ECONOMIC EVALUATION OF RESIDENTIAL ENERGY SYSTEMS USING MILP DESIGN OPTIMIZATION COMBINED WITH A REAL OPTIONS APPROACH

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ABSTRACT

Utilizing deterministic MILP models for design optimization of energy systems has gained a huge popularity in research and by practitioners. These models find an optimal solution for defined economic conditions given by parameters such as energy carrier prices or investment costs. In reality, these quantities inhabit a significant amount of uncertainty and change substantially over time. To evaluate investment decisions in energy systems under dynamic changes of the underlying economic conditions, real option analysis arises as a promising approach in current research. It provides insights about potential optimal investment times for a given system. However, it lacks to serve in-depth understanding about what an optimal system design might be for a set of given investment conditions. Therefore, we propose a two-step economic evaluation approach for local energy systems combining both methods. The first step is to use a MILP model to determine the optimal system designs under the economic conditions of today and different years in the future. In the second step we use a least squares Monte Carlo based option pricing model to value the real option to defer an investment. We conduct a case study given by a typical single-family house in Germany. Our case study considers a range of technology options, including photovoltaics, battery storage, electric air-to-water heat pumps, thermal storages and condensing gas boilers. The results show that the systems prioritization regarding their economic value changes by different maximum waiting times for the deferral option. The economic optimal decision is therefore based on the timespan a decision maker is willing to consider waiting to make an investment decision. Furthermore, in the underlying case study, the timing of the investment has a much greater impact on the economic value than the different system designs of the optimal energy systems for the years we considered in our study.

1 INTRODUCTION

In the context of using models to plan energy systems, navigating uncertainties in the energy sector emerges as a critical concern, given that deterministic optimization approaches are sensible to fluctuations in input parameters (Bertsimas & Sim, 2004). Of particular significance are financial parameters, such as energy prices, which exhibit high levels of uncertainty (Moret, 2017) and are challenging to predict accurately. Consequently, it is advisable to explore numerous potential pathways for the evolution of financial parameters. To address this need, a variety of approaches and methodologies are available (Alonso-Travesset et al., 2023; Hong & Apolinario, 2021; Roald et al., 2023).

The two main methodologies currently used in the research of energy system design are mathematical optimization and real option analysis as stated in a recent review by (Alonso-Travesset et al., 2023) Considering uncertainty each of the methods offers a different perspective. On one hand, using scenario analysis deterministic optimization approaches provide an optimal design for each of the scenarios. On

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the other hand, real option analysis gives the answer for what is the optimal timing of an investment for a given system design considering different future scenarios. Their combined application can provide more insights for the evaluation of an optimal energy system design. In (Alonso-Travesset et al., 2023) it is acknowledged that despite of the huge potential of the combination of both approaches, there remains still only a limited number of studies that exploit this.

Therefore, in this study we propose a two-step economic evaluation workflow that analyzes optimal energy system designs using mixed-integer linear programming (MILP) design optimization and Real Option Analysis (ROA) based on a least-squares-Monte-Carlo option pricing model for the optimal investment timing under uncertainty. We apply the workflow on a case study, which is given by a residential family-house as the decarbonization of the building sector poses a significant challenge for both policymakers and private stakeholders. Moreover, recent reviews of real options analysis applied to renewable energy projects indicate that despite the growing popularity of real option methods in energy system research, only a very limited number of studies specifically address residential energy systems (Alonso-Travesset et al., 2023; Kozlova, 2017; Lazo & Watts, 2023; Nadarajah & Secomandi, 2023). So far, in the residential scale the focus in the real option literature mainly lies on the economic assessment of PV systems. Existing studies proved that a real option approach can lead to additional insight for making better investment decisions (Gahrooei et al., 2016; Ma et al., 2020). Therefore, the goal of this study is, to investigate the potential of this combined evaluation workflow and provide some further insights into investments decisions related to residential energy systems including the electricity and heating sector.

