter 315 EUR and for installation, cables, framework and further equipment 4603 EUR (photovoltaik4all.de, 2022). With the statistical linear regression, the price of a PV-system is separated into two parts and the price for each system size is calculated. The dependent variable for the regression is the price and the independent variable is the power in Kilowatt-Peak (kWp). Instead of estimating the price for a system using the number of modules (*NRM*), the power (*P*) is chosen. This is done because the power is the product of the number of modules, the solar panel yield, and the module area. Due to the higher comparability of the offers and therefore more accurate results, an estimation with the number of modules as the independent variable is not as sufficient as estimating the price with the power of the system.

Equation 1: Linear regression for PV-system price estimation in EUR

$$P_{PV} = 3854.28 + P * 1393.93$$

The constant of *Equation 1* is unrelated to the number of modules and is 3854.28 EUR. This number is lower than the average cost of 4603 EUR in *Section 3.1.1*, nevertheless, these costs include increases due to the *NRM* installed for each offer. These additional costs are incorporated in the coefficient. The coefficient is entirely related to the number of modules and increases with each installed Kilowatt-Peak 1393.93 EUR. This regression is sufficient, as the R^2 is 0.92. *Figure 2* displays the regression and the original offers received. Furthermore, this regression method decreases the impact of outliers.

Figure 2: Comparison of estimated prices and original prices (Y-Axis: EUR, X-Axis: kWp)



To increase the applicability of the work, the assumption is made that 0.395 kWp solar modules are used. With that, the price estimation is transformed to *NRM*. Unfortunately, no supplier offered the installation of polysilicon modules. Therefore, an estimation for illustrative purposes is done. The price of the monosilicon modules is approximately 27.3% higher, but the cost increase is compensated by a 29% higher efficiency (photovoltaik4all.de, 2022). The lower degradation supports the installation of monosilicon modules. Further information is shown in *Table 13* in the *Appendix*. For the illustrative estimation, the factors for price and efficiency are applied to the coefficient of the regression. With regards to that, the *NRM* is no longer correct after transformation, but the installed power is. This estimation shows, due to better financial metrics, that monosilicon is the preferred module type for residential usage.

The maintenance costs for the PV-system are expected to be at 26 EUR per installed kWp in 2022 (Kost, 2021). In the following years, the costs increase with inflation. Subsequently, deinstallation costs are estimated. Even if dismantling does not necessarily have to occur, there is still a risk of roof renewal or replacement of modules, which requires this necessary assumption. Therefore, the owner has to pay at the end of 25 years 1729 EUR. This number is calculated by taking 50% of the average labor costs of assembly and then the costs are linked to inflation.

The factor of 50% is applied since it provides a reasonable estimation of the reduction in costs compared to the initial installation.

Table 1: Estimated prices for the PV-system

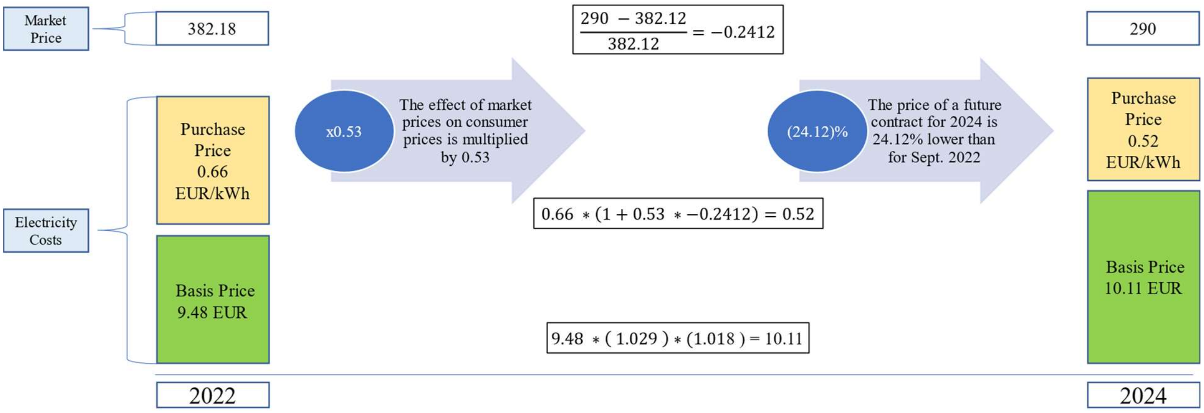
NRM	**1**	**3**	**5**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**15**	**17**	**19**	**21**	**23**	**25**
kWp	0.395	1.185	1.975	2.765	3.16	3.555	3.95	4.345	4.74	5.135	5.925	6.715	7.505	8.295	9.085	9.875
Price (€)	4404.49	5504.90	6605.31	7705.72	8255.93	8806.13	9356.34	9906.54	10456.75	11006.96	12107.37	13207.78	14308.19	15408.60	16509.01	17609.43

3.2.2 Electricity Costs

One of the most important factors determining the profitability of the PV-system is the cost of electricity consumption. Especially in the current price environment, it represents a significant factor. Even if the lifetime of a PV-system is 25 years, two years of high-level prices have a significant impact. This relationship is elaborated in *Section 6*. Several electricity providers are surveyed for prices in September 2022. The cheapest one is provided by the municipal company *Stadtwerke Bonn GmbH*. The costs are constructed out of two parts. The first is a fixed cost called the base price. This price is for September 2022 at 9.48 EUR per month and increases annually with inflation. The second part is the energy price per consumed kWh, declared as the purchase price. If the consumer prefers to consume conventional power and not renewable energy, it is 0.66 EUR/kWh. In order to receive the most accurate results, the purchase price is linked to *EEX German Power Futures* (European Energy Exchange AG, 2022). The prices for wholesale futures are calculated by taking the average of *baseload* and *peakload* futures from the *EEX* for each year. If the *peakload* futures are not available, only the *baseload* prices are considered. Those futures represent the wholesale prices, at which power providers like *Stadtwerke Bonn GmbH,* purchase supply on the exchange.

