REAL OPTIONS ANALYSIS APPLIED ON RESIDENTIAL ENERGY SYSTEMS USING LEAST SQUARES MONTE CARLO SIMULATION

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ABSTRACT

Fossil fuel technologies still play a major role in residential heating, but the transition to cleaner alternatives such as heat pumps, photovoltaics, and energy storage is crucial. For the economic assessment of these residential energy systems discounted cash flow analysis is usually utilized e.g. by calculating the net present value (NPV). This approach's shortcoming is its neglect of flexibility in the decision-making process, as it values each system assuming an immediate investment. To address this issue, we apply real options analysis considering the real option to defer an investment to account for future changes of the investment conditions. To value the real option, we use a least squares Monte Carlo simulation option pricing model and calculate the enhanced net present value (ENPV) of each system. A typical single-family house located in Germany is used as a case study. Photovoltaics, battery storages, electric air-to-water heat pumps and condensing gas boilers as well as combinations of these technologies are considered as investment options. The results show that incorporating the real option value leads to a shift in the economic assessment of the systems. In the long-term, the highest ENPV are reached by the combination of a heat pump with photovoltaic whereas with the traditional NPV the economic most favorable decision is a new gas boiler. Furthermore, an examination of different scenarios for heat pump subsidy schemes and CO2 price trends is presented. The analysis shows that the heat pump subsidy schemes lead to a substantial increase of the ENPV even for low deferral periods. In contrast, CO2 price trends alone do not offer the same level of encouragement for an early optimal investment time but provide a significant long-term economic incentive for transitioning to cleaner technologies in the residential heating sector.

1 INTRODUCTION

In 2045 Germany wants to reach a climate neutral energy system across several sectors. A major challenge lies in the decarbonization of the national building stocks. Most of the heat supply for residential buildings relies currently on natural gas boilers (BDEW, 2023). Studies investigating potential future pathways for achieving a climate-neutral energy system in Germany show that heat pumps will become the primary heating technology in the residential sector (Brandes et al., 2021; Sensfuß & Maurer, 2022). This result is robust across several scenarios within the studies. In addition, the number of photovoltaic systems is also expected to increase together with the number of battery systems to further increase the self-consumption of locally produced electricity.

For many households the technology switch is challenging as huge investments under uncertain conditions must be made. Heat pumps have higher investment costs than gas boilers which hinders a fast adaptation. Current studies indicate that heat pump systems can have economic advantages even under today's investment conditions in comparison with a new gas boiler (Langreder et al., 2022, 2023; Meyer et al., 2024). But these results are heavily dependent on the assumptions made regarding the long-term development of energy costs and the subsidy schemes for heat pump investments. Especially the energy costs are either modelled as a constant value or a specific development path is considered, which is very likely to deviate a lot from the actual costs developments that may appear in the future.

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Furthermore, many of these studies focus solely on immediate investments without considering the potential economic benefits of deferring investments to a later time when conditions may be more favorable. For instance, due to technological learning, a decrease in the investment costs is to be expected for relevant technologies (Louwen & Junginger, 2021). Moreover, an increase of the CO2 price will lead to higher gas consumptions costs which might result in an economic advantage of heating technologies based on electricity.

Real options analysis provides a solution to assess investment strategies under uncertainty by considering the managerial flexibility e.g. to defer, expand or relocate a project. Several literature reviews (Kozlova, 2017; Lazo & Watts, 2023; Liu et al., 2019; Nadarajah & Secomandi, 2023) show that the application of real options analysis for the evaluation of renewable energy projects is of growing interest. However, studies that focus on the evaluation of investment strategies incorporating real options analysis in the residential sector are very scarce and mainly focus on the electricity sector with PV and battery as investment projects.

This study presents a real option pricing model, that is based on the least squares Monte Carlo algorithm proposed by Longstaff and Schwartz (2001). We investigate the value of the real option to defer an investment. To the best knowledge of the authors, this is the first time this method is applied for the economic evaluation of residential energy systems involving investments in new heating technologies in addition to the evaluation of PV-systems and battery storages. To further investigate the effects of the CO2 price and the subsidy schemes for heat pumps, a scenario analysis is performed by changing the deterministic trend function of the gas price and heat pump capex accordingly.

