Optimized waste heat utilization in the steel industry with industrial heat pumps and low-temperature distribution system

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Abstract:

Requirements regarding reduction of emissions, energy efficiency and flexibility are increasing and force the implementation of corresponding measures in the industry. In this work, opportunities for the substitution of mostly natural gas fired steam supply in steel processing industry are analyzed. Heat recovery from flue gas and other waste heat sources is evaluated using a systematic approach including pinch analysis and mathematical optimization.

A basic analysis is carried out for four individual facilities which shows potentials for direct heat recovery and heat pump integration. The analysis further shows that the remaining surplus of waste heat from one of the facilities could be transferred to the other facilities. A mathematical design optimization model including optimal heat-exchanger network synthesis, heat pump integration and the implementation of a steam driven low temperature distribution system is used to identify economically feasible efficiency measures. Possible future development of costs for energy and industrial heat pumps were considered through three different scenarios with parameter variations as input for the following optimization.

The results show that using direct heat recovery alone 20-80% of the steam output can be substituted. This potential can be further increased using industrial heat pumps to 30-100% and with an inter-plant low temperature distribution system to 100%. Depending on the technical configuration of the system and forecast for energy and equipment costs, payback times between 1 to 4 years could be realized.

Keywords: Mathematical Programming, Steel making sector, Low Temperature Distribution System, Heat Pump Integration

Introduction

Besides renewable energy generation and reduction of greenhouse gas emissions, efficiency enhancement of industrial processes is one of the most important pillars of a strategy against

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global warming and a sustainable energy policy. Especially, the iron & steel industry bears a huge potential with approximately 3.4 Gt CO_2 emitted in the year 2019 [1] which accounts for around 7% of global CO_2 emissions [2]. The value is expected to rise further as the global demand for steel is forecasted to increase until 2050 by approximately 50 % (1.7 billion tons in 2018 to 2.6 billion tons in 2050) [3].

According to Wilk et al. [5], steam production accounts for up to 16 % of the final energy demand In the Austrian steel industry whereas Statistik Austria claims that in Austria process heat below 200°C accounts only for 1 % of the final energy consumption [4]. Steam in steel processing is used for heat distribution and in the steelmaking process itself and is in many cases generated burning natural gas. Heat recovery (HR) studies in the steel industry showing varying potentials but they show that besides direct heat recovery (DHR) measures electrification and thereby especially the utilization of industrial heat pumps (HPs) can play an important role on the path to decarbonization [7][8][9].

Typical methods for the identification of these potentials are pinch-based total site analysis and mathematical programming approaches such as superstructure-based heat exchanger network synthesis (HENS) as highlighted by Klemeš and Kravanja [14] with additions for the integration of HPs [15] and distribution systems [16]. With the concept of the *grand composite curve* Pinch Analysis can be used to identify feasible integration points for heat pumps from a thermodynamic viewpoint [15]. Pinch Analysis also yields important insights for total site integration and thus for inter-facility heat transfer. Depending on the imbalance between heat demands and available excess heat within the individual facilities inter-facility distribution systems can increase the overall energy efficiency of the industrial site substantially [17].

In the following chapters, the workflow applied in this work for identification of economically viable HR measures is described, models for HPs and heat distribution systems used within a mathematical programming formulation are presented and results for a specific use case from the steel making industry are presented.

Methodology

Figure 1 shows the essential steps taken for the optimization of the plant heat recovery network.

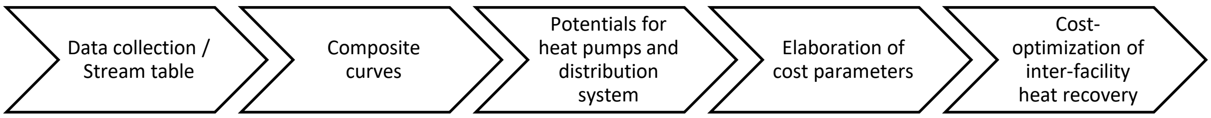

Figure 1: Flow chart of proposed methodology

At first, a basic Pinch Analysis was performed as it is an efficient and proven method to identify HR potentials and thermodynamic bottlenecks in industrial processes [10]. The first and the most important step is to identify actual process requirements for heating and cooling which need to be fulfilled though connections with external utilities or by HR. These requirements are called process streams and are specified through inlet and outlet temperatures, mass flows and specific heat capacity or heat duties. Each process stream is classified either as a hot stream or a cold stream which defines whether energy must be removed or supplied. The overall goal is to match appropriate hot and cold streams to maximize HR. Often, there is a gap between current and ideal energy consumption, which offers potential for a retrofit of the heat exchanger network (HEN).