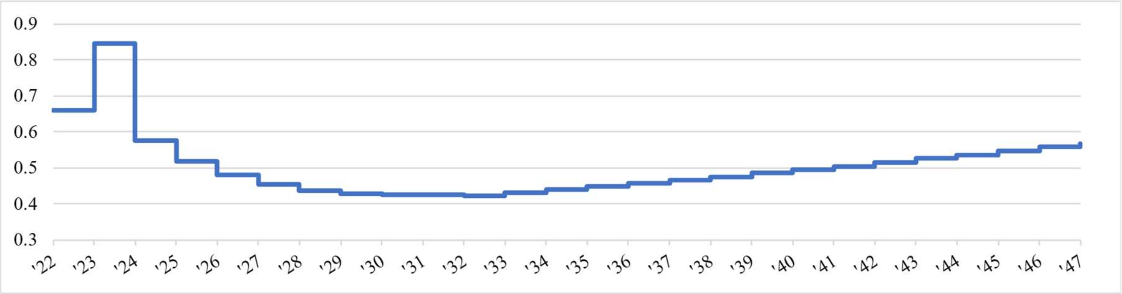
The current consumer power prices are then set in relation to the current *EEX German Power Futures*. Further information on the prices is shown in *Table 14* in the *Appendix*. The price development is estimated with the method presented in *Figure 3*.

Figure 3: Calculation method of electricity price forecasts



The change in wholesale prices is applied to the current household purchase price of the year 2022. The effect wholesale market prices have on consumer prices is on average 53% and applied to the change in wholesale prices (BDEW, 2022). Subsequently, this factor is multiplied with the current consumer purchase price. This is reasonable since the consumer price consists of multiple taxes and further factors besides the wholesale prices. The electricity price is calculated using this method until 2032. After 2032, the price is linked to inflation. Compared to assuming an average price of 0.39 EUR/kWh, this methodology considers the current market environment and resulting incentives (BDEW, 2022).

Figure 4: Purchase price development from 2022 until 2047 in (Y-Axis: EUR/kWh, X-Axis: Year)



Furthermore, the electricity prices are linked to the respective year. The case that the consumer is allowed to fix the prices for one year is excluded since future contracts for the respective whole year are considered. *Figure 4* shows lifted prices in 2022 and a massive spike in the year 2023. This spike can be explained by the current environment of uncertainty and decreased supply of fossil fuels by Russia.

3.2.3 Feed-In Tariff

The selling price of energy is fixed by the German government. The remuneration the producer receives depends on the month the PV-system is installed, the type of energy consumption and the size of the system (Bundesnetzagentur, 2022). This price is implemented through the *German Renewable Energies Sources* Act (*EEG*) of 2000. The ultimate goal of the *EEG* is to shift the energy supply and increase the share of renewables until 2050 to 80% in Germany. The tariff is received for a period of 20 years. Assuming the system is installed in September 2022 and a part of the produced energy is consumed, the producer receives for the following 20 years 0.082 EUR/kWh for the first 10 kWp and for the additional 30 kWp 0.072 EUR/kWh. If the produced energy is only feed-in, those rates are respectively 0.13 EUR/kWh and 0.109 EUR/kWh (Bundesnetzagentur, 2022). Since this rate is fixed by the government, forecasts based on market prices are unreasonable. However, German experts from the consumer advice center predict feed-in tariffs at 0.04 EUR/kWh to 0.02 EUR/kWh after 20 years (Seltmann, 2021). Therefore, the assumption for the first 10 kWp at 0.035 EUR/kWh and 0.025 EUR/kWh for additional 30 kWp is made. Those rates apply for the last 5 years of the PV-system and are therefore not as important as the rate stated by the government.

3.2.4 Taxation

The owner of a PV-system with power below 10 kWp has the decision to pay taxes on his profits. Since the main goal is to maximize profitability, no taxes are applied. Especially since a 10 kWp system requires more area than the typical roof size in the city of Bonn, the case of above 10 kWp is not considered. In addition, the government plans to release at the beginning of 2023 all taxes on income for residential PV-systems with power below 30 kWp (Diermann, 2022).

3.2.5 Financing

The financing for the first base case is a 75% debt share and a 25% equity share. The equity share is paid at installation. The optimal loan is determined by the lowest overall interest payment. In comparison to loans offered by regular banks, the *Kreditanstalt für Wiederaufbau (KfW)* offers special loans supported by the German government to raise third-party capital. Those loans are originated to support the sustainable renewal or reconstruction of houses. If the household consumes partially the energy produced, it is allowed to use *The Renewable Energy Standard Programme (270)* with a maturity of 10 years and a fixed interest rate of 2.23% (KfW, 2022). For the base case, a family household is assumed, that lives in a single-family house in the city of Bonn and therefore the highest credit rating for the loan is applied. All rates are retrieved on the 22/09/2022. The loan is repaid with the cash flow received from the feed-in revenue and the savings produced by the PV-system. Furthermore, an annual amortization is assumed, and no grace period is taken. This grace period would require further assumptions regarding the household financials and therefore distort the results. Concerning the subsidies, the city of Bonn pays each private installer of a rooftop PV-system for each kWp 100 EUR at installation until the system reaches 30 kWp (Bundesstadt Bonn, 2022). The assumed inflation rate is provided by the *International Monetary Fund* and reaches the preferred level of 2% in 2027 (International Monetary Fund, 2022). For the discount rate, the *EUR 10 yr Swap* rate of 2.77% is chosen (Financial Times, 2022)

4 Optimization Model

The framework in *Equation* 6 in the *Appendix* pursues the optimization of the NPV by changing the number of installed modules. Calculations regarding the assumptions and forecasts of the input variables are explained in *Section 3*. Main determinants like annual energy output, consumption rate and energy sold to the grid are computed in the technical simulation. It is preferred to consume the produced energy instead of selling it to the grid. This decision is taken by comparing the price of consumption and the feed-in price. As long as there is a positive spread, the energy is always preferably consumed. The optimal number of modules has to be a positive integer due to technical feasibility. By changing the input for the number of modules, the excel tool adjusts the inputs and calculates the NPV. In order to receive a broader picture of the financial side of the project, the financial metrics PP, IRR and LCOE are calculated. The LCOE compares the average total cost of a project per unit of total electricity generated. It is a specific measurement to compare methods of energy production (CFI Education Inc., 2022). Here, the LCOE is calculated by finding the cost of electricity for which the NPV is at par.

