4th Conference on Production Systems and Logistics

Optimizing Investment Planning For District Heating Coupling Of Industrial Energy Systems Using MILP

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Abstract

Industrial energy systems are being transformed to decrease energy costs, reduce emissions, and ensure security of supply. The increasing integration of renewable energies and industrial waste heat leads to complex and interconnected industrial energy systems. At the same time, the decarbonization of the heating sector is still in its infancy and possibilities are discussed to make excess heat from industrial companies available for building supply via district heating networks or to use district heating for thermal energy supply in the industrial sector. In this paper, we present an optimization-based investment planning approach to calculate the optimal dimensioning of a potential heat transfer station connecting industrial sites to district heating systems. The approach is based on a model library that includes typical components of industrial energy systems. Moreover, it integrates different energy demands such as heating, cooling, or electricity of production systems and sites as well as waste heat of production processes depending on predominant temperature levels. The approach manages to include transformation strategies of the industrial energy system by integrating different scenarios using regret optimization, giving decision makers a better overview of the impact of the investment in a heat transfer station on the overall factory planning. The approach is applied to the planning process of an industrial company. In the use case, a positive net present value shows the benefits of an investment in a heat transfer station. Moreover, energy costs and carbon dioxide emissions can be reduced over the planning horizon and through the higher utilization of waste heat as well as the more efficient use of energy systems.

Keywords

Industrial energy system; waste heat; heat transfer station; transformation strategies; regret optimization

1. Introduction

Increasing energy costs as well as the socio-ecological goal of reducing greenhouse gas emissions and achieving climate neutrality pose major challenges for industrial companies. To align with the goals of the Paris agreement [1], industrial companies must invest in a transformation of their on-site energy system [2,3], hereinafter referred to as industrial energy systems (IES). The industry's share of the global energy demand is about one third [4] within which the energy demand for heating appliances accounts for up to 70 % [5]. Thus, focusing on the transformation of industrial heat supply is a key element for climate neutrality [6]. Besides transforming IES, industrial companies must adapt to new energy markets for the cost- and emission-efficient as well as secure provision and use of energy [7]. Due to the goal of integrating

DOI: https://doi.org/10.15488/13426
ISSN: 2701-6277
publish-Ing.

renewable energies and waste heat into the overarching energy system, energy-related products such as electricity flexibility [8] or the sale of surplus heat [9,10] become more and more available. While the former takes place via national and international energy markets, the marketing of surplus heat often must be negotiated with the operator of the local district heating system (DHS) [10,11]. Due to technical and organizational barriers within the planning phase of such projects, only 7 % of the German DHS heat demand is supplied with waste heat [12] although a potential of up to 127 PJ (over 25 %) is estimated [13,14]. Whether an integration is economically suitable for the industrial company strongly depends on the investment costs, but also on the available heat quantity and its temperature level, the heat pricing and finally, the transformation of the IES at the site. To support companies in their investment decision and thereby help exploiting the shown potentials, we address the investment planning to couple IES with DHS using mathematical optimization. After laying out the fundamentals in section 2, the approach for an optimal investment planning of coupling IES and DHS is presented in section 3. The underlying modeling is outlined in section 4, which is applied to a use case in section 5. The paper closes with a summary in section 6.

2. Fundamentals

In the following, the fundamentals of investment planning in IES with a focus on thermal energy systems and transformation strategies, coupling to DHS as well as mathematical optimization are further introduced.

2.1 Transformation of industrial energy systems

IES are used to meet the various energy requirements of industrial production systems and sites and supply different forms of energy such as electricity, gas, process heating and cooling, space heating, and air conditioning or compressed air [15]. Moreover, increasing integration of renewable energies and industrial waste heat leads to complex and interconnected IES, especially within their thermal energy supply [16,17], which often consists of central heating and cooling networks (see Table 1).