The present paper is structured as follows: In the second section an overview on real option evaluation and the theory regarding the real option pricing model based on least squares Monte Carlo simulation is presented. The third section presents the case study which is given by a single-family house and the parametrization of the option pricing model. Section four presents the results and in the fifth section the conclusions are given with some advice for further research directions.

2 METHODOLOGY

In this section we introduce the methodology of the economic evaluation approach based on real options analysis.

2.1 Discounted Cash Flow Analysis (Net Present Value)

Traditional Economic Assessment is based on the discounted cash flow analysis (DCF) to determine the Net Present Value. The Net Present value shows whether the initial capital expenditures taken on the year of investment are covered by the positive discounted cashflows in the subsequent years. In this case the positive Net Present value becomes positive and thus an investment is profitable. Otherwise, in the case of a negative Net Present value, the investment should be rejected. In this study the net present value of a given system is defined by

$$NPV_{Sys_{t_{inv}}} = \frac{-CAPEX_{Sys_{t_{inv}}} + CAPEX_{Ref_{t_{inv}}}}{(1+r)^{t_{inv}}} + \sum_{t=t_{inv}}^{Lifetime} \frac{OPEX_{Ref_t} - OPEX_{Sys_t}}{(1+r)^t}. \tag{1}$$

This formulation of the NPV compares the total cost of a given energy system with a reference system. The revenue to cover the investment costs is therefore defined by the savings of operational cost against a reference. The operational costs include electricity, gas and maintenance costs. Furthermore, potential revenues by grid feed-in tariffs are also covered as negative costs in the OPEX terms. The NPV becomes positive, if the total costs from a given system are less than the reference system.

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2.2 Real Options Analysis

Real options analysis expands on the DCF approach by considering the value of investment opportunities beyond the present. Real options analysis allows for a more comprehensive evaluation of investment opportunities. While DCF helps decision-makers determine the most valuable investment opportunity, it assumes that the investment must be made immediately. This "now or never" approach neglects the flexibility a decision maker would have in the real world. Someone could defer, expand, stage, switch, or abandon an investment. This flexibility options referring to investment decisions upon real assets are called real options. To account for the added value through flexibility in the decision making the Enhanced Net Present Value (ENPV) is defined as the sum of the traditional Net Present Value (NPV) and the Real Option Value (ROV):

$$ENPV = NPV + ROV \tag{2}$$

As we look at the real option to defer an investment, the analogy to a financial American call option can be drawn. A call option is defined as the opportunity but not obligation to buy a stock or any other underlying asset for a defined price in the future, namely the strike price. An American option can be executed at any time in the future until its expiration time. Thus, an American call option becomes profitable if a stock price in the future exceeds the strike price. The difference of the stock price, at the time the option is executed at, and the strike price is the payoff Π of the option. In conclusion, the expected pay-off of this option defines its value. In our case, the assessment of the value of deferring an investment into an energy system, the expected pay-off can be interpreted as the expected difference between the current value defined by NPV_{t_0} (the strike price) and the expected future value of $NPV_{t_{inv}}$, where t_{inv} is the expected optimal time to invest. In this case the expiration time can be interpreted as the maximum waiting time someone is willing to plan and thus defer the decision to invest in a given energy system.

2.3 Least Squares Monte Carlo Simulation

There exist various methods for valuing real options which are derived from financial option pricing models. In this work we choose the least squares Monte Carlo algorithm to calculate the value of the option to wait. The algorithm was proposed by Longstaff and Schwartz (2001) as a method for pricing financial options. Among different methodologies for real options analysis in the realm of energy systems design this approach is considered state-of-the-art and of growing interest in research (Alonso-Travesset et al., 2023). In the following, its main ideas are presented based on the application of our use case. A more detailed and general presentation for the application on investments in PV systems is given in An et al. (2021), Ma et al. (2020) and Pringles et al. (2020).

