energies

MDPI

Article

Assessing the Flexibility Potential of Industrial Heat–Electricity Sector Coupling through High-Temperature Heat Pumps: The Case Study of Belgium

Chiara Magni [1], Robbe Peeters [1], Sylvain Quoilin [2,*] and Alessia Arteconi [1,3,4,*]

1 Department of Mechanical Engineering, KU Leuven, B-3000 Leuven, Belgium
2 Integrated and Sustainable Energy Systems (ISES) Research Unit, University of Liège, B-4000 Liège, Belgium
3 EnergyVille, Thor Park, B-3600 Genk, Belgium
4 Department of Industrial Engineering and Mathematical Sciences (DIISM), Marche Polytechnic University, 60131 Ancona, Italy
* Correspondence: squoilin@uliege.be (S.Q.); alessia.arteconi@kuleuven.be (A.A.)

Abstract: Thermal processes represent a significant fraction of industrial energy consumptions, and they rely mainly on fossil fuels. Thanks to technological innovation, highly efficient devices such as high-temperature heat pumps are becoming a promising solution for the electrification of industrial heat. These technologies allow for recovering waste heat sources and upgrading them at temperatures up to 200 °C. Moreover, the coupling of these devices with thermal storage units can unlock the flexibility potential deriving from the industrial sector electrification by means of Demand-Side Management strategies. The aim of this paper is to quantify the impact on the energy system due to the integration of industrial high-temperature heat pumps and thermal storage units by means of a detailed demand–supply model. To do that, the industrial heat demand is investigated through a set of thermal process archetypes. High-temperature heat pumps and thermal storage units for industrial use are included in the open-source unit commitment and optimal dispatch model Dispa-SET used for the representation of the energy system. The case study analyzed is Belgium, and the analysis is performed for different renewable penetration scenarios in 2040 and 2050. The results demonstrate the importance of a proper sizing of the heat pump and thermal storage capacity. Furthermore, it is obtained that the electrification of the thermal demand of industrial processes improves the environmental impact (84% reduction in CO_2 emissions), but the positive effect of the energy flexibility provided by the heat pumps is appreciated only in the presence of a very high penetration of renewable energy sources.

Keywords: high-temperature heat pumps; energy flexibility; electrification; RES curtailment

Citation: Magni, C.; Peeters, R.; Quoilin, S.; Arteconi, A. Assessing the Flexibility Potential of Industrial Heat–Electricity Sector Coupling through High-Temperature Heat Pumps: The Case Study of Belgium. *Energies* **2024**, *17*, 541. https://doi.org/10.3390/en17020541

Academic Editor: Ioan Sarbu

Received: 13 December 2023
Revised: 15 January 2024
Accepted: 19 January 2024
Published: 22 January 2024

1. Introduction

The heating and cooling sector is responsible for around half of the total European energy consumption [1] and 75% of its greenhouse gas emissions [2]. For this reason, the sustainable energy transition of this sector is considered of utmost importance to reach the 55% carbon emission reduction goal set by the EU for 2030 [3].

A significant fraction of the total heating and cooling demand is linked to industrial heat [1], which is currently supplied mostly from fossil fuel-based technologies (typically gas boilers). The high temperatures of the involved processes make the electrification and the integration of renewable energy challenging in this sector considering the off-shelf technologies. In this regard, Thiel et al. [4] discuss four cross-cutting R&D areas that would enable the efficient and competitive decarbonization of industrial heat, namely (1) zero-carbon heat, (2) electrification of heat, (3) zero-carbon fuels and (4) improved heat management.

1.1. Toward the Deep Electrification of Industrial Thermal Processes

The importance of industrial thermal demand electrification and its potential benefits have been demonstrated by Bühler et al. [5], who assess the electrification potential of industrial processes in Denmark, proving that a substantial share of industrial heat in the country could be electrified through the large-scale integration of heat pumps. These latter are identified in the work as the most promising power-to-heat technology for the cost-optimal decarbonization of the sector. The large deployment of these devices could lead to a significant reduction in greenhouse gas (GHG) emissions and increased efficiency for the industrial actors involved. Schüwer et al. [6] investigate the long-term potentials and impacts of industrial process heat electrification and demonstrate its impact for primary energy saving and greenhouse gases emission reduction, highlighting the importance of considering the diversities between different processes. Finally, Brolin et al. [7] affirm the central role of industrial thermal demand electrification for the transition toward a low-carbon economy in the case of Sweden. The report identifies the research gaps in this field, underlying the importance of energy consumption data, of the assessment of the potential economic and GHG emission impact and also of the investigation of the technical and economic potential for flexibility in industrial electricity use. Electric boilers, resistive heating and high-temperature heat pumps are identified in these works as the most promising technologies for the electrification and decarbonization of industrial thermal processes.

High-temperature heat pumps are considered preferable to other power-to-heat options in terms of performance thanks to the high efficiencies and to the possibility to recover and reuse on-site waste heat sources. However, one of the barriers for the deployment of these devices in industry is the limited temperatures achievable. Hamid et al. highlight all the technical, regulatory and economic challenges faced by HTHPs [8]. Nevertheless, in recent years, a lot of effort has been devoted to the research and development of high-temperature heat pumps (HTHPs) suitable for industrial application. Arpagaus et al. [9] present an overview of the HTHPs, concluding that widely commercially available units can reach up to 165 °C and that their coefficient of performance (COP) varies between 2.4 and 5.8. The heating capacities of these devices are in the range between 20 kW and 20 MW. Ongoing R&D projects such as Upheat-INES [10], Encore [11], Qpinch [12] and HeatUp [13] aim to increase the maximum output heat temperature up to 200 °C. Qpinch [12] and Turboden [14] have recently proved the possibility to achieve these temperatures in laboratory demonstrations. Achieving output temperatures up to 200 °C would enable the possibility to deploy high-temperature heat pumps to cover up to 37% of the industrial heat demand in EU [15].

1.2. Industrial Thermal Demand and High-Temperature Heat Pumps (HTHP) Integration

Industrial thermal processes suitable for the integration of HTHPs are the ones with a large heat demand at temperatures up to 200 °C and high availability of waste heat at temperatures up to 100 °C. The heat demand associated with different temperature ranges has been investigated in the literature both through top–down and bottom–up methods. The top–down approach is employed by Naegler et al. [16] and Nicolas et al. [17]. However, the only studies which specifically address the quantification of the heat demand in the range between 100 and 200 °C are bottom–up studies, such as the ones by Rehfeldt et al. [18] and Marina et al. [19]. Rehfeldt et al. [18] analyze the industrial heating and cooling demands in Europe for 2012. Despite the use of different methodologies, the results obtained are in agreement with the results obtained by Naegler et al. [16] and Pardo et al. [17]. Nevertheless, a significant limitation of the study is the lack of process-specific information in particular regarding the presence of a waste heat source suitable for HTHPs. Such an analysis is presented by Marina et al. [19]. In their work, the authors estimate the HTHP market potential in EU28 proving the significant market potential for these devices. The above-mentioned studies agree in identifying the (petro)-chemical, food and paper sectors as the ones with higher potential for HTHP integration.