Table 1: Typical industrial thermal networks with flow and return temperatures as well as applications [16]

	Flow / °C	Return / °C	Typical applications
Steam	120-240	80-160	Process heat for chemical processes, drying application
High temperature	90-120	70-90	Metal washing, space heating, domestic hot water
Medium and low temperature	50-70	30-50	Space heating, cleaning processes, potential for waste heat uptake
Cooling	10-30	15-40	Cooling of industrial equipment, air conditioning
Cold water	1-6	6-12	Cooling of industrial equipment / chemicals, air conditioning

The supply for process and space heating is still mainly based on fossil fuels such as combined heat and power (CHP) units or gas-fired boilers [15]. To achieve climate neutrality, transformation strategies are developed and applied to these systems. For planning heat integration with DHS, these potential strategies must be included since future surplus heat might be dependent on the transformation of the IES. Main transformation strategies for industrial thermal networks can be summarized as follows [18–22]:

- Efficiency: Reducing heating and cooling demand, installing more efficient energy converters,
- Waste heat integration:
    - Direct integration without substituting cooling, e. g. from heat treatment furnaces,
    - Direct integration with substituting cooling, e. g. from compressors for pressured air,
    - Indirect integration via heat pumps, e. g. from cooling networks,

- Electrification: Use of electric boilers or heat pumps instead of fossil fuel-based boilers or CHP,
- Low carbon fuels: Construction of a hydrogen infrastructure, switch to biogas,
- Additional: use of renewable energy sources (photovoltaic, solar thermal, geothermal), interconnection of thermal grids via heat exchangers and heat pumps.

2.2 Heat integration in district heating systems

DHS are a climate-friendly and cost-effective way of distributing heat due to economies of scale and the potential to integrate renewables and waste heat over longer distances [10]. The potential for heat integration is dependent on the topology and parameters of the DHS, which can be classified into four generations with decreasing flow temperatures and increasing integration of decentral energy sources [23]. For third party heat integration, the temperature levels within the IES and the DHS determine the possible structure of a heat transfer station (HTS). If the temperature of industrial surplus heat does not meet required temperatures, heat pump technology can be integrated [24]. Moreover, the fluctuating energy demand in DHS, which is highly dependent on the season, outdoor temperature, and time of the day, must be considered for a potential feed-in. The temporal difference between heat demand and surplus heat can partly be solved by using heat storage [25]. The DHS operator must guarantee the security of supply. Thus, irregular heat sources must be secured by backup capacities [26]. Considering these technical requirements in combination with the complexity of IES, HTS between IES and DHS must be planned and operated comprehensively [27].

For third-party feed-in and its investment decisions, potential revenues and costs are important. The costs of heat supplied in DHS consists of the three components: costs for heat generation, costs for distribution and costs for connecting customers. These are passed on to the customers as a connection fee, fixed costs for network maintenance, and variable costs per unit of heat purchased [28]. The marginal costs of the DHS determine the maximum profit of the IES. These can change over time depending on the utilized energy converters and primary energy prices [29,11]. If the IES can supply a base load an additional compensation is provided [10]. Investment costs include the costs for energy converters and heat exchangers as well as costs for pumps, pipes, valves, etc. Missing transparency in analyzing potential heat sources in IES and technical requirements as well as missing knowledge about potential revenues and costs in the investment planning are major barriers for industrial energy management to initiate such investment projects [11].

2.3 Optimal investment planning for heat transfer stations in industrial energy systems

Mathematical programming is a broad approach to optimize IES from component to system level regarding design and operational strategies [30]. At the system level, optimization can support investment decisions, taking multiple types of energy demands and technologies into account and evaluating economic and ecological goals [31]. An analysis of several approaches shows that the formulation as mixed integer linear programming (MILP) is most common for IES on the system level as it is a good compromise between model detail and computation time [32]. In investment planning there are several criteria to evaluate investment decisions. For optimizing IES, the net present value (NPV) method as goal function is considered the most appropriate [33]. The economic criterion can also include ecological terms by economizing ecological factors, e. g. as with carbon pricing. The uncertainty during the investment planning about the development of energy prices and demands or changes in the IES are considered in mathematical programming through stochastic, robust or regret optimization and can be used next to parameter and scenario studies [34]. In this work, regret optimization is used to integrate transformation strategies. The minimization of regret focuses on decision makers who want to undergo the least amount of opportunity costs in the worst-case scenario [35]. The mathematical formulation is presented in [36] as a minimax rule.