This study is divided into four main sections. In section 2 we present our workflow for the economic evaluation of the energy system, which is divided into two steps, namely mixed-integer linear programming design optimization and Real Option Analysis. Section 3, introduces the energy system and its components. We then provide an overview of the assumptions made for the single-family house and the resulting energy demands. Afterwards we briefly introduce the modeling approach of the MILP design optimization. Section 4 gives a condensed description of the ROA approach. The results and the discussion are shown in section 5.

2 ECONOMIC EVALUATION APPROACH

The aim of the economic evaluation approach is to determine the optimal design of an energy system for different support years as well as the optimal time of investment of each of the resulting design over a timeframe ranging from today to the year 2045. This allows gain a holistic insight about, what system design overs the most economic value across the given decision period.

The workflow of our analysis is divided into two main steps. The first step is the design optimization. This step determines the optimal technology selection and dimensions for the energy supply of a single-family home, as well as the related energy consumption. In this analysis, the investment costs of the technologies and the energy costs vary for each of the five support years (see also ***Table 1*** and ***Table 2*** in section 3). However, the energy demand for heat, hot water and electricity, the technology parameters and the weather data are fixed. Due to the lack of adequate data and projections.

In the second step, many Monte Carlo paths considering operational expenditures (OPEX) and capital expenditures (CAPEX) for each technology and year are generated and used as input for the Real Options Analysis. The energy consumption and the technology selection and sizing are fixed for each run. The result of the least squares Monte Carlo Real Options analysis yields the net present value (NPV), the enhanced net present value (ENPV) and a distribution of the optimal points in time for the investment for each energy system. **Figure *1*** summarizes the workflow schematically.

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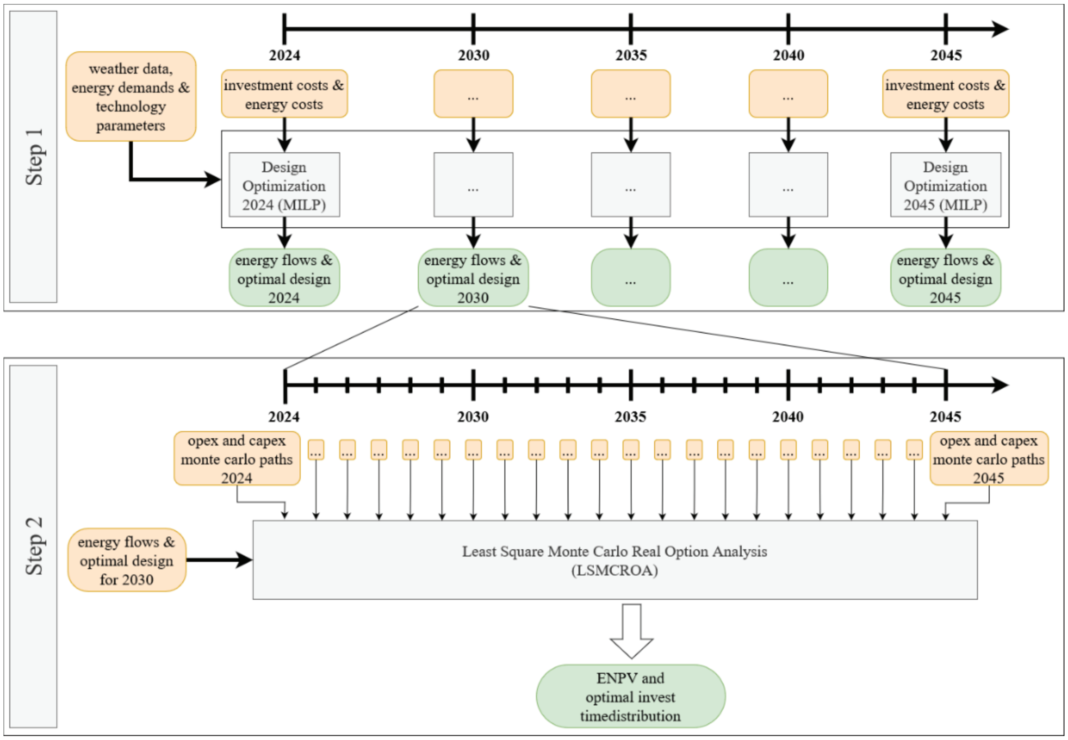