1.3. Demand Response Investigation in Industrial Thermal Processes

The expected electrification of the heating sector combined with the increasing penetration in the energy system of non-dispatchable renewable sources (such as wind and solar power) will rapidly impose additional constraints to maintain the balance between demand and supply. Energy systems will therefore need higher flexibility, which is expected to be increasingly provided by demand-side actors such as households, commercial and industrial sites.

The large deployment of flexible heating devices in the residential sector has been widely investigated, proving to have great potential for tackling balancing issues and integrating higher shares of renewables in energy systems [20]. Nevertheless, the lack of metering, information and communication infrastructure still represent a critical barrier for the uptake of demand–response (DR) programs in the residential and commercial sectors [20,21].

In this regard, large electricity consumers such as energy-intensive industries are better candidates for flexibility provision in the short–medium term since they are already part of the portfolios of flexibility aggregators [22]. The expected electrification of this sector in the coming years will unleash new opportunities for the participation in DR programs through the integration of flexible heat pumps or thermal storage systems. These latter could help ensure the demand–supply balance of the electric grid without interfering with the quality of the processes involved. Therefore, it is relevant to accurately investigate the flexibility potential of the industrial thermal demand and of its economic value for the actors involved. Nevertheless, up to now, the research has mainly focused on general assessments of the industrial flexibility potential related to electric (non-thermal) loads.

Heffron et al. [23] introduce a first monitoring approach for the "flexibility transition" of industry. The article discusses the main benefits and challenges associated to demand–response programs in the industrial sector and the (economic) risks for the companies in case the security of electricity supply cannot be ensured. M.H. Shoreh et al. [24] present existing DR applications in different industrial segments, underlying the need for proper regulations and market design and for methods that effectively and precisely demonstrate the economic benefits for all the actors involved. Söder et al. [25] present a review of demand-side flexibility potential in northern Europe for the residential, industrial and commercial sector. It is worth noting that the reviewed studies do not consider the interaction between the industrial demand and the energy system. Because of this, it is not possible to forecast the economic potential of the flexible resources, which could be unlocked by factors such as the increased penetration of variable renewable energy systems, changes in the energy market design or deployment of new technologies in the system.

Other studies measure flexibility as the load-shifting potential of the electricity demand for different industrial processes, meaning by "load shifting" the load management technique consisting in moving the demand from one time to another in the day. Xenos et al. [18] and Ma et al. [26] evaluate the demand–response capability of a chemical plant and a roller press, respectively. The aim of these two works is to provide a methodology that could help the involved actors perform a first economic analysis for the participation in the electricity market. Heitkoetter et al. [27] assess the flexibility potential at the NUTS-3 level for Germany by defining a set of load-shifting parameters: flexible load share, time frame constraints, load increase and decrease constraints, and load-shifting costs. Power-to-heat technologies are identified as the option that provides the highest DR potential. However, the work only includes electric heaters to satisfy the industrial thermal demand. Paulus et al. [28] perform an assessment of the technical and economical DR potential for five types of energy-intensive industrial processes for the case of Germany. The study includes the case of an electric arc furnace, which is the only thermal process analyzed. The flexibility of the processes is modeled through the definition of technical flexibility parameters (maximum load shedding per hour, maximum/minimum duration of load shedding, minimum time lag, run-up and shut-down speed, storage size) but also economical parameters that define the costs of the DR technologies. The industrial processes flexibility is then integrated in the Dispatch and Investment Model for Electricity Markets in Europe (DIME), which is a linear optimization model used to provide long-term forecasts. Results show that the industrial processes investigated could significantly help providing balancing power (up to 50% in the case of positive tertiary balancing in the 2030 scenario) in systems with high shares of renewables. Finally, Papadaskalopoulos et al. [29] present a novel modeling framework to comprehensively quantify the potential economic benefits of Flexible Industrial Demand (FID) in the European power system, which is simulated through a whole-electricity system model (WeSIM). The flexibility of the industrial sector is represented through the definition of a maximum reduction/increase in the overall electricity demand for each time step. A constraint is applied to ensure that the total electricity consumption remains unvaried with respect to the non-flexible case over the considered time horizon. Results demonstrate multiple significant economic benefits for the industrial demand flexibility, including capital cost savings by avoiding investments in additional generation, transmission and distribution capacity, as well as a reduction in operating cost by enabling a higher integration of renewable generation sources and providing balancing services. It also demonstrates that the total economic benefits are in the order of billion Euros per year and proved to increase under a higher level of renewable generation in the European system. However, the paper does not disaggregate the industrial sector in its subsectors.

This review demonstrates that the existing literature assesses the flexibility potential of industrial thermal processes by oversimplifying or neglecting them. As highlighted also by Sadjjadi et al. [30], a techno-economic analysis of energy-flexible heat pumps in different industrial processes should be carried out. The current state of the art focuses on a few already existing power-to-heat appliances (e.g., electric arc furnaces and electric boilers) but fails to address the upcoming electrification of industrial processes, thus completely neglecting high temperature heat pumps. Furthermore, the operating temperatures of the processes are usually not considered, which does not allow for linking them to the most suitable power-to-heat or waste heat recovery technologies to be employed. Another limitation of the current research is that most of the works focus exclusively on the demand side, neglecting the mutual interaction between industrial users and the energy system. In general, detailed models of the industrial processes without the integration in an energy system model can be useful to perform a cost–benefit analysis from the consumer perspective under current market conditions (price-taker), but they fail in forecasting the impact on the energy system. On the other side, focusing only on the representation of the energy system leads often to neglect or oversimplifying thermal processes and power-to-heat devices. Therefore, the mutual interaction of demand and supply should be taken into account.