Mathematical optimization is often used in research for planning and operating DHS [37] and include industrial waste heat for reducing costs and emissions. Within these models, such as in [38,39], industrial waste heat is just one parameter that neglects the complexity of IES. Moreover, the decision making of industrial sites is often excluded in the modelling. Approaches such as [40,41] minimize the joint costs of both parties, not individual goals of industry and energy supplier. Research on optimizing IES [32] and waste heat integration [42] mostly focuses on the internal use of waste heat. Therefore, research on investment planning which focuses on the connection to DHS and the integration of the complexity of IES, the goals of industrial companies and transformation strategies is necessary. Thus, after researching operational strategies [27,43] we now extend the approaches to the overarching investment planning.

3. Approach

In the following, we present an optimization-based investment planning approach to calculate the optimal dimensioning of a HTS connecting IES to DHS. The approach aims to support decision makers of industrial companies. It integrates a modelling approach for IES with different forms of energy demands as well as waste heat of production processes depending on predominant temperature levels. Moreover, the approach manages to include transformation strategies of the industrial site by integrating different scenarios.

3.1 Contextualization within factory planning

The investment planning of a DHS connection is part of the IES planning, in general following the goal of an economical supply and use of energy to fulfill the corporate purpose. The industrial energy management must meet the goals for quality, time, cost, and socio-ecological effects. Thus, investing in a HTS between DHS and IES should ensure the supply of the industrial site in quality (temperature levels and energy amount) and time (fluctuating energy demands) [44]. Moreover, the investment aims to reduce energy costs, e. g. by economizing surplus heat. In former work, we showed that these goals can be met in operation [43], but for investment planning in the context of the factory planning process (Figure 1) [45], tools must evaluate long payback periods as well as consider risks [46,11]. Mathematical optimization models especially support the concept phase, using information of the basic evaluation and giving a structure for detailed planning. The investment planning of an DHS connection can be seen as one planning phase within a broader transformation strategy including several single investment planning cycles. During the planning cycle of the DHS connection there is an uncertainty about subsequent planning cycles which might affect the IES or the overall industrial site and, thus, the profitability of the DHS connection. This influence and its uncertainty must be considered early on during the DHS connection investment planning cycle.

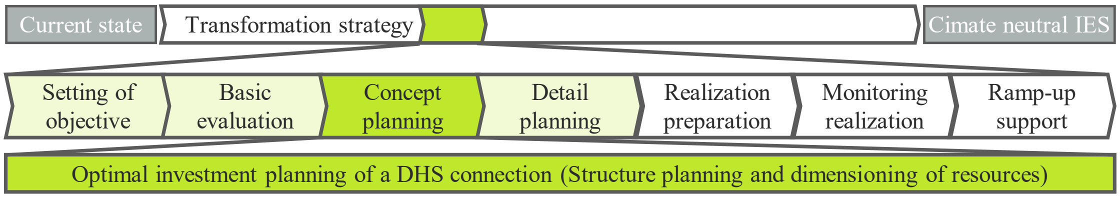

Figure 1: Optimal investment planning of IES in the context of factory planning [45] and transformation strategies.