The evaluation of the option to defer comes down to an estimation of the optimal investment time within a given time span. This time span is determined by the maximum waiting time for the consideration of a specific energy system. In our study we apply the least squares Monte Carlo option pricing approach model by Longstaff and Schwartz (2001) for our investment decision scenario. It is based on a Monte Carlo simulation of the state variable of an investment e.g. a stock price or in our case NPV_t. It solves the optimal stopping problem by introducing a continuation value $\Phi_{\mathrm{t_i}}\left(NPV_{t_i}(\omega)\right)$ which is an estimator for the conditional expected value of $NPV_{t_{i+1}}$, the NPV at the subsequent time step of t_i. It is evaluated for each Monte Carlo path ω at t_i. Afterwards, the following stopping rule is applied to decide whether an optimal investment time is reached or the decision maker should further hold the option:

$$if\ \Phi_{\mathrm{t_i}}\left(\Pi_{\mathrm{t_i}}(\omega)\right) \ \leq\ \Pi_{\mathrm{t_i}}(\omega), \qquad then\ \tau(\omega) = t_i. \tag{3}$$

With $\tau(\omega)$ being the optimal stopping time for the Monte Carlo path ω and $\Pi_{\mathrm{t_i}}(\omega)$ the options pay-off at t_i in ω. The latter is defined as

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$$\Pi_{t_i}(\omega) = max\{NPV_{t_i}(\omega) - NPV_{t_0}, 0\}. \tag{4}$$

The continuation value $\Phi_{t_i}(\Pi_{t_i}(\omega))$ is calculated by a regression model determined by a set of basis functions of the relevant state variables (Longstaff & Schwartz, 2001). In our case, we use simple power polynomials of order n=3 as a basis function and the payoffs $\Pi_{t_i}(\omega)$ as our state variable:

$$\Phi_{t_i}(\Pi_{t_i}(\omega)) = \sum_{k=0}^{3} a_{k,t_i} \Pi_{t_i}(\omega)^k. \tag{5}$$

The coefficients a_{k,t_i} are determined by regression with the discounted optimal payoffs of the subsequent time steps $\Pi_{\tau\in[t_{i+1};T]}$ as the dependent variable and the current payoffs Π_{t_i} as the independent variable across all Monte Carlo paths.

The stopping rule in equation (3) is applied recursively at every Monte Carlo path by starting with the latest time step t_n and updating the optimal stopping time $\tau(\omega)$ until the first timestep t_1 is reached. This results in the distribution of the optimal stopping time for every Monte Carlo path. Finally, the expected option value can be estimated by calculating the mean of the discounted real option payoffs for each optimal stopping time $\tau(\omega)$ within each Monte Carlo path ω:

$$ROV = \frac{1}{\Omega} \sum_{\omega\in\Omega} (1+r)^{-\tau(\omega)} \Pi_{\tau(\omega)}(\omega). \tag{6}$$

To model the uncertainty of specific variables of interest, such as energy and investment cost, in the system configuration, stochastic processes are utilized to generate Monte Carlo paths of option payoffs. In this study, we use the Geometric Brownian Motion, which is defined by the following stochastic differential equation.:

$$dX = \mu X_t + \sigma X_t dW. \tag{7}$$

The Geometric Brownian Motion consists of two terms that describes the mathematical behavior of the random variable X over time. The first term, called the drift-term, defines a deterministic drift of the random variable, which is determined by the parameter μ. Commonly, the drift term is modeled with a constant of μ. In this study we define μ as time depended, such as that the expected value of the stochastic process follows a given trend function. The second term, called volatility-term, models the random movements of the variable which are defined by the Brownian Motion W and volatility σ.

3 CASE STUDY

In this section we introduce the case study and present the parametrization of our model.

3.1 Residential Energy System

For the above-mentioned methodology, we conduct a case study on different residential energy systems of a German single-family house based on the DE.N.SFH.08.Gen TABULA archetype building (Loga et al., 2015). The building is constructed between 1984 and 1994, has a reference area of 150.2 m^2 and a specific heat consumption of approx. 100 kWh/m^{2}a. The residential energy system configurations in Table 1 are simulated using *Dymola* and the *Modelica*-based component Library *TransiEnt* (Senkel et al., 2021). Demand profiles for electricity, heating and domestic hot water (DHW) are generated with the *Districtgenerator* (Henn et al., 2024) and for weather data, the TRY dataset for climate zone 4 (Potsdam, Germany) is selected.