For these reasons, the aim of this work is to assess (1) the impact deriving from the deep electrification of industrial thermal processes and (2) their flexibility potential by means of a novel approach that considers accurately both the demand side and the overall power system characteristics. This is performed through the integration of the industrial heat demand and power-to-heat devices in an existing energy system model. The work focuses on the representation of flexible high-temperature heat pumps coupled with thermal energy storage (TES) systems by taking into account different applications and supply temperature levels. The potential impact in the Belgian industry and energy system deriving from the large deployment of these devices is evaluated from both the demand-side (industrial actors) and supply-side (energy system operators) point of view. Results are quantified in terms of peak-shaving potential, renewables integration, system costs, emission reduction, and overall system flexibility. The flexibility of the demand is assumed to be provided by the exploitation of thermal energy storage units. Such results are paramount because the quantification of the impacts for both the demand and supply side of the energy system, together with the clear and effective communication of costs and benefits to the demand-side actors, are considered fundamental key enablers for the diffusion of DR programs in the industrial sector [21,31,32].

This paper is organized as follows: Section 2 presents the existing model used for the representation of the energy system, the description of the considered industrial thermal processes and power-to-heat technologies and the description of the scenarios analyzed. In Section 3, the results are presented and discussed. Finally, conclusions and further developments are described in Section 4.

2. Materials and Methods

In this section, the integration of the industrial heat demand and flexible power-to-heat units in an existing energy system model is presented and applied to the case study of the Belgian industry and power system. The main characteristics of the energy system model (Section 2.1) are described followed by the adaptations and modifications applied to introduce power-to-heat technologies into the model (Section 2.2) and by an accurate description of the industrial heat demand representation (Section 2.3).

2.1. Dispa-SET

The power system is represented through the existing open-source unit commitment and optimal dispatch model Dispa-SET [33]. The model represents the operations of large-scale power systems with a high level of detail with the aim to solve the unit commitment problem for the chosen time horizon for each time step that corresponds to one hour. The model includes the following features: minimum and maximum power for each unit, power plant ramping limits, reserves up and down, minimum up/down times, load shedding, curtailment, pumped-hydro storage, non-dispatchable units (e.g., wind turbines, run-of-river, etc.), power-to-heat (heat pumps, electric boilers, CHP and TES units), start-up costs and ramping costs.

The main optimization variable is the total system cost that is composed by fixed costs, variable costs, start-up and shut-down costs, ramp-up and ramp-down costs, shed load costs and transmission costs as described by Equation (1).

$$\begin{aligned} SystemCost_i = & \sum_{u,n} \Big(CostStartUp_{u,i} + CostShutDown_{u,i} + CostFixed_u x \delta_{u,i} \\ & + CostVariable_u x P_{u,i} + CostRampUp_{u,i} + CostRampDown_{u,i} \\ & + PriceTransmission_{i,l} x Flow_{i,l} \\ & + CostLoadShedding_{i,n} x ShedLoad_{i,n} \Big) \end{aligned} \quad (1)$$

The main constraint for the system is represented by the demand–supply balance that must be ensured at each time step and is described in Equation (2).

$$\begin{aligned} & \sum_u (Power_{u,i} \times Location_{u,n}) + \sum_l (Flow_{l,i} \times LineNode_{l,n}) \\ & \quad = Demand_{n,i} \\ & \quad + \sum_s \Big(StorageInput_{s,i} \times Location_{s,n} \Big) - ShedLoad_{n,i} \\ & \quad + \sum_{p2h} \Big(PowerConsumption_{p2h,i} \times Location_{p2h,n} \Big) - LL_{MaxPower,n,i} \\ & \quad + LL_{MinPower,n,i} \end{aligned} \quad (2)$$

In addition to the demand–supply balance constraint, the model ensures that the reserves requirements are met for each time step through the reservation of a certain amount of capacity from the available power plants.

All power units are characterized by the definition of the must-run generation level, specific available capacity and ramping capabilities. Moreover, a minimum online time is defined for each unit. Heat pumps are modeled by fixing the heating capacity, ramping capability and coefficient of performance (COP) that can be alternatively defined by the user or calculated through an empirical formula dependent on the heating temperature. Finally, storage units are defined by their storage capacity, inflow, outflow, charging capacity, charge/discharge efficiency, etc.

More details regarding the supply-side model Dispa-SET (Figure 1) are available at [33].

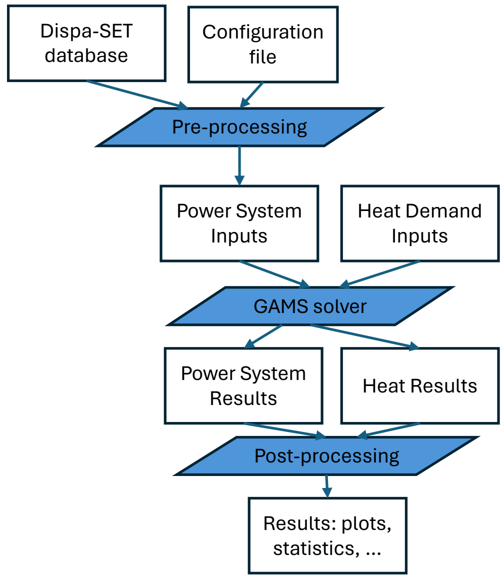


Figure 1. Dispa-SET model optimization scheme.

2.2. Industrial High-Temperature Heat Pumps

For the aim of this work, the representation of the heat pumps in the Dispa-SET model is adapted to the industrial case. Differently from the residential case, industrial heat pumps exploit waste heat streams as heat sources. The performance of these devices is strongly related to both heat sink and heat source operating temperatures. The modeled HTHP are vapor-compression heat pumps, since this technology is the more mature on the market [9].

The coefficient of performance of HTHPs is calculated through the multiplication of the ideal efficiency by a "Quality Factor" (QF), which is estimated based on the literature on existing industrial heat pumps (Figure 2). Regarding the ideal efficiency, the use of the Lorentz COP instead of the Carnot COP is more accurate for the estimation of HTHP performance in the presence of temperature glides for the heat sink and/or heat source [34]. Therefore, a pre-calculation for the COP of HTHP based on the input and output temperature of the sink and source streams is integrated in the model as described in Equation (3).

$$COP_{HTHP} = COP_{Lorentz} \times QF \quad (3)$$

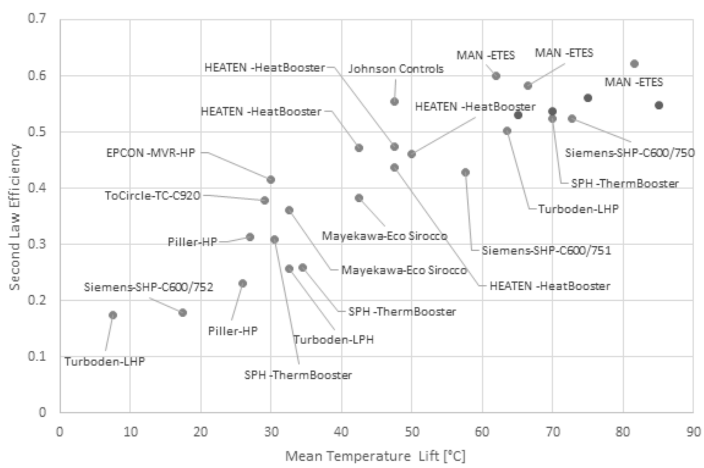


Figure 2. Second-law efficiency (i.e., QF) of existing HTHPs [15].