3.2 System boundary of the modeling approach

In Figure 2 the overall system boundary of the optimization modeling approach is depicted based on the fundamentals in section 2. The industrial site is modeled with a focus on the IES. The IES is divided into several components: energy converters, waste heat sources, energy storages and supply networks. Thermal networks for heating and cooling on different temperature levels depending on the demand requirements in the IES and DHS (see Table 1) define the possible heat flows and the energy converters are connected to different energy grids. The energy demands of the industrial site with their temperature requirements are integrated as parameters. The IES modelling is built up in a modular model library. Thus, different kinds of IES can be modelled within the generic modelling approach. To address transformation strategies, the IES can be adapted by instantiating new versions of the IES with different energy converters. The DHS site models the necessary requirements such as heat pricing models, temperature levels and maximum feed-in energy. The HTS can be connected to different grids via heat exchangers and heat pumps as explained in [27]. Moreover, heat storage sizing as well as costs for pumps and pipes are modelled. The overall optimization problem is then to minimize the NPV in combination with regret optimization.

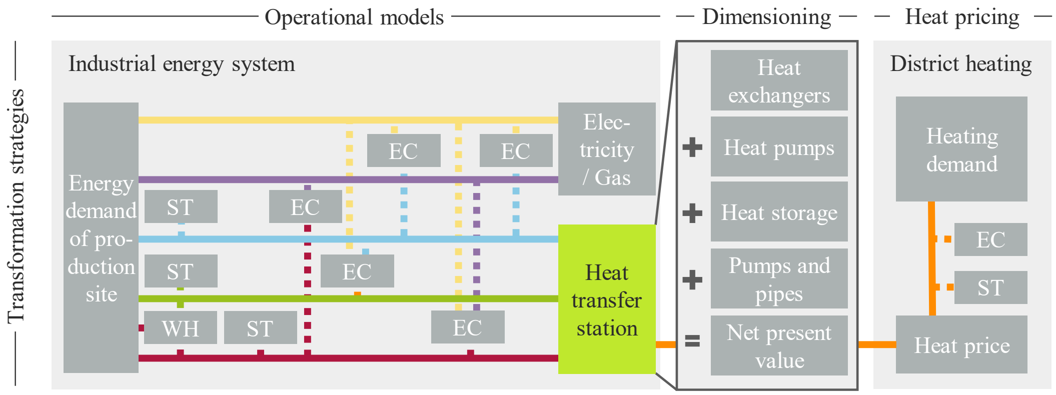

Figure 2: System boundary for investment planning approach, colored lines display energy networks (yellow: electricity; violet: gas; blue: cooling; green, orange, red: heating on different temperature levels); EC: energy converter; WH: waste heat; ST: storage.

3.3 Modelling

The approach uses a MILP model for the different parts of the system boundary formerly explained. To address the appropriate model detail, some basic assumptions are made:

- The operational models of the energy systems are modelled as energy balances considering temperature levels, energy demands and, energy pricing as parameters [43].
- To address the non-linearity of technical systems and parameters, piecewise linearization for part load behavior and investment costs is used (not included in the following equations) [32].
- The annual operational strategy is based on design days by using time series aggregation based on the methodology presented in [47]. These scenarios contain time-varying model parameters such as energy demands or temperature-dependent efficiencies.
- The DHS is modelled in this work as a linear programming model.

For the operation of the IES, energy converters are modeled as defined in Equation (*1*). The converted energy $P_{d,t,i}^{\mathrm{out}}$ for each design day in D and time step in T is calculated by the input energy $P_{d,t,i}^{\mathrm{in}}$ and an efficiency parameter $\eta_{d,t,i}$. Moreover, it is restricted to minimum $\mathrm{P}_i^{\mathrm{min}}$ and nominal $\mathrm{P}_i^{\mathrm{nom}}$ power by the operating decision variable $\delta_{d,t,i}^{\mathrm{on}}$. The specific models for energy converters are further explained in [32,43].

$$\mathrm{P}_i^{\mathrm{min}} \cdot \delta_{d,t,i}^{\mathrm{on}} \leq P_{d,t,i}^{\mathrm{out}} = P_{d,t,i}^{\mathrm{in}} \cdot \eta_{d,t,i} \leq \mathrm{P}_i^{\mathrm{nom}} \cdot \delta_{d,t,i}^{\mathrm{on}} \quad \forall d \in \mathrm{D}, \forall t \in \mathrm{T}, \forall i \in \mathrm{I} \qquad (1)$$