Figure 1: Schematic representation of the two-step economic evaluation workflow that analyzes optimal energy system designs using mixed-integer linear programming (MILP) design optimization and Real Option Analysis (ROA) based on a least-squares-Monte-Carlo option pricing model for the optimal investment timing under uncertainty

3 CASE STUDY: RESIDENTIAL ENERGY SYSTEM

This study focuses on the energy system of a single-family house. The house is defined as the DE.N.SFH.08.Gen TABULA archetype building (Loga et al., 2015). This relates to a typical building in Germany that has been 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. For the weather profiles the TRY dataset for Potsdam (Germany) is used. The technology options for the energy system consist of a heat pump, a gas boiler, a heat storage, and a battery storage system as well as a PV system. ***Figure* 2** illustrates the possible technology options and potential energy flows within the system.

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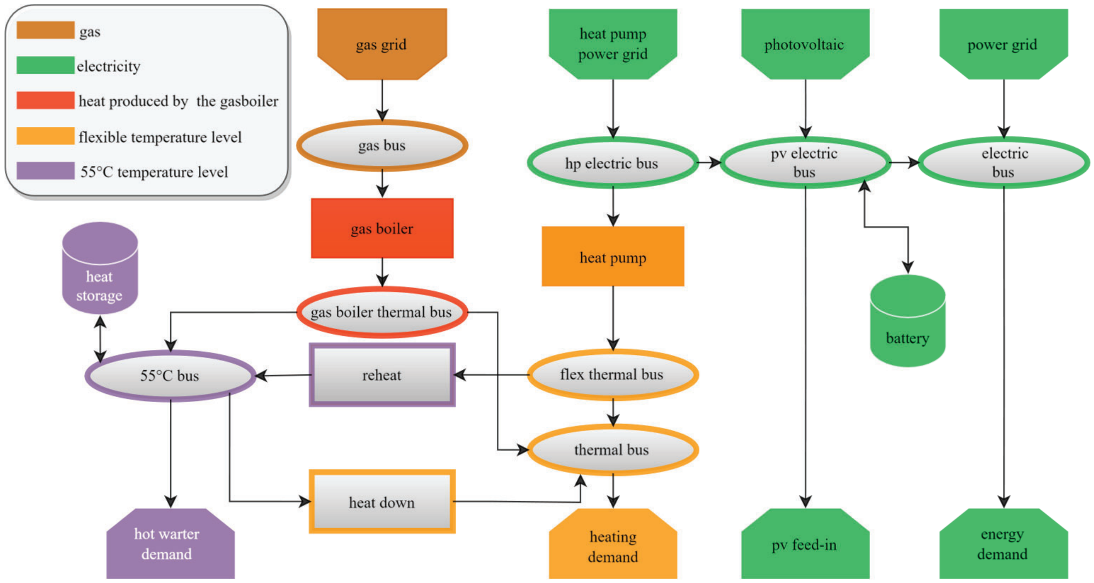

Figure 2: Schematic representation of the residential building energy system

The energy prices for all five support years used in the design optimization can be taken from ***Table 1***.