With (Equation (4))

$$COP_{Lorentz} = \frac{\overline{T_{sink}}}{\overline{T_{sink}} - \overline{T_{source}}},\ \overline{T_{sink}} = \frac{T_{sink,out} - T_{sink,in}}{ln\frac{T_{sink,out}}{T_{sink,in}}},\ \overline{T_{source}} = \frac{T_{source,in} - T_{source,out}}{ln\frac{T_{source,in}}{T_{source,out}}} \quad (4)$$

The "Quality Factor" corresponds to the second-law efficiency of the devices and is defined based on the results of the analysis performed on available data of existing industrial HTHP available in the literature and from the IEA Annex 58 documentation [15]. This factor is strongly correlated to the mean temperature lift, as shown in Figure 2. Typical values of QF are between 0.4 and 0.6 for the range of temperatures considered in this work.

The HTHP units are modeled with a maximum heating capacity equal to the base thermal load associated to each industrial thermal demand multiplied by an increasing factor (i.e., 1.3) to allow the exploitation of the flexibility provided by the coupling with the thermal storage. In such a configuration, the heat pump can work with a variable electrical power demand that minimizes the costs, while the heat supply to the industrial process is always satisfied thanks to the storage. A minimum partial load for the heat pump equal to 0.5 is also assumed.

The storage is dimensioned to provide 3 h of the thermal load of the industrial process. The value has been obtained by simulating different configurations in terms of HTHP and storage system sizes in comparison with a reference configuration with no storage and an HTHP which is sized according to the peak heat demand.

As shown in Figure 3, by increasing the storage size from 3 h capacity to 4 h or the HTHP size from 1.3 times the base load to 1.4 times the base load, the further decrease in costs is so limited (<1%) that it would not compensate the greater initial cost for the largest HTHP/storage. This justifies the choice of the system sizing for this analysis.

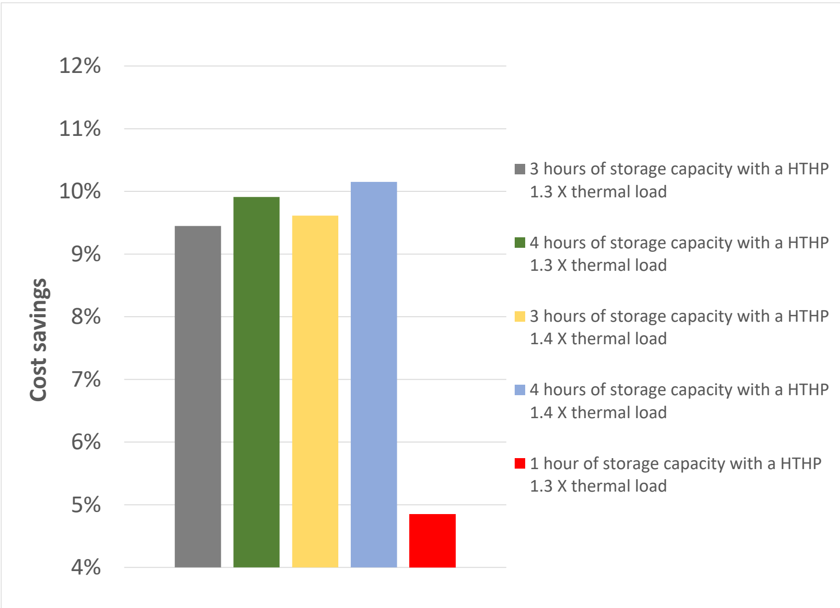


Figure 3. Electricity cost reduction in different configurations of HTHP and storage systems compared with a system with base load capacity HTHP and without storage.

2.3. Industrial Thermal Storage Units

For the storage system, a sensible thermal energy storage is chosen. This storage is easy to modulate, and the maximum temperature of the system is 200 °C. For the storage material, pressurized water is selected for its good thermodynamic properties and its cost-effectiveness compared to other options [35].

In order to easily represent the stratification of the storage, a two-zone perfectly stratified thermal energy model is used [36]. This model is a good representation of large-scale sensible heat storage. It consists of two zones, one zone at high temperature (outlet of the HTP/inlet for the process) and a low-temperature zone that comes from the return of the process (Figure 4).

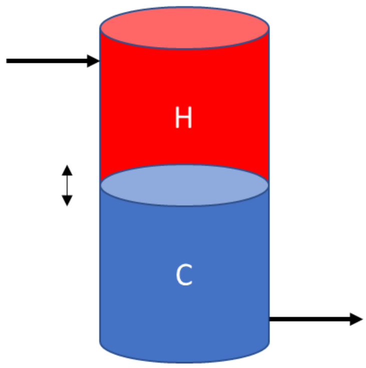


Figure 4. Thermal storage model schematic.

When the storage is charged, the amount of heat at high temperature (T_H) increases and vice versa when discharging. The amount of heat that is stored is calculated via the following equation (Equation (5)):

$$Q_t = Q_{t-1}(1-\beta) - \gamma * Q_N - \delta + Q_{in,t} * \eta_{in} * \Delta t - \frac{Q_{out,t}}{\eta_{out}} * \Delta t \quad (5)$$

Q_t is the energy available in the storage at time t, while Q_{t-1} is the amount of energy at the previous time step, $Q_{in,t}$ is the amount of heat charged and Q_{out} is the amount of heat discharged from the storage, η is the charging (in)/discharging (out) efficiency of the system.

The terms β, γ and δ represent, respectively, the heat loss factors for the (i) losses through the lateral surface of the hot part of the water body, depending on the state of charge; (ii) losses through the total lateral surface assuming the storage to be empty; and (iii) losses through the top and bottom surfaces. They are calculated with the following equations:

$$\beta = \frac{U * 4}{d * \rho * c} * \Delta t$$

$$\gamma = \frac{U * 4}{d * \rho * c * \Delta T_{HC}} * \Delta T_{C0}$$

$$\delta = \frac{U * \pi * d^2}{4} * (\Delta T_{H0} + \Delta T_{C0}) * \Delta t$$

where U is the overall thermal transmittance, d is the tank diameter, ρ is the water density; c is the water-specific heat; ΔT is the driving temperature difference in the hot (H) and cold (C) part of the storage.