Energy converters are connected to the supply networks N. The energy balances of thermal networks consist of the input $P_{d,t,i}^{\mathrm{in}}$ and output $P_{d,t,i}^{\mathrm{out}}$ power of energy converters $\mathrm{I}_n^{\mathrm{out}}$, $\mathrm{I}_n^{\mathrm{in}}$ and waste heat sources J_n with power

$P_{d,t,j}^{\mathrm{WH}}$ (Equation (*2*)) of network n. These energy sources must supply the energy demands of the network $\mathrm{P}_{d,t,n}^{\mathrm{dem}}$. Moreover, energy storage $P_{d,t,n}^{\mathrm{ST}}$ can be used.

$$\sum_{i\in\mathrm{I}_n^{\mathrm{out}}} P_{d,t,i}^{\mathrm{out}} + \sum_{j\in\mathrm{J}_n} P_{d,t,j}^{\mathrm{WH}} = \mathrm{P}_{d,t,n}^{\mathrm{dem}} + P_{d,t,n}^{\mathrm{ST}} + \sum_{i\in\mathrm{I}_n^{\mathrm{in}}} P_{d,t,i}^{\mathrm{in}} \quad \forall d \in \mathrm{D}, \forall t \in \mathrm{T}, \forall n \in \mathrm{N} \tag{2}$$

The HTS is connected to the thermal networks of the IES. The possible connections must be defined before the optimization. For the dimensioning of the components K of the HTS, a binary decision variable x_k^{buy} is integrated (Equation (*3*)). The variable P_k^{nom} defines the optimal nominal power of components within the HTS which is constrained to $\mathrm{P}_k^{\mathrm{nom,max}}$. The operational models and investment cost curves of dimensioned components within the HTS are further explained in [32].

$$P_{d,t,k}^{\mathrm{out}} \leq P_k^{\mathrm{nom}} \leq x_k^{\mathrm{buy}} \cdot \mathrm{P}_k^{\mathrm{nom,max}} \quad \forall d \in \mathrm{D}, \forall t \in \mathrm{T}, \forall k \in K \tag{3}$$

The system is optimized by maximizing the NPV (Equation (*4*)-(*6*)) considering design days for every year Y with a weighting factor $\omega_{y,d}$. The NPV includes the investment costs I, the operating costs C_y in year y as well as a discount factor with the interest rate i. The operating costs are compared to those in case no HTS is bought $\mathrm{C}_y^{\mathrm{base}}$. The investment costs include costs for the components of the HTS $\mathrm{c}_k^{\mathrm{fix/var}}$. Moreover, costs for pumps and pipes $\mathrm{c}^{\mathrm{p,fix/var}}$ can be integrated. The operating costs include energy costs $\mathrm{c}_y^{\mathrm{el/gas/th}}$ as well as revenues for the sold thermal energy $\mathrm{r}_y^{\mathrm{th}}$. Also, a base load factor $\mathrm{r}_{y,d}^{\mathrm{th,base}}$ can be integrated.

$$\max NPV = -I + \sum_{y\in\mathrm{Y}} \frac{C_y - \mathrm{C}_y^{\mathrm{base}}}{(1+\mathrm{i})^y} \tag{4}$$

$$I = \mathrm{c}^{\mathrm{p,fix}} + P^{\mathrm{th,max}} \cdot \mathrm{c}^{\mathrm{p,var}} + \sum_{k\in\mathrm{K}} x_k^{\mathrm{buy}} \cdot \mathrm{c}_k^{\mathrm{fix}} + P_k^{\mathrm{max}} \cdot \mathrm{c}_k^{\mathrm{var}} \tag{5}$$