Table 2: Main inputs and assumptions

Household and Ecomics		**PV System**	
Name	**Value/[Min,Max]**	**Name**	**Value/[Min,Max]**
Consumption	3519.4	PV Price	NRM dependent
Inflation	[5.5%, 1.8%]	Deinstallation Costs	Average
Cost of Equity	2.77%	Lifetime	25
Cost of Debt	2.23%	Perf. Ratio	87.98%
Equity Rate	25%	Degradation	[3%,0.7%]
Debt Rate	75%	Irradiation	1223.08 kWh/m^{2}a
Purchase Working Price	[0.42€,0.85€]	Number of Modules	1 to 30
Purchase Base Price	9.48 €		
Selling Price	[0.025€,0.082€]		

5 Technical Simulation

Following the system set up, the technical simulation and the resulting cash flow calculation are performed. For each of the 8760 hours of the year, the simulation calculates the generated amount of power, the amount sold to the grid and the residual load. The residual load is the power amount the user has to consume from the grid instead of the PV-system, due to insufficient power supply. This calculation is done for each year. Therefore, different performance ratios and electricity prices can be applied. The main driver of the simulation is the amount of electricity savings (*ES*). This metric indicates the savings by using the PV-system without accounting for interest or other costs. The amount that would have been spent without a PV-system is computed, then the cash inflow of the electricity sold to the grid is added and reduced by the cost of consumption from the grid. This metric is optimal for the residential level because it is assumed that the required energy is consumed in any case. For a utility scale PV-system, this metric is less applicable.

Another metric to compare the different sizes of PV-systems is energy autonomy. As this topic is already mentioned in *Section 1*, the advantages of energy autonomy on the residential level have to be emphasized. The energy autonomy measurement indicates the share of energy produced when the energy is needed. The goal of our PV-system in terms of energy autonomy is to fill the area below the consumption graph, for example in *Figure 5*. The larger the filled area, the higher is the autonomy. Even if the electricity grid is highly reliable in Bonn, an increased energy autonomy prevents the consumer from unexpected price volatility.

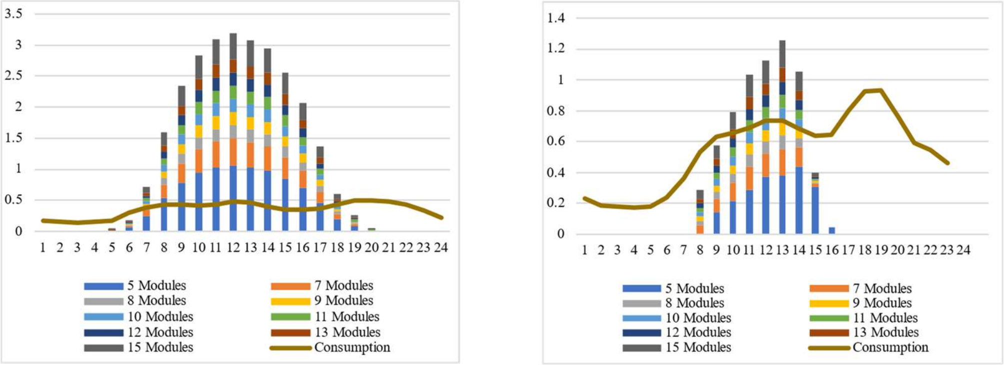
Table 3: Energy autonomy for NRM

NRM	**2**	**4**	**6**	**8**	**10**	**12**	**14**
Energy Autonomy	21.4%	35.1%	40.9%	44.2%	46.3%	47.7%	48.8%
Difference		13.7%	5.9%	3.2%	2.1%	1.5%	1.1%

Table 3 represents the relation between energy autonomy and power of the PV-system. The timing of the supply creates here the diminishing increase of the energy autonomy.

The local maximum is 52.51% with the installation of 30 modules. This is just an increase of approximately 6.34% compared to the energy autonomy with 10 modules. This is less efficient considering the 300% increase in the number of modules. Additionally, *Figure 11* in the *Appendix* presents the mismatch between consumed and produced energy per month for different system sizes. *Figure 5* elaborates on the mismatch further. While the PV-system performs from 7 am to 6 pm sufficiently in the summer, the energy is insufficient in the winter. In particular, an 8 module PV-system performs satisfactorily during the summer and for comparable performance in the winter, the installation of more than 10 modules would be necessary.

Figure 5: Hourly energy mismatch for June 2022 and December 2022 (Y-Axis: kWh, X-Axis: Hour)



6 Economic Valuation

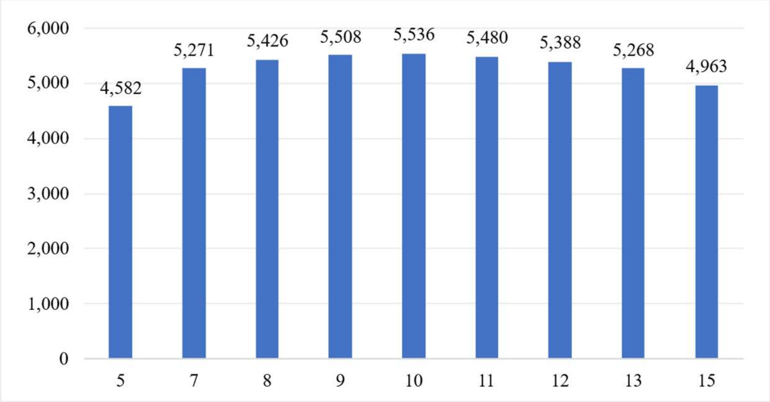
Before it can be said that residential PV-systems are the solution, easing the demand for energy from the wholesale market and decreasing the energy dependency, the PV-system has to be evaluated from an economic standpoint. This is especially important, because the owner of the rooftop has to be incentivized to install a PV-system. In *Section 5*, the technical information is calculated to compute the cash flows for the PV-system. The first step is to figure out the respective cash flows for each year. Those include, next to the *ES*, the loan repayment, the equity investment, government subsidies and maintenance costs.