2.4. Thermal Demand Representation

Since the case study chosen for this analysis is based on the Belgium energy system and industrial sector, the assumptions for the representation of the industrial heat will be based on the Belgian industrial sector. In this regard, Figure 5 presents the Belgian industrial heat demand for different temperature levels based on the estimation provided by the Heat Roadmap Belgium report [37].

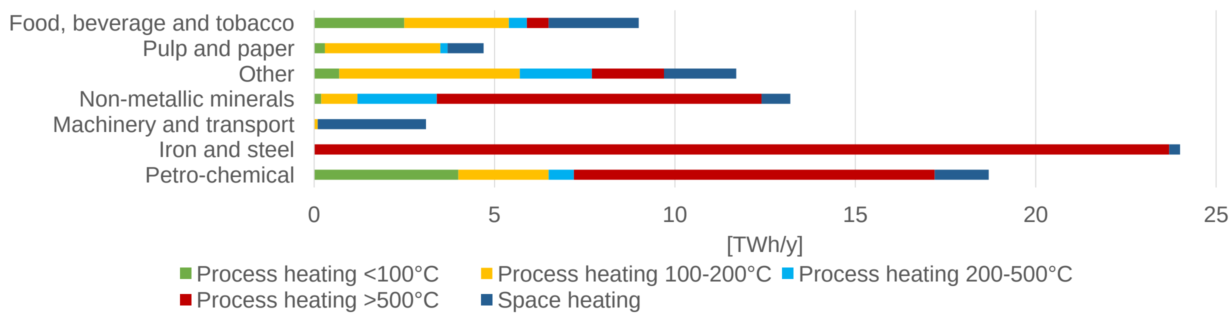


Figure 5. Industrial heat demand per sector [37].

For the aim of this work, only thermal processes suitable for the integration of HTHPs are modeled. Therefore, only the heat demand in the range between 100 and 200 °C is considered. A penetration rate of the heat pump technology is assumed: one third of such heat demand (i.e., the total heat demand estimated by the Belgian Heat Roadmap for the range between 100 and 200 °C) is considered to be electrified through HTHPs. The distribution of the heat demand inside this temperature range is based on the work of Marina et al. [19]. That work provides the different shares of heat at different temperature levels for several industrial processes in the EU, which are subsequently applied to the Belgian industry case. Based on the share of thermal demand associated with each temperature in the range between 100 and 200 °C, a set of representative archetypes is defined. The specifications of the thermal processes associated with each archetype are based on the literature as specified in Table 1, where the identified archetypes are reported.

Table 1. Specifications of the thermal processes of the representative archetypes.

Process/Archetype	Tsink_in (°C)	Tsink_out (°C)	Tsource_in (°C)	Tsource_out (°C)	Total Thermal Load (MWth)	Ref.
1. Chemical Distillation 1	120	120.1	100	99.9	125.3	[38]
2. Steam Network 1	140	145	100	99.9	74.8	[39]
3. Steam Network 2	140	140	110	90	74.8	[15]
4. Steam Network 3	100	160	100	85	68.7	[15]
5. Steam Network 4	120	180	115	95	46.5	[15]
6. Chemical Distillation 2	184.1	184.2	139.9	139.8	46.5	[40]
7. Chemical Distillation 3	197.7	197.8	103	90	20.2	[41]

The thermal demand is assumed to be constant for each time step of the year considered in the simulations, which is in line with the typical operation of energy-intensive industries such as the chemical, food and paper sectors. On the basis of the temperature level of the processes, the COP of each archetype process is calculated as explained in Section 2.2 and reported in Table 2.

Table 2. Performance of the archetype processes.

	$COP_{Lorentz}$	QF	COP
Archetype 1	19.56	0.22	4.30
Archetype 2	9.76	0.38	3.71
Archetype 3	10.29	0.37	3.81
Archetype 4	10.93	0.35	3.83
Archetype 5	9.52	0.42	4.00
Archetype 6	10.32	0.41	4.23
Archetype7	4.64	0.63	2.92

2.5. Scenarios

The case study considered in this work is the Belgian power system and its industrial sector. In order to assess the potential flexibility of power-to-heat, three different scenarios are defined for the representation of the power system: (1) a base case scenario, including the existing power units currently present in Belgium, (2) the 2040 scenario (32 GW installed of RES plants) and (3) the 2050 scenario (46 GW installed of RES plants).

The selection of these scenarios is based on the availability of reliable data for the reference case and for future predictions. For the base case scenario, indeed, the units are assumed to be the ones present in the database of Dispa-SET that refers to the year 2015. For the high-renewables scenarios, the available power production units are the ones identified by the "e-highway ENTSO-E" project database [42].

Eventually, a last ideal case is assumed with a very high amount of RES penetration (double than the values in the 2040 scenario) to further investigate the potential of flexibility in curtailment.

3. Results

In this section, the results of the simulation of the optimization model (represented by Equations (1) and (2)) for the scenarios mentioned above are reported and discussed. In each scenario, the electricity costs are compared in the presence or not of the high-temperature heat pumps. To have a better insight also of the seasonality, an average price for the total electricity produced in each season is calculated. The values obtained are summarized in Figure 6.