$$C_y = \sum_{d\in\mathrm{D}} \omega_{y,d} \cdot \left(P_{y,d}^{\mathrm{th,base}} \cdot \mathrm{r}_{y,d}^{\mathrm{th,base}} + \sum_{t\in\mathrm{T}} P_{y,d,t}^{\mathrm{th,sell}} \cdot \mathrm{r}_y^{\mathrm{th}} - P_{y,d,t}^{\mathrm{th,buy}} \cdot \mathrm{c}_y^{\mathrm{th}} - P_{y,d,t}^{\mathrm{el}} \cdot \mathrm{c}_y^{\mathrm{el}} - P_{y,d,t}^{\mathrm{gas}} \cdot \mathrm{c}_y^{\mathrm{gas}} \right) \quad \forall y \in Y \tag{6}$$

If several transformation strategies and pricing or demand scenarios α are to be evaluated, the goal function is adapted to a regret minimization (Equation (*7*)). Here, instances for each scenario are created. Then, each single scenario is optimized, resulting in its NPV_α^*, after which the overall regret optimization is conducted. The solution of regret minimization leads to the investment NPV_α that would be least regretted by the decision maker in the worst case scenario [35].

$$\min_{I,C_y} \max_{\alpha} (\mathrm{NPV}_\alpha^* - NPV_\alpha) \tag{7}$$

4. Evaluation

In this section, the modelling approach is applied to the IES of an industrial company for a first concept and dimensioning of a HTS to the local DHS. The industrial site of the use case is planning a transformation to climate neutrality of the IES. Within a research project, the coupling to the local DHS is under consideration.

4.1 Use Case

The IES of the industrial company consists of five different thermal networks as depicted in Table 1. The networks are supplied by gas-fired CHP and boilers as well as compression chillers and cooling towers.

Moreover, it is planned that the networks are connected via heat pumps and heat exchangers and that waste heat from compressors for pressurized air can be used. The potential HTS can only be connected to the low temperature network due to spatial issues. Thus, the IES can supply heat to the DHS via heat pump or receive heat via heat exchanger. An additional storage can be connected to the HTS. The parameters for the existing components were supplied by the industrial company. For a theoretical evaluation of the approach within this paper, parameters, and investment costs for the components of the HTS were taken from [32]. In the application within the project, data on specific components from suppliers are used. Eight design days containing the energy demand for each network, the availability of waste heat as well as the ambient temperature and solar irradiance are derived from measurement data spanning one year. The heat price was set to the marginal heat cost of the DHS. To adapt the optimization to potential developments of the IES, two transformation strategies besides the conventional IES supply are considered for implementation in four years: electrification with heat pumps, electric boilers, photovoltaic and battery storage on the one hand and a built up of a hydrogen infrastructure with electrolysis, hydrogen fired CHP and electric boilers on the other hand. Besides the conventional, electrification and hydrogen strategies, three projections of gas and electricity prices are assumed based on [48]. Thus, nine scenarios for a future development of the IES and prices are integrated in the optimization.

4.2 Results

The overall model is built up in the python based optimization modeling language Pyomo and solved by the commercial solver CPLEX for a time horizon of ten years and an interest rate of 4.5 % [35]. The theoretical optimization for each scenario is depicted in Table 2. It shows the NPV for the optimal HTS for each single scenario, the NPV for each single scenario with the optimal investment for the conventional and average pricing scenario as well as the NPV with the investment determined by the regret optimization. By utilizing the regret optimization, the maximum regret for any scenario can be reduced from 7.87 to 0.19 M€. The investment in the regret optimal HTS yields savings between 1.6 and 10.1 M€ over the time horizon of ten years compared to the NPV without a HTS. A total emissions reduction of the IES and the DHS of up to 3.9 % can be reached. However, one scenario results in higher total emissions of 0.5 %. In all scenarios heat is supplied to the DHS, but in some scenarios no heat is received. Furthermore, the optimal investment decisions for each single scenario are shown. For each scenario a heat pump is bought. However, for only some scenarios the investment in a heat exchanger and storage is optimal. The regret optimal HTS consists of a heat pump with 5.9 MW and a heat exchanger with 4.9 MW nominal power for a total of 0.65 M€. With these results, further detail planning of the HTS is conducted with the industrial company.