Subsequently, the economic metrics are calculated. The optimization begins with the calculation of the NPV for each installation option. In the technical simulation, the factors are applied to the time series for each option. Subsequently, the highest NPV indicates the optimal *NRM*. For this system set-up, the remaining three metrics, IRR, PP and LCOE are calculated.

6.1 Base Case

For the base case, three different financing scenarios are applied. The first is a 75% debt and 25% equity share financing including government subsidies. The second is a 100% equity share financing and includes additional government subsidies. The last case excludes any external financing and subsidies. Even if the *EEG* is applied as a law, for illustrative reasons, an electricity selling price of 0.01 EUR/kWh is used for the case without subsidies and the option to take the *KfW 270* loan is excluded. The NPV for all base case variations of *NRM* is calculated for the 22/09/2022. *Figure 6* below shows an overview of the most reasonable solutions for standard financing.

Figure 6: NPV in EUR per NRM (Y-Axis: EUR, X-Axis: NRM)



The results prove the profitability of residential PV-systems in the city of Bonn in any reasonable case. In the range from 1 to 30 installed modules, the only non-profitable solution is the installation of 1 module. This is due to high fixed costs.

For further analysis, the base range of 5 to 15 modules is considered. The optimal number of modules is 10 with a power of 3.95 kWp. For the range presented, the NPV spread is 964.28 EUR. The energy autonomy increases from 38% to 46% on the left side of the optimum and 3% on the right-hand side.

Table 4: Overview of results for the range of 5 to 15 NRM

NRM	5	7	8	9	10	11	12	13	15
kWp	1.975	2.765	3.16	3.555	3.95	4.345	4.74	5.135	5.925
NPV (€)	4581.65	5271.23	5426.48	5507.98	5535.93	5480.43	5388.21	5267.95	4963.17
Energy Autonomy	38%	43%	44%	45%	46%	47%	48%	48%	49%
PV Price (€)	6605.31	7705.72	8255.93	8806.13	9356.34	9906.54	10456.75	11006.96	12107.37
Self-Consumption	72%	57%	51%	47%	43%	40%	37%	35%	32%

This shows the mismatch between energy provided and needed. With increasing *NRM*, the amount of energy produced increases, but the energy has to be required simultaneously. This relation is also shown in *Figure 5*. In addition, the fact that 5502.06 EUR more is spent in the 15 module case compared to the 5 modules case and still a higher NPV is returned, stresses the benefit of the energy autonomy. Furthermore, *Table 4* indicates that the energy autonomy rate is a better indicator compared to the self-consumption rate. The self-consumption rate shows the share of the consumption of the energy produced by the PV-system, presented in *Equation 3* in the *Appendix*. However, this rate ignores the importance of timing and price environment.

If the feed-in tariff would match the price of consumption from the grid, the optimal solution would shift upwards in terms of the installed power. In addition, the concavity of the function of the NPV shows the presence of a global optimal solution. In the case of abnormally high feed-in tariffs, the solution could be to install as many modules as possible, assuming linear pricing and technical feasibility. This stresses that the current incentive environment favors the installation of PV-systems mainly for personal needs instead of maximizing the energy supply.

In order to examine the results further from the financial side, three different financing scenarios are applied, and additional financial metrics are provided.

Table 5: Financial metrics for the 3 financing methods

Optimal NRM: 10	NPV (€)	PP	IRR	LCOE (€)
W/ subisidies 75% debt	5535.93	11.22	15.35%	0.1395
W/ subsidies 100% equity	5342.83	10.18	8.32%	0.1418
W/o subsidies 100% equity	2426.09	14.04	5.30%	0.1464

All financial metrics for the case of 10 module PV-systems are sufficient. The IRR of 5.30% without external financing underlines the economic viability of the PV-system. The return of the residential PV-system exceeds in any financing case the return of a 10-year BUND (Bloomberg L.P., 2022). This is highlighted by the PP of 11.22 in the best case. Comparing the return of the BUND and the return of the PV-system under the consultation of the risk profile, the spread in returns is impressive. However, the importance of the benefit of not purchasing energy from the grid has to be emphasized because the direct consumption from the PV-system is the main driver of cash flows. Therefore, this IRR is not comparable to the utility level. The LCOE is mainly driven by high maintenance and PV-system costs. Important is that the profitability of the PV-system does not rely on external financing and subsidies. Instead, a high electricity price environment is sufficient to guarantee the current profitability. It is even more reasonable to apply the electricity price for renewable sources of electricity. However, there is no exchange to receive the information for the future. The current purchase price for renewable electricity is 0.67 EUR/kWh and the fixed costs are 15.35 EUR per month. Assuming the same development of electricity prices for standard and renewably produced electricity, the NPV for the 22/09/2022 is 5857.15 EUR. This represents an IRR of 16.19%. This return is even more accurate, because the entire electricity is ecologically produced.

For further improvement, the NPV can be adjusted for energy security and decreased price volatility. Both factors drive the added value upwards. In the case of a NPV at par, energy security and decreased volatility represent motives for a residential user to install a PV-system.

6.2 Installation Date Scenarios

For further analysis, the option of when to install the PV-system is examined. Besides current bottleneck supply chain difficulties, the choice of if and when to install the PV-system has to be made. This valuation expands the assessment of the influence of different factors. Due to the current electricity price environment, it is highly preferable to install the PV-system as soon as possible. If the PV-system would have been installed on the 01/01/2022, the NPV would be 5821.68 EUR. One year later, the NPV is 5602.25 EUR.