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Table 1: Residential energy system configurations

System	Electricity		Heating		
	PV (6.4 kWp)	Battery storage (5 kWh)	Gas boiler (7.6 kW$_{th}$)	Heat pump system (7.6 kW$_{th}$)	Thermal storage (0.5 m^3)
Ref			x		
PV	x		x		
PV_Bat	x	x	x		
HP				x	x
HP_PV	x			x	x
HP_PV_Bat	x	x		x	x

Table 2: Energy flows of the simulated systems in kWh/a

System	Gas from grid	**Electricity from grid** (residential + DHW-booster)	**Electricity from grid** (heat pump system)	Electricity to grid
Ref	17407	4044	0	0
PV	17407	2477	0	3349
PV_Bat	17407	1453	0	2233
HP	0	4474	5279	0
HP_PV	0	2685	5020	2858
HP_PV_Bat	0	1865	4766	1706

Table 3: Assumptions for the investment costs for each component in the year 2023.

Component	Size	CAPEX [€$_{2023}$]	Source
PV	6.4 kWp	11463	(Kraschewski et al., 2023)
Battery storage	5 kWh	4250	(Kost et al., 2021)
Heat pump system	7.6 kW$_{th}$	17271	(Langreder et al., 2022)
Gas condensing boiler	7.6 kW$_{th}$	6117	(Streblow & Ansorge, 2017)
Thermal storage	0.5 m^3	1366	(Streblow & Ansorge, 2017)

The gas condensing boiler provides for both, space heating and DHW and is sized according to the standard heating load of the investigated building, which is calculated based on DIN EN 12831-3:2017. In the heat pump systems, the air source heat pump is operated in a bivalent-parallel mode with an electric heating rod. The combined power of the heat pump system is matched to the standard heating load of the building while the individual sizes are distributed in such a way that the heat pump covers approx. 97 % of the total annual amount of provided heat. The coefficient of performance (COP) in each operating point is calculated based on the Carnot efficiency with a second law efficiency of 0.546 for the heat pump, leading to a seasonal performance factor of 3.0 for the heat pump system. The supply temperature of the system follows a heating curve with supply temperatures ranging from 23 °C – 65 °C over the year. For a hygienic DHW supply, electric booster rods are assumed to bridge the gap when the supply temperature falls below 50 °C. The size of the PV-System is calculated based on the available roof area of the building and assumptions on orientation, tilt and roof elements. For the battery storage, a capacity of 5 kWh with a depth of discharge of 90 % is assumed.

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The simulation of the residential energy systems leads to the energy flows presented in Table 2. The CAPEX of the respective components shown in Table 3 are calculated based on cost functions of the given sources and adjusted to the year of 2023 using the consumer price index according to DESTATIS (2024).

3.2 Monte Carlo Simulation Setup

The investment and energy costs are modelled as a stochastic process by a Geometric Brownian Motion to perform a Monte Carlo simulation of the economic value of each system defined by equation (1) for NPV_{Sys}. As a sample size 100 000 Monte Carlo paths are used for each variable. For the investment costs we use experience curves to model the deterministic part of the stochastic process. Every assumption regarding their parametrization are given in Table 4. The experience curves are defined by a learning rate which describes the relative cost reduction that can be expected by every doubling of the cumulative production of a certain technology. For each component we consider a range of learning rates given in Köhler et al. (2018) and for the heat pump we consider the data from Heptonstall and Winskel (2023). Assumptions for the number of installations of a given technology in Germany until 2045 are based on Brandes et al. (2021). We set the volatility σ such that the interquartile range for the CAPEX of a technology in 2045 corresponds to the uncertainty given by the range of learning rates. The trend function is defined by the experience curve for a mean learning rate. We assume no technological learning effects for the gas boiler and thermal energy storage as they are already well-established technologies.

Table 4: Assumptions for the modeling of the cost developments for each component where technological learning effects are considered.

Component	Learning rate trend	Learning rate range	Volatility σ
PV	19 %	11 – 26 %	0.06
Battery storage	16 %	9.5 – 22 %	0.05
Heat pump system	14 %	8 – 20 %	0.08

The trend functions for the energy costs regarding the household electricity and gas price (Figure 1) in Germany are based on Langreder et al. (2023). Values beyond 2045 are extrapolated for the electricity price and for the gas price the trend function is assumed to stay constant. For simplicity reasons we only model the household electricity costs as a stochastic process and assume the heat pump tariff to have a constant off-set of 7 ct/kWh. Based on historical electricity and gas consumer prices given by BDEW (2023) we define the volatility for the electricity σ_{elec} as 0.035 and for gas σ_{gas} as 0.03.

3.3 Scenarios for CO2 and heat pump subsidies

To investigate the influence of regulatory developments that might significantly influence the value of the real option, we formulate three scenarios each for the CO2 price and subsidies for heat pump investment costs as shown in Figure 2.