5. Summary and Discussion

In this paper, we present an optimization-based investment planning approach to calculate the optimal dimensioning of a potential HTS connecting IES to DHS. The approach is contextualized in the factory planning supporting the concept phase within investment projects. The MILP model of the IES integrates energy demands of production systems and sites as well as waste heat of production processes depending on predominant temperature levels with models of energy converters, storages, and thermal networks. Transformation processes for climate neutrality of the IES are integrated by applying regret optimization for comparing different transformation strategies and price scenarios. The approach is applied to the planning process of an industrial company which is currently in the concept phase of planning an HTS to the local DHS. Results indicate that the investment in the regret optimal HTS yields substantial savings over the time horizon of ten years compared to the NPV without a HTS. Moreover, by utilizing the regret optimization, the maximum regret for any scenario can be reduced substantially. However, the results must be validated in further steps (detail planning) of the project, e. g. with simulation models for detailed components, as well as at the end of the project.

The presented approach mainly focuses on the dimensioning of the components of the HTS considering techno-economical aspects. Regulatory and contractual aspects such as limitation on emissions or heat feed-in, restrictions on groundwork within residential areas as well as specific pricing regulation must be discussed with local administration as well as the energy supplier upfront or integrated in the model in a second iteration. Thus, generated results by using the approach can be seen as a first indication for concept planning which must be validated and concretized in detail planning. In detail planning also the hydraulic connection between the IES and the DHS must be considered, e. g. by integrating simulation models. As the approach can be used iteratively in the concept planning and integrates complex modelling such as regret optimization, expert knowledge is necessary. In future work, the usability for a broader use could be improved. Moreover, in future research the approach can be extended by integrating different possible variants of the HTS in form of a structure optimization or apply different pricing schemes of DHS.

Table 2: Results of the use case. Transformation strategies: conventional (C), electrified (E) and hydrogen (H2). Electricity and gas price projections: average prices (A), high electricity and low gas price (H) and low electricity and high gas price (L).

Scenario α	C&A	C&H	C&L	E&A	E&H	E&L	H2&A	H2&H	H2&L
NPV_{α}^{*} in M€	1.8	5.4	6.6	2.8	9.7	6.2	1.4	10.3	3.7
NPV_{α} (C/A HTS) in M€	1.8	2.5	6.2	2.5	3.0	6.0	1.1	2.4	3.5
Regret to NPV_{α}^{*} in M€	0.0	2.84	0.39	0.34	6.69	0.26	0.29	7.87	0.21
NPV_{α} (regret opt.) in M€	1.6	5.2	6.4	2.6	9.5	6.0	1.2	10.1	3.5
Regret to NPV_{α}^{*} in M€	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Emissions (no HTS) in Mt CO_2	2.18	2.18	2.08	1.82	1.78	1.86	2.36	2.29	2.43
Emission reduction in %	2.1	0.0	3.6	2.2	0.0	3.9	1.0	-0.5	2.7
Heat supplied in GWh/a	16.1	9.7	38.7	16.3	10.1	35.0	9.7	7.5	32.1
Heat received in GWh/a	0.7	19.6	0.0	7.5	23.8	0.0	9.3	26.4	0.0
Heat pump in MW	4.3	3.4	6.9	4.3	3.1	5.7	4.3	3.4	5.7
Heat exchanger in MW	0.3	5.0	0.0	4.3	4.5	0.0	4.3	5.0	0.0
Heat storage in MWh	0.0	0.0	0.0	24.7	10.2	5.0	0.0	0.0	0.0

Acknowledgements

The authors gratefully acknowledge the financial support of the project Living Lab: DELTA (grant agreement No. 03EWR002A) which is funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and managed by the management agency Project Management Jülich (PTJ).

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