Figure 7: NPV for different installation dates for various PV-system sizes (Y-Axis: EUR, X-Axis Date)

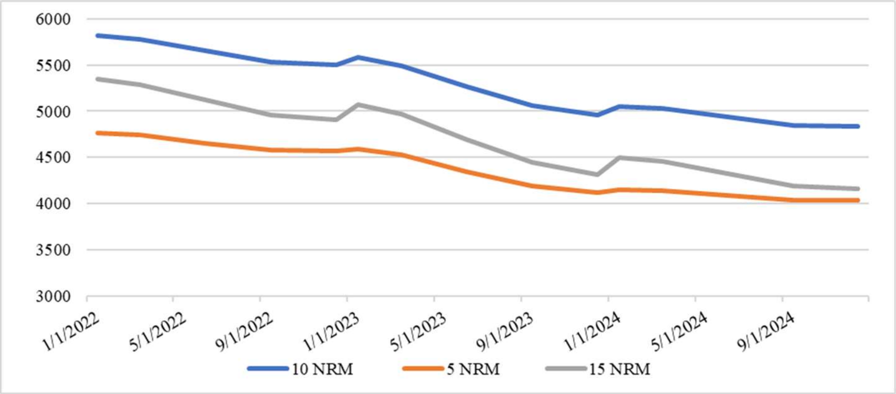


Figure 7 shows the importance of the beneficial electricity price environment. The high electricity costs offset the PV-system price and drive up the electricity savings. The linear guess is that the NPV for 22/09/2022 should be significantly higher compared to an installation on the 01/01/2023. However, if the project is started at the end of September, the high irradiation months of April until August are not taken into account. Therefore, this difference is reduced. Here, the interplay of timing and prices is significantly affecting our NPV.

This interplay is similar to the interaction of irradiation and energy consumption. However, here it is the interplay of electricity costs and monthly irradiation. This relationship is stressed by *Figure 7*, because the peaks around January increase with installed power. For further elaboration, the development of the PV-system price represents an important factor as well, but due to the lack of information, any forecasts would irritate the results above. Additionally, because of the marginal possibilities of prediction, the application of different feed-in tariffs is excluded.

6.3 Price Cap Analysis

The German government has announced a cap on household electricity prices on the 01/01/2023 (Reuters, 2022). This is done to relieve the economic pressure on households triggered by the supply shock following the Russian attack on Ukraine. On the one hand, the government supports German households and tries to prevent a recession. On the other hand, market mechanisms are suspended. With the price cap, the balancing mechanism of supply and demand is disabled and the decrease in demand, due to the increased prices and shortage in supply, will not happen. This increases the risk of further shortages in the short-term and mid-term. In order to analyze how a price cap will affect the expansion of residential PV-systems, a price cap on the grid price is applied. The planned price cap will be at 0.40 EUR/kWh for 80% of basic consumption and comes to effect on the 01/01/2023 (Reuters, 2022). Due to the complex electricity price in Bonn, a wholesale market price of 100 EUR/MWh was applied to the calculation explained in *Section 3.2.2*. This results in a purchase price of 0.40 EUR/kWh. In the simulation, the consumer still pays the fixed costs without a price cap. Due to the lack of exact information about the implementation, this is the most accurate illustration. In the case of a constant price cap with a duration of one year, the NPV is 4828.54 EUR. The price cap reduces the NPV compared to the base case and the same financing method by 707.38 EUR. This is a reduction of 13%.

Table 6 shows that with increasing maturity of a price cap, the NPV decreases. Furthermore, the analysis shows a decrease in incentives with a decreasing price cap level. If the supply of energy by PV-systems is considered exclusively, the price cap reduces the incentives of installing a PV-system in a period with strong demand for power supply. In connection with *Section 6.2*, it would be more profitable to wait and delay the installation. In the case of a one-year price cap, the NPV for the 01/01/2023 is 164.33EUR lower than the NPV for the installation one year later. With regard to the increased demand for renewable energy and energy independence, this represents an important implication.

Table 6: NPV for several price cap scenarios (NPV in EUR, price cap in EUR/MWh)

		Price Cap					
	NPV	60	80	100	120	140	160
Years	1	4770.76	4799.65	4828.54	4857.44	4886.33	4915.22
	2	4447.84	4504.81	4561.78	4618.75	4675.73	4732.70
	3	4220.41	4304.67	4388.94	4473.20	4557.46	4641.73

7 Comparison of Heidelberg, Germany and Bonn, Germany

Table 7: Overview of natural conditions for Bonn and Heidelberg

	Bonn	**Heidelberg**
Longitude [°]	7.101	8.695
Latitude [°]	50.736	49.409
Average Temperature [C°]	10.6	10.7
Days of Rain [d]	105	114
Elevation [m]	69	119
Average Hours of Sunlight [h]	6.7	7
Rainfall [mm]	847	927

Heidelberg is located in southwest Germany, while Bonn is situated in the far-west. *Table 7* compares both cities from a natural conditions' standpoint. Comparing both cities, Heidelberg proposes a better environment for the operation of PV-systems. For example, the number of average sunlight hours per day is higher and the elevation of Heidelberg is more favorable than of Bonn. The annual consumption in Heidelberg is 540 kWh higher than in Bonn. Electricity purchase prices – consisting of a purchase price per kWh and a fixed monthly payment, called basis price – in Bonn are above the German average, which is underlined by the significantly lower price in Heidelberg. Since the German feed-in tariff is fixed by the *EEG*, both cities share the same selling prices. In addition, the favorable loan conditions provided by the *KFW*, which support the expansion of renewable energy, are available in both cities. Furthermore, Heidelberg and Bonn subsidize the installation of residential PV-Systems with 100 EUR per kWp until 100 kWp and 30 kWp, respectively. Both PV system prices were estimated by linear regression and resulted in a difference of 69 EUR for panel-dependent and 991 EUR for panel-independent costs in favor of Heidelberg. An overview of the data is presented in *Table 8*.