The first set of scenarios analyzes the effect of the CO2 price on the general gas price trend in the stochastic process. The base scenario, in the following called Prognos-scenario, is given by the CO2 price path in Langreder et al. (2023). In addition, a second CO2 price path given in the T45-BMWK long-term scenarios is considered (Sensfuß & Maurer, 2022). This path is modified in a third scenario to account for an earlier rise of the CO2 price that might appear due to the switch of the national ETS system towards the European ETS-II in 2027. The scenario for the CO2 price given until 2030 from (Agora Energiewende and Agora Verkehrswende, 2023) is used and assumed to converge to the values of the T45-BMWK scenario afterwards.

For the heat pump subsidies, the base scenario comprises the current subsidy scheme of the German Federal Government featuring a specified decrease of the subsidy rates starting in 2029 (BMWK, 2024).

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Based on this, low and high subsidy scenarios with similar decreases at different times are formulated as shown in Figure 2.

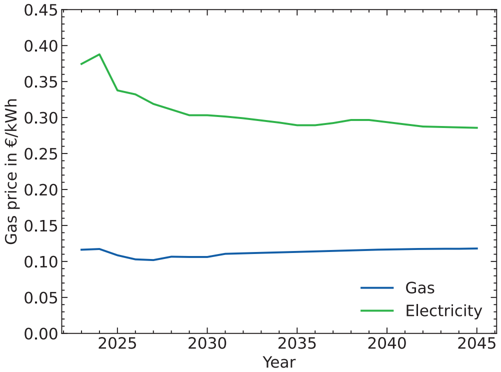

Figure 1: Trend functions for the household electricity and gas prices (Prognos scenario) based on Langreder et al. (2023)

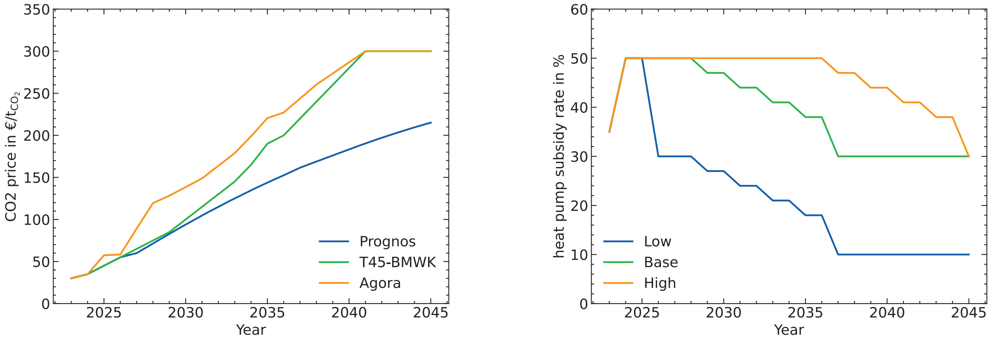

Figure 2: CO2 price scenarios (left) and subsidy scenarios for heat pump investment costs (right)

4 RESULTS

In this section the results are presented. At first, the real options analysis of every system configuration is given. Afterwards, the effect of the CO2 price and the subsidy rates for the heat pump CAPEX scenarios are shown based on the system configuration HP_PV.

4.1 Real options analysis of the residential energy systems

The comparison of the real option results for the complete set of residential energy configurations, defined in Table 1, shows the significant impact of considering the added value of the deferral option in the economic assessment.

Figure 3 and Figure 4 show the results of the deferral option analysis for a maximum deferral time of 22 years which relates to a decision period from 2023 (year 0) up to 2045 (year 22). The Distribution of optimal investment times of each Monte Carlo path shown in Figure 3 indicates that without any further investment cost subsidies an optimal investment times can be expected after a decade. Especially systems including a heat pump are reaching optimal investment time before the expiration time of the option is reached. Firstly, the system HP relying on a stand-alone heat pump is starting to reach optimal investment times after about 9 years. In the subsequent years the systems HP_PV followed by HP_PV_Bat show optimal investment times as well. In contrast, most optimal investment times for the PV and PV_Bat Monte Carlo paths appear to be at the end of the waiting period due to the fact that

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these systems do not profit from increasing gas prices because the heating demands are still covered by a gas boiler.