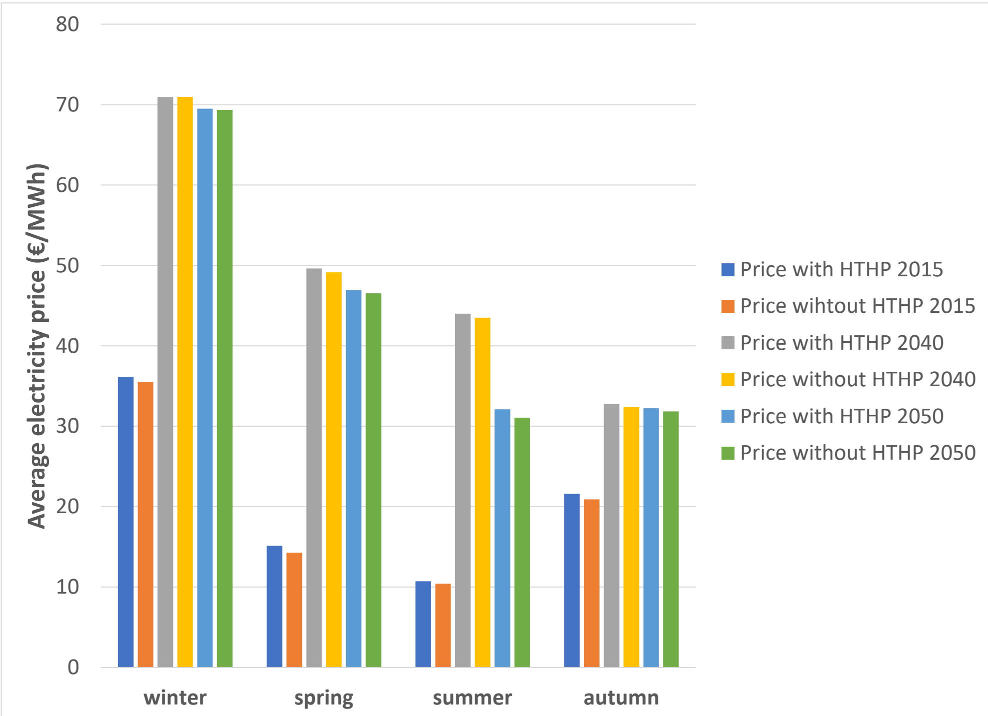
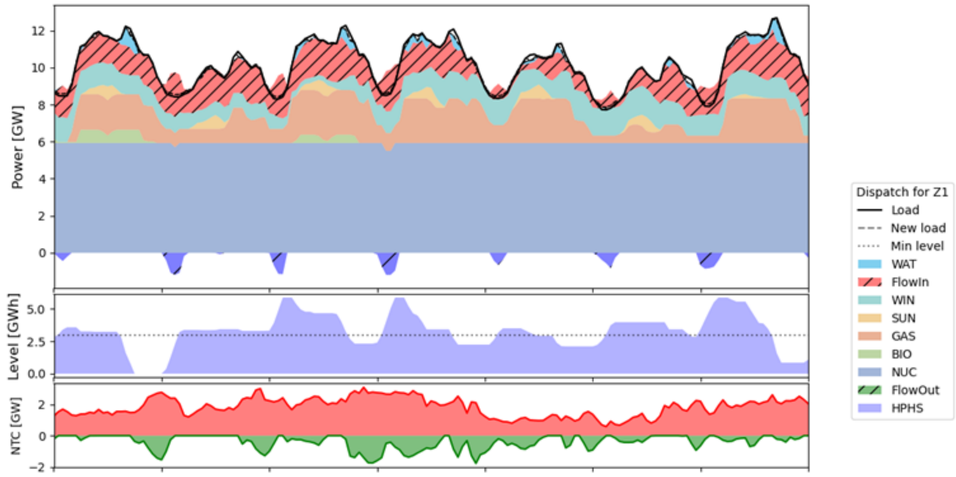
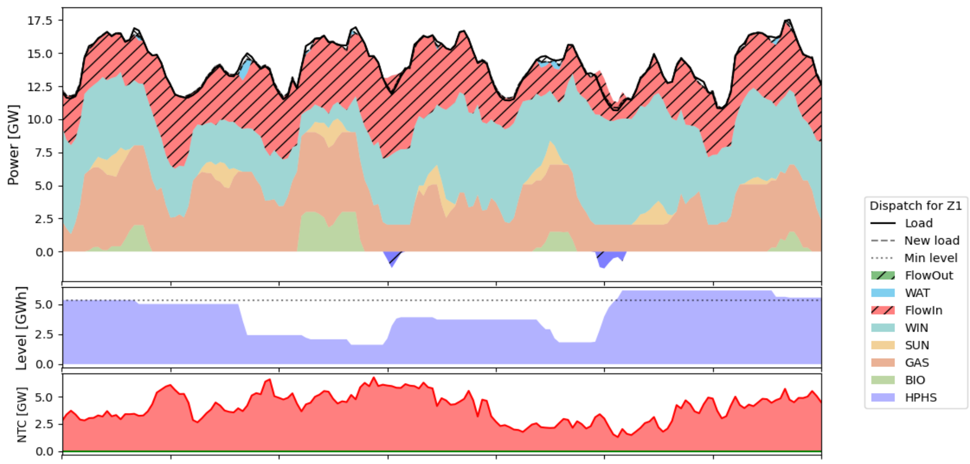


Figure 6. Electricity price assessment for the different scenarios.

It is possible to notice that the electricity price varies according to the season due to the different availability of RES. Furthermore, the average price depends on how the electricity is produced: in 2015, the price was much lower than in the other cases due to the production of electricity via nuclear power plants, while in 2040 and 2050, these are replaced by gas turbines and additional RESs. In general, the introduction of HTHPs to cover the thermal demand of industry results in an increase in the overall electricity use and therefore of the electricity price. In Figure 7, the generation of electricity for the present and future scenario is shown for a week in autumn.



(**a**)



(**b**)

Figure 7. Electricity power in the scenario of 2015 (**a**) and 2040 (**b**) for the week 10–17 November. Note: Level: is the amount of energy that is available in the storage of the hydro-pumped power plants, when power is going below zero, the model is charging the storage (pumping up water to the higher reservoir). NTC: (Net Transfer Capacity) is the red amount is the amount of electricity that is being imported; the green part is the amount of electricity that is exported.

In addition to the negative effect on the price when implementing heat pumps in the system, HTHPs have a major positive environmental impact compared to traditional gas boilers, which are at present mostly used in industrial processes. Gas boilers have a CO_2 emission factor of 0.244 kg CO_2/kWh of heat [43], which corresponds to a total of 122,482.64 kg CO_2 when applied to the 501,978 kWh industrial heat demand between 100 and 200 °C. The HTHPs, instead, use electricity as input and, referring to Belgium, the emission factor for producing 1 kWh of electricity is 0.164 kg CO_2 using the current CO_2 intensity of the Belgian grid [44]. In total, an average of 116,420.7 kW of electricity is required to heat the processes with the heat pumps by using the COP calculated in Table 2. This results in 19,092.99 kg CO_2, corresponding to an emission reduction of 84.4%.

As described in the presentation of the scenarios, a case where there is a huge penetration of RES is evaluated. This case is considered in order to better assess the energy flexibility introduced by the electrification of the thermal demand in industry. A system that has a lot of renewable energy sources is subject to curtailments that can be reduced by means of a smart management of the heat pumps and their thermal storage systems, leading to a more efficient energy system. This is confirmed by the results presented in Table 3.

Table 3. Curtailments reduction in the ideal 2040 case.