Table 8: Main input data for both cities

	Bonn	**Heidelberg**
Irradiation incl. System Losses (14%) [kWh/m²a]	1051.58	1065.93
Consumption [kWh]	3519	4059
Elelctricity Price		
Basis Elelctricity Price [EUR/kWh]	113.76	21.5
Working Electricity Price [EUR/kWh]	0.66	0.48
Subsidies		
Electricity Selling Price [EUR/kWh]	0.082	0.082
Subsidies at installation [EUR/kW]	100	100
PV Price		
Module Dependent [EUR]	1393.93	1325.29
Constant [EUR]	3854.28	2863.45
Maintenance Costs [EUR/kW]	26	26

The optimal solution for Heidelberg is the installation of 18 modules (385 Wp) with an NVP of 10250.11 EUR. In contrast, the optimal solution in Bonn is scaled smaller, involving the installation of 10 modules (395 Wp) with an NPV of 5535.93 EUR. Further financial metrics are shown in *Table 9*.

Table 9: Overview of the optimal solution

	Bonn	Heidelberg
kWp	3.95	6.93
Modules	10	18
NPV [EUR]	5535.93	10250.11
IRR [%]	15.35%	9.36%
Payback Period [Year]	11.22	9.7
LCOE [EUR]	0.1395	0.1328

For a better comparison of both areas, an example installation of 14 modules was simulated as shown in Table 10. To understand the determining factors for the discrepancy in profitability, the difference for each cost or revenue stream was set in relation to the NPV following *Equation 5* in the *Appendix*.

Table 10: Comparison of Bonn and Heidelberg for a 14 modules PV-system

14 Modules	NPV	Cost of PV-System	Maintenance Costs	Electricity Savings
Bonn	5125.28	-11557.16	-4691.26	27628.14
Heidelberg	10175.75	-10006.76	-6428.99	33736.83
Difference	-5050.47	-1550.40	1737.73	-6108.69
Weight	-	30.70%	-34.41%	120.95%

Comment: Maintenance Costs and Electricity Savings (ES) are not discounted to Present Value. ES includes savings and revenue. Positive values present favorable conditions for Heidelberg. Negative values support Bonn.

Following this rationale, *Electricity Savings* were identified as the main value driver. Since the same selling price applies in both areas, the difference evidently results from *ES*. At first glance, this is contradictory since the electricity purchase prices in Bonn are higher. However, as Heidelberg has a larger annual energy consumption, higher self-consumption is implied, which leads to increased monetary savings overall. The residual value drivers *Cost of PV System* and *Maintenance Costs* virtually neutralize each other. On the one hand, the installation costs of PV-systems in Heidelberg are generally lower. On the other hand, higher maintenance costs occur. The latter may also be distorted, as insurance costs in Heidelberg are added to the maintenance costs.

Overall, the subsidies, loan conditions and prices for PV-systems in both cities are well comparable. However, the time at which the data was collected plays an important role. For example, the discount rate and inflation assumption vary in both models. In addition, the different energy prices, and the adoption of deinstallation costs in the model for Bonn limit the comparability significantly.

8 Limitations

This techno-economic analysis relies heavily on assumptions and forecasts. Therefore, its limitations have to be stressed. First, this analysis uses current information on inflation and interest rates. Those factors influence profitability and represent important conditions of the analysis. However, the economic environment can change rapidly. Therefore, the results cannot be applied in the long-term. Each forecast is made from the most reasonable standpoint on the 22/09/2022. It is important to contextualize each factor, hence policy implications are not subject to market mechanism. Particularly, the temporal analysis of when to install the PV-system is mainly based on the energy price forecast. Further factors, like the development of PV-system prices, electricity market mechanisms or other main inputs are not further considered. The technical simulation is restricted by limitations in data. Each input information is used with regards to the city of Bonn in Germany and the results are geographically and seasonally constrained.

9 Conclusion & Outlook

The techno-economic assessment of rooftop PV-systems adds value in the current geopolitical and economic environment since it analyses the incentives and the feasibility of a possible solution. To enable this analysis on the city level for residential use, each assumption is considered and forecasts for the inputs are made. Care is taken to ensure that each input is predicted realistically unless it is biased by random influence factors. Those inputs are embedded in an excel tool, which can be tailored to specific household and input variable characteristics. The technical analysis is conducted with the excel tool and economically evaluated. In this way, long-term value is created since the heterogeneity of residents can be applied here.

If all assumptions and forecasts hold, it can be stated that the only non-profitable PV-system is the 0.395 kWp (1 module) system. In any other case until 30 modules, it is profitable to install a residential PV-system. The highest NPV for the case of a standard family household in the city of Bonn is reached with the installation of 10 modules. The optimal timing for the installation is as soon as possible. This is driven by the high prices of energy consumption. A price cap on household electricity prices would decrease the profitability of the PV-system. However, it can be added that due to the high electricity prices, the incentives to install a PV-system are high and an increase in the feed-in tariffs would effectuate an expansion in the supply of residential renewable energy.

For further research, it would be interesting to elaborate on different approaches to feed-in tariff mechanisms. Especially interesting would be the optimal and sustainable price framework for reaching maximum supply with residential systems.

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11 Appendix

11.1 Variables

All non-derivable variables for the optimization model are shown in *Section 11.4*. The framework only explains formulas that directly influence the optimal solution. For example, the inflationary increase of the OPEX is not directly connected to the optimal solution. Each exact calculation is presented in the excel tool. Further information is given in the excel tool.

11.1.1 Technical

NRM = number of modules installed

P = PV power installed in kW (kW)

IR_h = irradiance for each hour in Watt (W)

C = annual consumption in kWh

CN_h = consumption in each hour per Watt(h)

PR_t = performance ratio in year (t)

N = lifetime of PV in years (t)

EO_t= energy output in kW in year (t)

11.1.2 Economic

GS_t = government subsidies in year (t)

WP_t = purchase working price of power in year (t)

BP_t = purchase base price of power in year (t)

FiT_t = feed-in price in year (t)

PV_{NRM} = price of PV system (EUR)

$OPEX_t$ = operating costs of PV system per kWp installed in year (t)

r_{debt} = interest rate on loan (%)

n = loan maturity in years (t)

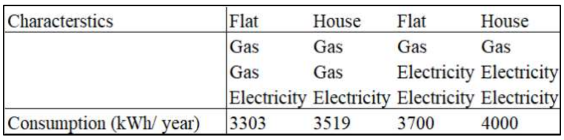
r_{equity} = cost of equity (%)

w_{equity} = equity share (%)

w_{debt} = debt share (%)