Table 1: Energy prices in €/kWh based on (Langreder et al., 2023)

year	*gas price*	*electricity price*	*heat pump electricity price*	*pv feed-in tariff*
2024	0.116	0.386	0.360	0.081
2030	0.106	0.303	0.237	0.081
2035	0.113	0.290	0.228	0.081
2040	0.116	0.294	0.230	0.081
2045	0.118	0.286	0.223	0.081

The investment costs for the various components are listed in ***Table 2***

Table 2: Investment costs of the components based on (ISE, 2021; Kraschewski et al., 2023; Langreder et al., 2022; Streblow & Ansorge, 2017)

year	*Gas boiler*		*Heat pump*		*Heat storage*		*Photovoltaic*		*battery*	
	C_{var} *[€/kW]*	C_{fix} *[€]*	C_{var} *[€/kW]*	C_{fix} *[€]*	C_{var} *[€/m³]*	C_{fix} *[€]*	C_{var} *[€/kWp]*	C_{fix} *[€]*	C_{var} *[€/kWh]*	C_{fix} *[€]*
2024	61	4794	1680	3860	1120	806	1200	3038	850	0
2030	61	4794	1318	1318	1120	806	1017	2575	544	0
2035	61	4794	1182	2716	1120	806	927	2347	453	0
2040	61	4794	1101	2530	1120	806	864	2188	420	0
2045	61	4794	1048	2410	1120	806	828	2096	409	0

The parametrization of the real option evaluation framework is described in the work of (Glombik & Fromme, 2024) including the trends and volatilities of the investment and energy costs. Their Prognos CO2-Price scenario without any subsidies for investment costs is used in this study.

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4 MODELS

Here, the specific models for the two-stage evaluation approach are presented.

4.1 Design Optimization

The case study is modeled as a mixed-integer linear design optimization problem. The modeling of the energy system has been previously described in detail in (Krisam et al., 2023). However, there are some variations in the modeling approach, which will be explained in the following. Notably, this updated model does not consider any restrictions for CO_2 emissions.
In contrast to the previous model and to accurately represent the varying temperature requirements of the domestic heating demand and hot water demand, and to account for the heating curve associated with the domestic heating demand, we have incorporated two distinct temperature levels into our model. One temperature level remains constant at 55°C and is connected to the hot water demand, while the other temperature level is flexible and corresponds to the heating curve of the building.

While the efficiency of the gas boiler is the same regardless of the temperature level, the coefficient of performance (COP) of the heat pump depends on the required temperature as well as the source temperature. To ensure that the heat pump can supply the heat demand as well as the hot water demand a reheat function was added, which adjusts the COPs accordingly.

$$\dot{Q}(reheat\ to\ 55°C\ bus) = \frac{COP_{55°C}}{COP_{heating\ curve}}\ \dot{Q}(flex\ thermal\ bus\ to\ 55°C\ bus)$$

The heat down functionality acts as a restrictive measure to prevent the transfer of energy from the 55°C temperature level to the flexible temperature level when the temperature of the flexible temperature level exceeds 55°C. Additionally, the thermal bus is utilized to prevent the energy from circulating continuously through the heat down and reheat functions and to prevent the gas boiler from accessing the reheat function, which in the worst-case scenario could potentially result in energy generation.

4.2 Least Squares Monte Carlo Real Option Analysis

This study expands upon the concept of Discounted Cash Flow (DCF) Analysis and the decision-making process based on the Net Present Value. This approach acknowledges the potential for future improvement in investment conditions by taking the real option to defer an investment. Real option analysis draws upon option pricing theories originally devised for the appraisal of financial options. In the context of our study, the decision to delay investment in a residential energy system is analogized to an American call option. The value attributed to the option to defer is characterized as the difference between the NPV at the initial time NPV_{t_0} and at the future investment time $NPV_{t_{inv}}$. Thus, the option value becomes positive when the expected $NPV_{t_{inv}}$ surpasses the NPV_{t_0}. Mirroring financial options, this difference is regarded as the payoff from a financial call option, wherein NPV_{t_0} serves as the strike price and $NPV_{t_{inv}}$ represents the stock price at a subsequent time. This call option is deemed American due to the investor's ability to execute the investment at any chosen time before the expiration date. The expiration date of the option is synonymous with the assumption for the longest time the investment can be deferred in the real option case. Given the Real Option Value (ROV) the NPV can be extended by introducing the Enhanced Net Present Value (ENPV) which is defined as follows:

$$ENPV = NPV + ROV \qquad (1)$$

The ENPV includes the added value of the flexibility given by the real option. It serves as an alternative key performance indicator to decide, which given investment opportunity inhabits the most economic value. In practice, an investment option or project might be rejected immediately if the NPV has a negative value. In contrast, under the consideration of the real option to defer an investment, the ENPV might become a highly positive value for the same project due to ongoing market trends. Therefore, the

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best decision in this case would have been to wait and reconsider the project in the future instead of choosing a less valuable, irreversible alternative today.

The least-squares-Monte-Carlo option pricing algorithm proposed by Longstaff & Schwartz (2001) is adapted for our specific scenario to calculate the ROV, which is a representation of a dynamic programming approach. The central idea of it is based on approximating the expected value of continuing to hold the option by using a regression model based on orthogonal polynomials applied to the Monte Carlo paths across different timesteps through backwards induction. Therefore, the algorithm defines an optimal exercise strategy for each Monte Carlo path by comparing the current value of exercising the option at time t_i of a given path with its continuation value. The continuation value approximates the conditional expected value of the option within the same Monte Carlo path at time t_{i+1}. If the current value at t_i is greater than the continuation value for t_{i+1} than the option is exercised and t_i becomes the current optimal exercise time. In the other case, where the current value at t_i is less than the continuation value for t_{i+1}, the option is hold and the optimal exercise time remains in one of subsequent timesteps in the future. The whole evaluation of the optimal stopping time is started at the last timestep t_n and progressed recursively until the first-time step t_1 for each path. This forms a distribution for the optimal exercise times given the Monte Carlo paths. Finally, the value of the option can be approximated by taking the discounted payoffs at every optimal exercise time for each path and averaging them.

More in depth explanations of the algorithm for the application of real option evaluation for renewable energy projects are given in (Ma et al., 2020; Pringles et al., 2020). The implementation of the real option evaluation framework for residential energy systems used in this study is developed by (Glombik & Fromme, 2024) and the model setup is presented therein.

5 RESULTS AND DISCUSSION

In ***Figure 3***, the results of the design optimization are presented. An energy system that integrates photovoltaic modules, a heat pump, and thermal storage emerges as the most economically optimal solution across all analyzed support years. Post-2030 a battery storage component is incorporated into the system as well. The installation of a gas boiler is not favored in any of the optimal system configurations. The capacities of the heat pump and the photovoltaic installation remain nearly constant for the duration of the evaluation period. The heat pump's capacity remains unchanged since it serves as the sole source of heat supply in the system. Whereas the photovoltaic capacity reaches its maximum in the year 2030 and is unable to expand further. In contrast, the capacity of the thermal storage experiences a decline, while the battery capacity exhibits an increase over the assessed timeframe. The results show a significant interdependence between the storage systems' capacities, as the flexibility initially provided by the thermal storage is partially taken over by the battery after 2030. Nonetheless, it is observed that a state of equilibrium is achieved from 2040 onwards, with post-2040 variations in size remaining within the bounds of the Mixed Integer Programming (MIP) Gap.