Figure 4 displays the results for the NPV, ROV and ENPV of every system. All NPV values are negative, thus no invest does not seem to be economically viable compared to the reference system. Still, the system HP has the best NPV, followed by PV and HP_PV. The ENPV incorporating the ROV values draws another picture: Every system with a heat pump shows a highly positive value, whereas PV and PV_Bat become barely economically viable.

Figure 5 extends the results from Figure 4 by displaying the ENPV development across increasing maximum waiting times. Within the first ten years a significant increase of the ENPV is evident for the heat pump systems (HP, HP_PV, HP_PV_Bat) compared to PV and PV_Bat, caused by the reduced operational cost of the heat pumps due to the gas and electricity price trends. Furthermore, after a maximum waiting time of two years the HP_PV_Bat systems ENPV exceeds the PV system. After about ten years the HP_PV system becomes the most valuable system by exceeding the HP systems ENPV. This shows that the economic prioritization of a given choice of systems might change depending on the expiration date of the considered waiting option.

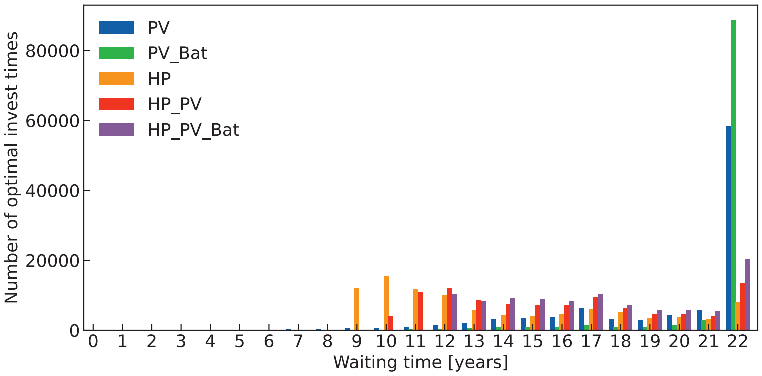

Figure 3: Distribution of optimal investment times for the residential energy system configurations

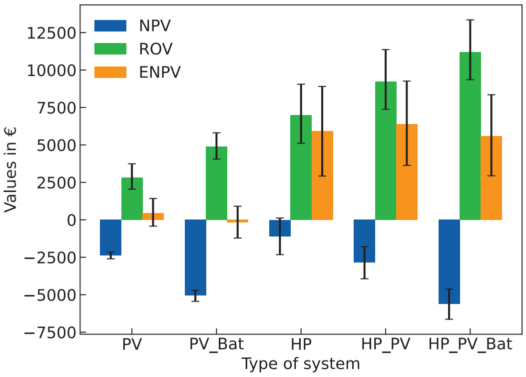

Figure 4: Mean values and interquartile range of NPV, ROV and ENPV estimation for the residential energy system configurations for a maximum waiting time until 2045

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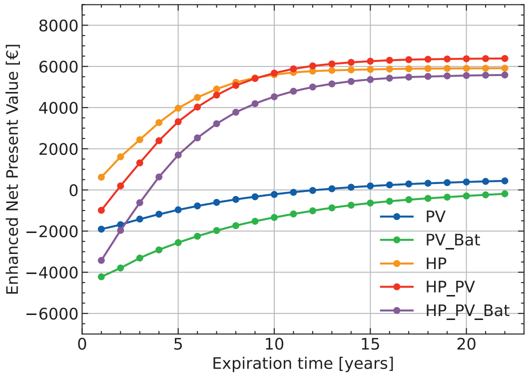

Figure 5: ENPV development with increasing expiration time

4.2 Scenario analysis for CO2 price and heat pump subsidy rate

The scenario analysis regarding the CO2 price and heat pump subsidy rate development reveals a substantial impact of regulatory measures on the deferral option. For the system configuration HP_PV the impact of every scenario and their combination on the ENPV with an increasing expiration time is shown in Figure 6.

The CO2 price scenarios show an increase of the ENPV within the first ten years. As there are no CAPEX subsidies considered, the values start from a low level, being even negative for the Prognos scenario. The Prognos scenario is the base scenario used in the previous section. The higher CO2 prices within the T45-BMWK and Agora scenarios lead to increased ENPV values early on in direct correlation with the CO2 price trends, due to more operational cost savings of the heat pump in comparison to the reference system with a gas boiler. As a result, the earlier CO2 price raise within the Agora scenario leads to a significant ENPV increase, indicating that earlier investments are becoming even more valuable compared to the T45-BMWK scenario.