11.2 Tables

Table 11: Household consumption scenarios in kWh per year



Characterstics	Flat	House	Flat	House
	Gas Gas Electricity	Gas Gas Electricity	Gas Electricity Electricity	Gas Electricity Electricity
Consumption (kWh/ year)	3303	3519	3700	4000

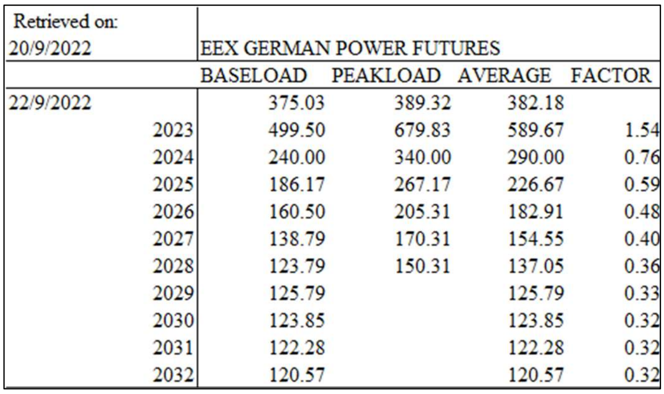
Table 12: NPV for 5, 10 and 15 NRM systems on different dates of installation

	10 NRM	5 NRM	15 NRM
22.01.2022	5817.772795	4764.232057	5343.812261
22.03.2022	5778.580064	4743.077354	5289.981218
22.06.2022	5650.066208	4656.20566	5118.556787
22.09.2022	5535.927526	4581.646044	4963.17439
22.12.2022	5497.99824	4568.372274	4905.479043
22.01.2023	5583.592806	4587.99603	5073.324142
22.03.2023	5491.784294	4524.167131	4963.886007
22.06.2023	5267.24578	4349.523635	4692.779223
22.09.2023	5065.243875	4194.141967	4446.43622
22.12.2023	4956.040096	4124.483052	4312.404956
22.01.2024	5054.151226	4151.675578	4494.815184
22.03.2024	5031.361441	4142.079058	4458.752599
22.06.2024	4935.799643	4084.580901	4321.819623
22.09.2024	4850.323232	4035.785501	4196.343451
22.12.2024	4832.448669	4035.445399	4161.020761

Table 13: Comparison of mono- and polysilicon modules

	Mono	Poly	Factor ON AVERAGE
Average Price	**267.5**	**210**	**79%**
Average Effciency	**0.2025**	**0.1575**	**129%**
Degradation Factor 1. Year			**110%**
Degradation Factor			**105%**

Table 14: EEX German Power Futures (20/09/2022)



Retrieved on: 20/9/2022	EEX GERMAN POWER FUTURES			
	BASELOAD	PEAKLOAD	AVERAGE	FACTOR
22/9/2022	375.03	389.32	382.18	
2023	499.50	679.83	589.67	1.54
2024	240.00	340.00	290.00	0.76
2025	186.17	267.17	226.67	0.59
2026	160.50	205.31	182.91	0.48
2027	138.79	170.31	154.55	0.40
2028	123.79	150.31	137.05	0.36
2029	125.79		125.79	0.33
2030	123.85		123.85	0.32
2031	122.28		122.28	0.32
2032	120.57		120.57	0.32

11.3 Figures

Figure 8: Cash Flow Profiles and Working Price (Y-Axis 1: EUR/kWh, Y-Axis 2: EUR, X-Axis: Date)

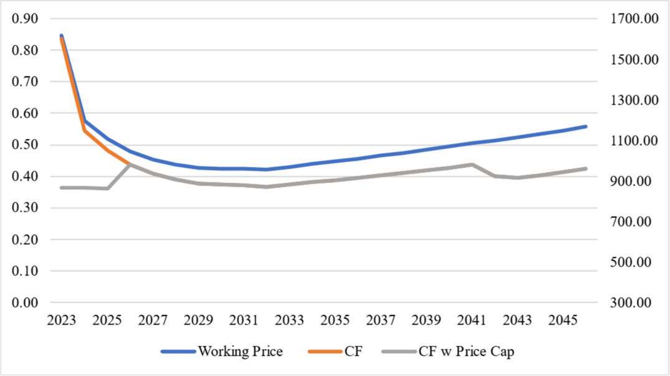


Figure 9: EEX German Power Futures (Y-Axis: EUR/MWh, X-Axis: Date)

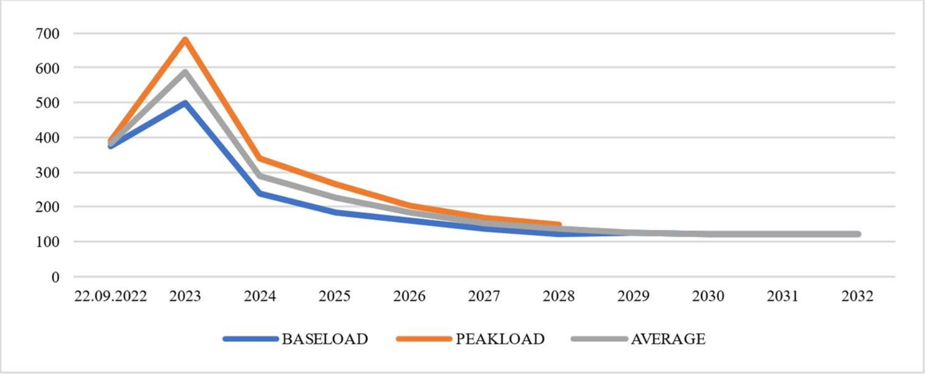


Figure 10: Transformation example of the irradiation data (Y-Axis: kWh, X-Axis: Hour)