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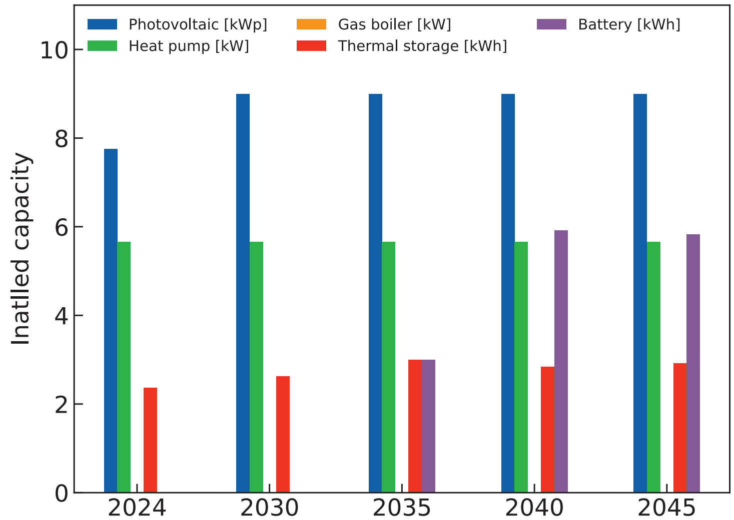

Figure 3 Selected technologies and their dimensions for the residential energy system for each support year (Results of the Design optimization)

The five systems are used for the Monte Carlo Real Option Analysis approach. ***Figure 4*** displays the number of optimal investment times per year for the 100 000 Monte Carlo paths with the maximal waiting option of 21 years (=2045). The distribution of optimal investment times according to the continuation value, which refers to the expected value increase in the subsequent time period of the Monte Carlo path, reveals that optimal investment times are reached after a decade.

When analyzing the results for the optimal energy systems of earlier support years, such as 2024 and 2030, there is a noticeable trend towards earlier optimal investment timings across the Monte Carlo paths. This trend is most evident in the tenth year, where the conditions for optimal investment are met for the first time.

For subsequent time steps beyond the first decade, the data does not display the same level of significant divergence. Although a decline in optimal investment times is noticeable after 12 years across all systems.

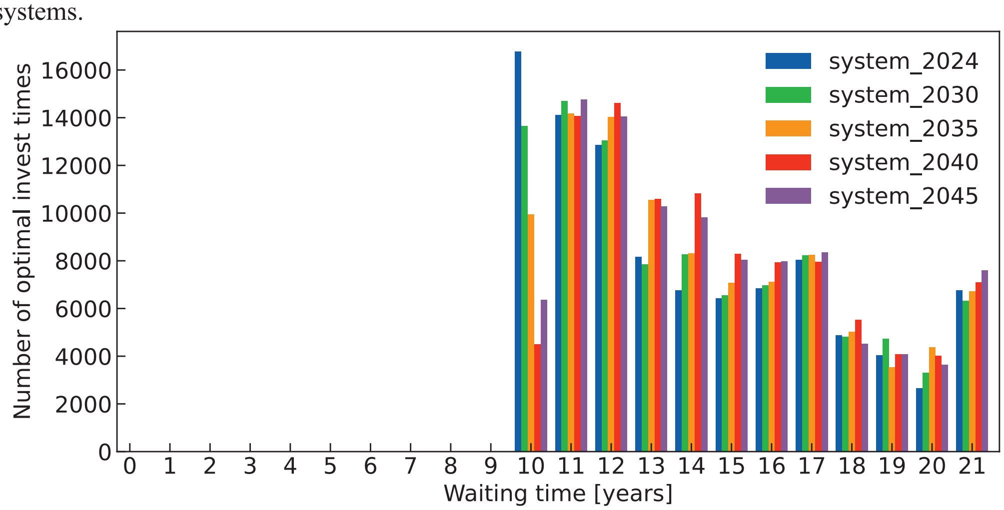

Figure 4 Number of optimal investment times of each energy system for the different waiting options

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Figure 4 illustrates the distribution of optimal investment times for the different energy systems. Additionally, ***Figure 5*** presents the total economic value of each investment option. This value is quantified as the net present value for immediate investment scenarios, together with the real option value for postponing investments and the enhanced net present value, which is the sum of the NPV and the option value. The ENPV therefore includes the added benefit of being able to delay an investment decision.

Overall, it is important to note that there are no significant deviations in all three values across all systems. However, while the total costs of the energy systems considered are relatively similar, the NPV analysis suggests that systems designed for future conditions may have lower economic value today or even be unprofitable today, as indicated by the negative NPVs. This is particularly evident for systems with battery storage when compared to heat pump and photovoltaic systems in the early support years.