	Winter	Spring	Summer	Autumn
Curtailment without HPs (MWh)	84,919.58	107,735.51	140,310.42	621,564.70
Curtailment with HPs (MWh)	82,349.08	101,980.44	132,199.35	603,612.2
Difference (MWh)	2570.5	5755.07	8111.07	17,952.53

It can be noted that when thermal processes are electrified, it is possible to reduce the amount of curtailment that is needed to maintain a balance on the grid. The amount that can be reduced depends on the amount of RES production during the day. In seasons where there is a high level of curtailment, like in autumn when there is a lot of wind, there is more need to reduce the RES curtailment (see Figure 8).

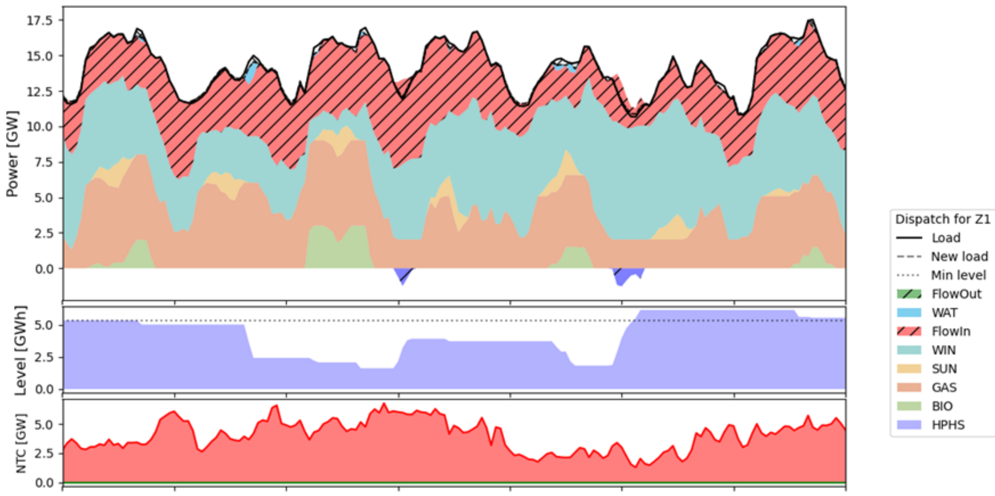


Figure 8. Electricity power in the ideal scenario 2040 (week 10–17 November) with double RES installation.

4. Conclusions

This paper aims at investigating the role of the electrification of thermal industrial processes with temperatures in the range 100–200 °C. The analysis is performed by means of a novel detailed model of the demand and supply side, which is developed in Dispa-SET and referred to the case of Belgium. It analyzes the comparison between the present energy system and future scenarios in 2040 and 2050 with highly renewable energy sources penetration in the generation mix. The results are summarized as follows:

- The electrification of the thermal processes by means of high-temperature heat pumps has a slightly negative effect on the electricity price because of the increase in the overall electricity demand.
- The storage coupled to the high-temperature heat pumps contribute to ensure that price increases are limited: with the right configuration in terms of the size of the heat pump and storage, the electricity cost can be reduced by around 9.6% compared with the case without the storage.
- In addition to the economic impact, high-temperature heat pumps can improve considerably the environmental impact. The greenhouse gases emissions are reduced up to 84.4% in comparison with gas boilers presently used.
- In the presence of a very high penetration of renewable sources (double the amount foreseen for 2040), the energy flexibility provided by the heat pump and the storage can be used to reduce the curtailments and increase the efficiency of the system.

Concluding, this work is a first attempt to quantify the impact of the electrification of industrial thermal processes on the energy system, and it demonstrates several potential benefits while highlighting the importance of a proper sizing of the technological devices. Furthermore, the contribution of high-temperature heat pumps to the energy flexibility of the power system by means of Demand-Side Management programs is not straightforward, and further analyses are needed to better understand this aspect.

Author Contributions: Conceptualization, C.M., S.Q. and AA.; Formal analysis, R.P.; Methodology, C.M.; Writing—original draft, C.M. and R.P.; Writing—review and editing, S.Q. and A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. JRC. *Decarbonising the EU Heating Sector*; European Union: Brussels, Belgium, 2019. [CrossRef]
2. European Commission. *A Clean Planet for All. A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*; European Commission: Brussels, Belgium, 2018.
3. European Commission. *The European Green Deal*; European Commission: Brussels, Belgium, 2019; Volume 53, p. 24. [CrossRef]
4. Thiel, G.P.; Stark, A.K. To decarbonize industry, we must decarbonize heat. *Joule* **2021**, *5*, 531–550. [CrossRef]
5. Bühler, F.; Holm, F.M.; Elmegaard, B. Potentials for the electrification of industrial processes in Denmark. In Proceedings of the ECOS 2019—The 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Wroclaw, Poland, 23–28 June 2019; pp. 2137–2152.
6. Schüwer, D.; Schneider, C. Electrification of industrial process heat: Long-term applications, potentials and impacts. *ECEEE Ind. Summer Study Proc.* **2018**, *2018*, 411–422.
7. Brolin, M.; Fahnestock, J.; Rootzén, J. Industry's Electrification and Role in the Future Electricity System—A Strategic Innovation Agenda. 2017. Available online: https://www.diva-portal.org/smash/get/diva2:1073841/FULLTEXT01.pdf (accessed on 15 January 2024).
8. Hamid, K.; Sajjad, U.; Ahrens, M.U.; Ren, S.; Ganesan, P.; Tolstorebrov, I.; Arshad, A.; Said, Z.; Hafner, A.; Wang, C.-C.; et al. Potential evaluation of integrated high temperature heat pumps: A review of recent advances. *Appl. Therm. Eng.* **2023**, *230*, 120720. [CrossRef]
9. Arpagaus, C.; Bless, F.; Uhlmann, M.; Schiffmann, J.; Bertsch, S.S. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. *Energy* **2018**, *152*, 985–1010. [CrossRef]
10. MoonshotFlanders. Upheat-INES. Available online: https://moonshotflanders.be/mot4-upheat-ines (accessed on 1 March 2022).
11. Encore—Next Generation Compression Heat Pump. Available online: https://ispt.eu/projects/encore (accessed on 1 March 2022).
12. Qpinch. Available online: https://www.qpinch.com (accessed on 20 April 2022).
13. Sintef—HeatUp Project. Available online: https://www.sintef.no/projectweb/heatup (accessed on 15 January 2024).
14. Turboden. Large Heat Pump. Available online: https://www.turboden.com/solutions/2602/large-heat-pump (accessed on 20 April 2022).
15. I.E.A. Annex 58—High Temperature Heat Pumps. Available online: https://heatpumpingtechnologies.org/annex58 (accessed on 15 January 2024).
16. Naegler, T.; Simon, S.; Klein, M.; Gils, H.C. Quantification of the European industrial heat demand by branch and temperature level. *Int. J. Energy Res.* **2019**, *2015*, 2019–2030. [CrossRef]
17. Pardo, N.; Vatopoulos, K.; Riekkola, A.K.; Perez, A. Methodology to estimate the energy flows of the European Union heating and cooling market. *Energy* **2013**, *52*, 339–352. [CrossRef]
18. Rehfeldt, M.; Rohde, C.; Fleiter, T.; Toro, F.; Reitze, F. A bottom-up estimation of heating and cooling demand in the European industry. *ECEEE Ind. Summer Study Proc.* **2016**, *2016*, 59–69. [CrossRef]
19. Marina, A.; Spoelstra, S.; Zondag, H.A.; Wemmers, A.K. An estimation of the European industrial heat pump market potential. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110545. [CrossRef]
20. Bloess, A.; Schill, W.P.; Zerrahn, A. Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials. *Appl. Energy* **2018**, *212*, 1611–1626. [CrossRef]
21. Strbac, G. Demand side management: Benefits and challenges. *Energy Policy* **2008**, *36*, 4419–4426. [CrossRef]
22. Verhaegen, R.; Dierckxsens, C. Existing Business Models for Renewable Energy Aggregators. 2016. Available online: http://bestres.eu/wp-content/uploads/2016/08/BestRES_Existing-business-models-for-RE-aggregators.pdf (accessed on 15 January 2024).