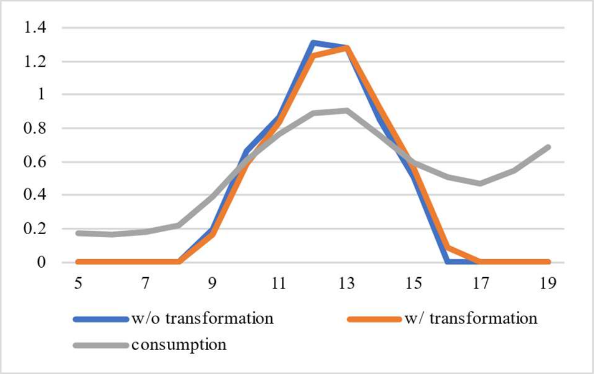
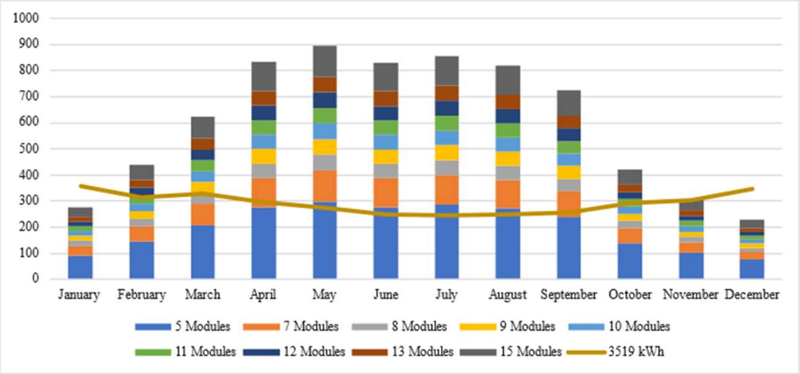


Figure 11: Energy and consumption mismatch for different PV-system sizes (Y-Axis: EUR, X-Axis: Month)



11.4 Equations

Equation 2: Energy Autonomy

$$Energy\ Autonomy = \frac{\sum Energy\ Needed}{\sum Energy\ Consumed} = \frac{\sum_{t=0}^{N} \sum_{h=0}^{8760} MIN(EO_h, CN_h)}{N * C}$$

Equation 3: Self-Consumption Rate

$$Self - Consumption\ Rate = \frac{\sum Energy\ Cnsumed}{\sum Energy\ Generated} = \frac{\sum_{t=0}^{N} \sum_{h=0}^{8760} MIN(EO_h, CN_h)}{\sum_{t=0}^{N} \sum_{h=0}^{8760} EO_h}$$

Equation 4: Example of a time series transformation

t_1: 00:10 to 01:10

t_2: 01:10 to 02:10

$t_{2(true)}$: 01:00 to 02:00

$$t_{2(true)} = \left(\frac{1}{6}\right) * t_1 + \left(\frac{5}{6}\right) * t_2$$

Equation 5: Weight calculation

$$Weight_{Input\ Factor} = \frac{Input\ Factor_{\ Bonn} - Input\ Factor_{\ Heidelberg}}{NPV_{\ Bonn} - NPV_{\ Heidelberg}}$$

Equation 6: Mathematical Framework

$$P = NRM * \frac{395}{1000}$$

$$EO_t = \sum_{h=0}^{8760} PR_t * \frac{IR_h}{1000} * P$$

$$EP_h = PR_t * \frac{IR_h}{1000} * P$$

$$ReC_t = \sum_{h=0}^{8760} (CN_h - EP_h) * WP_t + BP_t$$

$$RfG_t = \sum_{h=0}^{8760} (EP_h - CN_h) * FiT_t$$

$$C_{wo,t} = BP_t + CN_t * WP_t$$

$$ES_t = C_{wop,t} + RfG_t - ReC_t$$

$$CO_t = LA_t - OPEX_t - EQ_t$$

$$EQ_t = w_{equity} * PV_{NMR}$$

$$LA_t = \frac{1 - (1 + r_{debt})^{-n}}{r_{debt}} * w_{debt} * PV_{NMR}$$

$$CI_t = GS_t + ES_t$$

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1 + r_{equity})^t} = \sum_{t=0}^{N} \frac{(CI_t - CO_t)}{(1 + r_{equity})^t}$$

$$0 = \sum_{t=0}^{N} \frac{C_t}{(1 + IRR)^t}$$

$$0 = \sum_{t=0}^{PP} \frac{C_t}{(1 + r_{equity})^t}$$

$$LCOE = \frac{\sum_{t=0}^{N} \frac{CO_t}{(1 + r_{equity})^t}}{\sum_{t=0}^{N} \frac{EO_t}{(1 + r_{equity})^t}}$$

$$NPV = \sum_{t=0}^{N} \frac{(CI_t - CO_t)}{(1 + r_{equity})^t}$$

11.5 Data Sources

Electricity Consumption

1) https://www.stromspiegel.de/fileadmin/ssi/stromspiegel/Broschuere/stromspiegel-2021.pdf
2) eon.de
3) Bills provided by friends and family
4) https://www.stromspiegel.de/beratung/stromcheck/?menustep=bewertung
5) Estimation through statistical regression to fill in missing profiles
6) https://www.co2online.de/energie-sparen/strom-sparen/strom-sparen-stromspartipps/stromverbrauch-4personenhaushalt/#:~:text=Der%20durchschnittliche%20Jahresstromverbrauch%20von%204
7) https://www.e-wie-einfach.de/strom/ratgeber/stromverbrauch-4-personen

PV Price and Offers

Supplier	Website
SRW-Energy & Partner	https://srwenergy.de/
Zolar	https://zolar.de/
wegatech	https://www.wegatech.de/
Scm Energy	https://scm-energy.de/
Solarville	https://www.solarville.ch/
Sinus Photovoltaik	https://www.sinus-pv.at/
Enpal	https://www.enpal.de/

Financials

1) https://www.kfw.de/inlandsfoerderung/Privatpersonen/Bestandsimmobilie/F%C3%B6rderprodukte/Eneuerbare-Energien-Standard-(270)/
2) https://www.kfw.de/inlandsfoerderung/Privatpersonen/Bestandsimmobilie/F%C3%B6rderprodukte/Eneuerbare-Energien-Standard-(270)/
3) https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html
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