Using conventional net present value valuation methods, the system optimized for 2024 (system_2024) could appear to be the most economically advantageous option. However, when the option value and ENPV are included, a different picture emerges. The data shows that the ENPV increases for systems designed for later years. With a deferral option term of 21 years (until 2045), the system designed for 2045 (system_2045) should therefore be considered the most valuable investment if the value of flexibility is taken into account in investment planning.

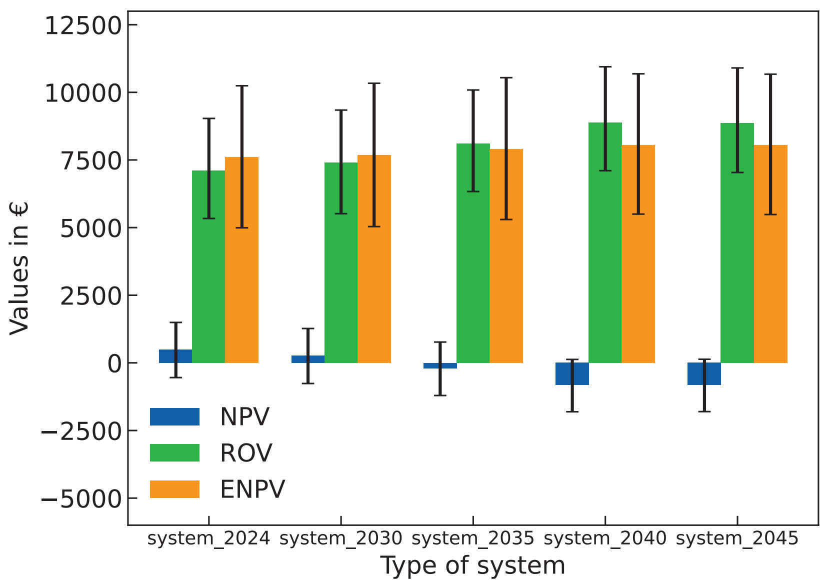

Figure 5 NPV, ROV and ENPV (mean values and interquartile range) for each energy system

While 2045 is the latest year to make the investment according to national emission targets, it may not be feasible to wait this long, because of changing regulations or break down of previous components. Analyzing the ENPV at various expiry times for the deferral option provides valuable insights into the economic viability of different energy systems regarding this issue. ***Figure 6*** shows the ENPV for increasing expiry times, where the expiry time is defined as the maximum time an investor is willing to wait before exercising the deferral option.

The results indicate that the five systems exhibit comparable behavior. The trajectory of the ENPVs across the various systems is quite similar for different expiration times of the deferral option, but differences can be observed. For expiry times of less than five years, the ENPV-based ranking of the systems remains consistent compared to the NPV-based ranking shown in ***Figure 5***, with the 2024 system being the most profitable and the 2040 and 2045 systems being the least profitable. At the five-

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year mark, there is a clear shift where the ENPVs of all schemes intersect. Beyond this threshold, at lifetimes of more than five years, the ENPVs for systems with battery storage begin to outperform those without battery integration. After a decade, the rate of increase in the ENPV becomes significantly slower and eventually reaches a plateau after 15 years.
The reversal in the ranking of the systems can be attributed to the modelled reduction in investment costs for batteries, which results from the expected technological learning effects. Other operating conditions and effects on energy costs may also play a role in this dynamic. The investment decisions derivable from the analysis suggest that investors who can delay their investment for five years or more should choose a system that combines a heat pump with photovoltaic and battery storage instead of choosing the optimal system for 2024, which lacks battery storage and has a slightly smaller PV installation. Furthermore, it is not recommended to postpone investment beyond 15 years from an economic perspective.