23. Heffron, R.; Körner, M.F.; Wagner, J.; Weibelzahl, M.; Fridgen, G. Industrial demand-side flexibility: A key element of a just energy transition and industrial development. *Appl. Energy* **2020**, *269*, 115026. [CrossRef]
24. Shoreh, M.H.; Siano, P.; Shafie-khah, M.; Loia, V.; Catalão, J.P.S. A survey of industrial applications of Demand Response. *Electr. Power Syst. Res.* **2016**, *141*, 31–49. [CrossRef]
25. Söder, L.; Lund, P.D.; Koduvere, H.; Bolkesjø, T.F.; Rossebø, G.H.; Rosenlund-Soysal, E.; Skytte, K.; Katz, J.; Blumberga, D. A review of demand side flexibility potential in Northern Europe. *Renew. Sustain. Energy Rev.* **2018**, *91*, 654–664. [CrossRef]
26. Ma, Z.; Friis, H.T.A.; Mostrup, C.G.; Jørgensen, B.N. Energy flexibility potential of industrial processes in the regulating power market. In Proceedings of the 6th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2017), Porto, Portugal, 22–24 April 2017. [CrossRef]
27. Heitkoetter, W.; Schyska, B.U.; Schmidt, D.; Medjroubi, W.; Vogt, T.; Agert, C. Assessment of the regionalised demand response potential in Germany using an open source tool and dataset. *Adv. Appl. Energy* **2020**, *1*, 100001. [CrossRef]
28. Paulus, M.; Borggrefe, F. The potential of demand-side management in energy-intensive industries for electricity markets in Germany. *Appl. Energy* **2011**, *88*, 432–441. [CrossRef]
29. Papadaskalopoulos, D.; Moreira, R.; Strbac, G.; Pudjianto, D.; Djapic, P.; Teng, F.; Papapetrou, M. Quantifying the potential economic benefits of flexible industrial demand in the european power system. *IEEE Trans. Ind. Inform.* **2018**, *14*, 5123–5132. [CrossRef]
30. Sadjjadi, B.S.; Gerdes, J.-N.; Sauer, A. Energy flexible heat pumps in industrial energy systems: A review. *Energy Rep.* **2023**, *9* (Suppl. 3), 386–394. [CrossRef]
31. Nolan, S.; Malley, M.O. Challenges and barriers to demand response deployment and evaluation. *Appl. Energy* **2015**, *152*, 1–10. [CrossRef]
32. Good, N.; Ellis, K.A.; Mancarella, P. Review and classification of barriers and enablers of demand response in the smart grid. *Renew. Sustain. Energy Rev.* **2017**, *72*, 57–72. [CrossRef]
33. Quoilin, S. The Dispa-SET Model. Available online: http://www.dispaset.eu/en/latest (accessed on 15 January 2024).
34. Jensen, J.K.; Ommen, T.; Reinholdt, L.; Markussen, W.B.; Elmegaard, B. Heat pump COP, part 2: Generalized COP estimation of heat pump processes. *Refrig. Sci. Technol.* **2018**, *2018*, 1255–1264. [CrossRef]
35. Manente, G.; Ding, Y.; Sciacovelli, A. A structured procedure for the selection of thermal energy storage options for utilization and conversion of industrial waste heat. *J. Energy Storage* **2022**, *51*, 104411. [CrossRef]
36. Oemof. Open Energy Modelling Framework—Python Toolbox for Energy System Modelling and Optimisation. Available online: https://oemof-thermal.readthedocs.io/en/latest/stratified_thermal_storage.html (accessed on 15 January 2024).
37. Paardekooper, S. *Heat Roadmap Belgium Quantifying the Impact of Low-Carbon*; Aalborg University: Aalborg, Denmark, 2018; Available online: https://vbn.aau.dk/ws/portalfiles/portal/287929422/Country_Roadmap_Belgium_20181005.pdf (accessed on 15 January 2024).
38. Kim, Y.H. Energy efficiency improvement in a modified ethanol process from acetic acid. *Entropy* **2016**, *18*, 422. [CrossRef]
39. Matsuda, K.; Kurosaki, D.; Hayashi, D.; Aoyama, K. Industrial heat pump study using pinch technology for a large scale petrochemical site. *Chem. Eng. Trans.* **2012**, *29*, 67–72. [CrossRef]
40. Wei, R.; Yan, C.; Yang, A.; Shen, W.; Li, J. Chemical Engineering Research and Design Improved process design and optimization of 200 kt / a ethylene glycol production using coal-based syngas. *Chem. Eng. Res. Des.* **2018**, *132*, 551–563. [CrossRef]
41. Luo, H.; Bildea, C.S.; Kiss, A.A. Novel heat-pump-assisted extractive distillation for bioethanol purification. *Ind. Eng. Chem. Res.* **2015**, *54*, 2208–2213. [CrossRef]
42. ENTSO-E. e-Highway 2050: Results. Available online: https://docs.entsoe.eu/baltic-conf/bites/www.e-highway2050.eu/results (accessed on 15 January 2024).
43. Emission Factor NG. Available online: https://www.climfoot-project.eu/en/what-emission-factor (accessed on 20 April 2022).
44. Emission Factor Electricity Production. Available online: https://ourworldindata.org/grapher/carbon-intensity-electricity (accessed on 20 April 2022).