In contrast, the heat pump CAPEX subsidy scenarios reveal a different development of the ENPV values. The Prognos CO2 price trend is considered across every subsidy scenario. The CAPEX subsidy results in high positive values for the ENPV very early on but in the long term there is lower value increase than in the CO2 price scenarios. Especially the Low-subsidy scenario with an early decrease of the CAPEX subsidy reveals that the best investment conditions are given within the time frame where a substantial part of the subsidy is still apparent. Afterwards, no further value increase is given for the underlying CO2 price trend.

These findings are underlined by the direct comparison of combinations of different scenarios. The addition of the base CAPEX subsidy scenario to the Prognos CO2 scenario leads to a shift towards earlier optimal investment conditions with no significant value improvement after five years. The combination of the base CAPEX scenario with the T45-BMWK scenario shows an overall increase of the ENPV but it is still evident, that no huge long-term increase of the ENPV value can be observed as without the investment subsidies. This indicates that even with a higher CO2 price the real option to defer only gains more value while the CAPEX subsidy is still apparent.

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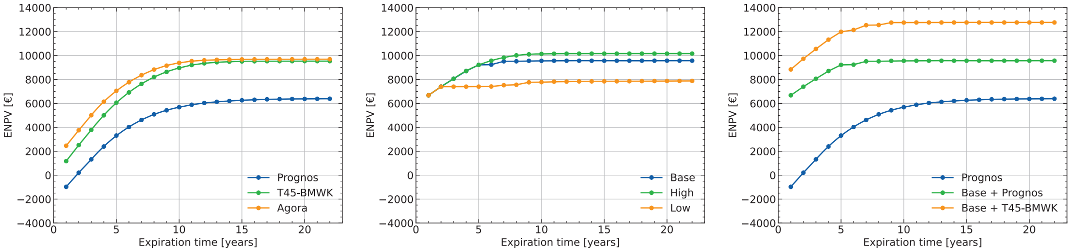

Figure 6: ENPV values with increasing maximum waiting times for different scenarios of CO2 price (left), heat pump CAPEX subsidies (middle) and its combinations (right).

5 CONCLUSIONS

In this study a real options approach for the economic assessment of residential energy system is shown considering the real option to defer an investment decision to a later point in time. A least square Monte Carlo approach is conducted to calculate the real option value. For every system the ENPV values are discussed and a scenario analysis for the CO2 price and subsidy rate for heat pump investment costs are presented. The results of the case study show that incorporating real options analysis can provide additional insights, that lead to better decisions for residential energy systems compared to the traditional discounted cash flow approach.

From the decision makers perspective e.g. a homeowner, the case study serves an example were the ENPV values lead to a different result for the economic viability of relevant system configurations than with the traditional NPV. The results for the NPV show negative values which means that the reference system given as a new gas boiler provides the lowest cost among every other system option. Under the consideration of the real option to defer an investment, current long-term trends for the energy and investment costs lead to an economic advantage of systems relying on a heat pump instead of new gas boilers. Further analysis within this study shows that the economically best system might change under the maximum time someone is willing or able to defer an investment decision.

Furthermore, this study demonstrates that the real options approach also can be used by policy makers for the evaluation of policy strategies. In this example the analysis of scenarios for the CO2 price and CAPEX subsidies reveals that the latter show a significant impact to enable the shift for an early adaption of heat pump-based systems. In contrast, the CO2 price alone leads to optimal investment times that lie further in the future but still has an important role in making the operation of the heat pump economically feasible at all. For the current German subsidy schemes it is shown, that the upcoming years might provide the best investment conditions for a heat pump in a long term.

The real option pricing model for residential energy system used in this study offers potential for improvements that could be incorporated within further research. For instance, more sophisticated models could be used for the formulation of the stochastic processes to better account for correlations between the uncertainty variables or using jump-processes to account for more extreme scenarios of subsequent years like the effect of energy crises. Other potential research directions are given by extending the option pricing model for more option types e.g. the option to stage an investment for each systems component. Furthermore, combining the real options approach with operational or design optimization might lead to more valuable outcomes as in this study only heuristic design and control rules were used for the design and simulation of the energy systems.

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