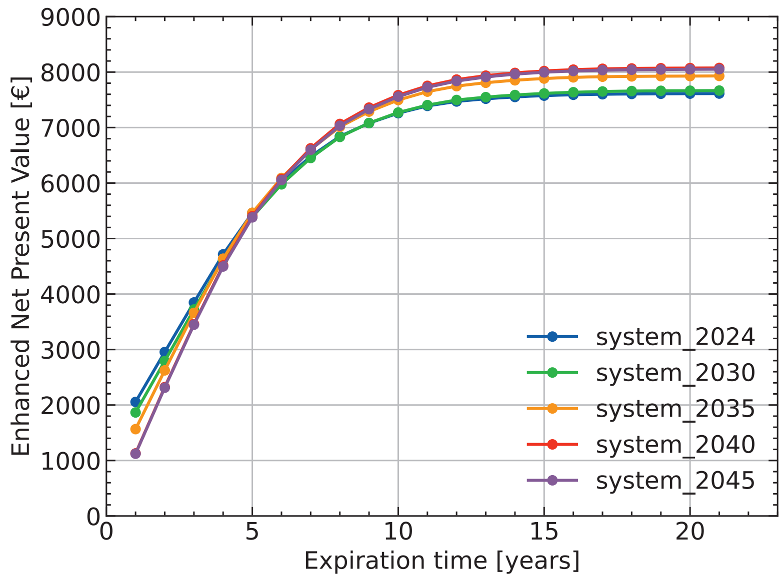

Figure 6 ENPV for each system under different expiration times (=maximum waiting time) of the deferral option

6 CONCLUSIONS

The value of optimized system designs is subject to change, particularly as future scenarios may fail to provide comprehensive information necessary for robust decision-making. The dynamic analysis, facilitated by the Real Option Analysis approach, allows for the evaluation of how the economic viability of energy systems evolves, considering the uncertainties inherent in the market. This study shows that the combination of both approaches, Design Optimization and Real Option Analysis, can provide further insights for the decision-making progress.

Our results demonstrate that uncertainty is a critical factor to consider, as evidenced by the performance of our design optimized systems across 100 000 price paths. The temporal effect of waiting before making an investment decision significantly influences the economic viability of all systems. In our case study we can see that the consideration of the real option to wait offers a significant value increase for maximum expiration time up to 10 years. In addition, the sensitivity of the results on the options expiration time shows that energy systems including battery storage systems become more beneficial than systems without if one considers the real option to wait with an expiration date of at least 5 years. In addition, the total values of the ENPV of the different systems, optimized for different points in time, do not show substantial differences. This underlines that for our case study the energy systems economic

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value is mainly determined by the investment timing than on the change of the optimized system design related to future scenarios.

In the future the approach demonstrated in this paper can be used to analyze more complex systems, providing a less computationally intensive alternative to scenario analysis, where for each scenario a complex MILP problem must be solved.

However, there are limitations and avenues for further research that merit attention. The variability of the weighted average cost of capital (WACC) was not considered in this study, which could affect the accuracy of cost data. A different choice of the WACC parameter could highly influence the system layout optimized in the design optimization.

Future research could also explore the added values of dynamic tariff designs and the corresponding demand for flexibility, which might alter the role of battery storage within energy systems. Moreover, expanding on the uncertainties and their correlations, especially concerning the optimization of operations, would enhance the robustness of the planning process. The application of real option algorithms on surrogate models of operation optimizations presents an intriguing extension of the model addressing the limitation of fixed energy flows within the Monte Carlo simulation.

Lastly, scenarios for trends in capital expenditure, energy price developments, and a more in-depth value-at-risk analysis could yield additional insights. While this study focuses on the evaluation of mean values, the Monte Carlo data has the potential to provide a more detailed risk assessment, offering a broader perspective on the economic implications of energy system investments.

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algorithm, data curation, visualization, methodology, validation, writing-original draft; E.S.: Supervision, writing—review and editing

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