Data collection and extraction is usually difficult and time consuming. In order to reduce this effort, information from the plant managers, estimates and calculated approximate values were used in order to perform a rough pinch analysis. Additional information such as the feasibility of heat transfer from excess heat sources in terms of market available HR equipment and stream pollution, operating hours and temporal profiles were considered in the study. For the following analysis, only HR options with high technology readiness levels were considered.

After establishing HR potentials for DHR, for HP and for low temperature distribution (LTD) systems, a mathematical programming model was set up, that allows for simultaneous optimization of the energy system considering these HR measures. A preliminary study on the suitability of thermal oil, pressurized hot water and low-pressure steam was carried out. The most promising alternatives were included in the optimization model and the selection of the optimal system was subject to optimization. The optimization model is based on a linearized version [18] of the often-used MINLP HEN superstructure proposed by Yee and Grossmann [19] with extensions for heat pump integration and the introduction of heat distribution systems. The models used for heat recovery are presented in the following.

For heat transfer between process streams, HPs and **different types of heat exchangers** (HEXs) are considered for the individual media combinations. For instance, if a process stream is corrosive stainless-steel components are necessary. Cost data for HEXs (carbon steel, stainless steel, graphite) are taken from a cost database (DACE price booklet) and were expressed in the form

$$C_{inv} = C_{Fix} + C_{Var}A^{\beta}$$

for the considered heat exchanger (HEX) types (Figure 2).

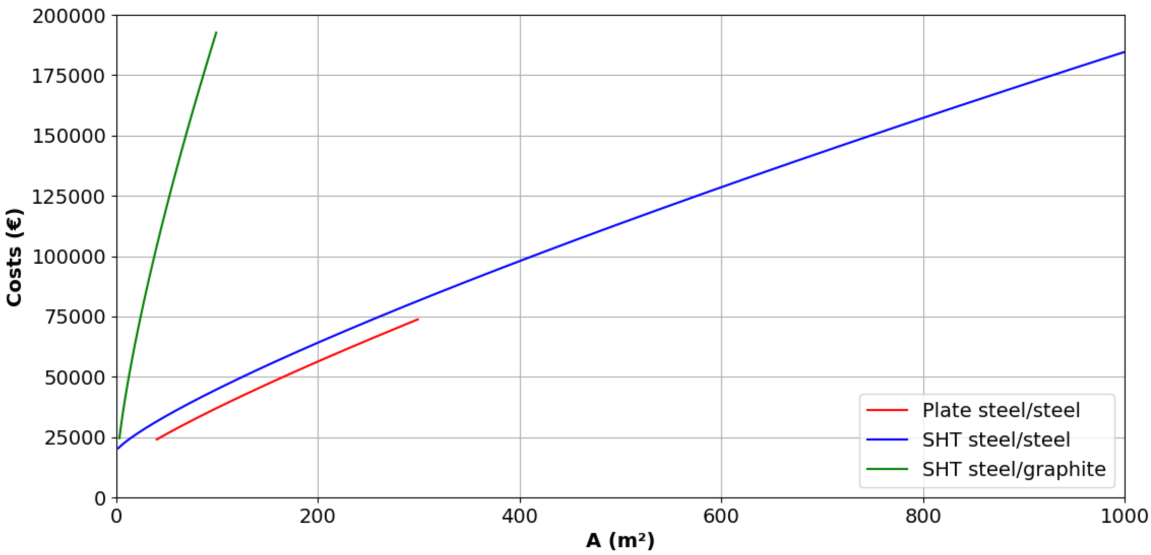

Figure 2: Costs for different heat exchanger types (SHT means shell and tube)

The **HP model** used in this work is a linearized Carnot-model. In this linearized model, virtual condenser and evaporator capacities are introduced. In contrast to e.g. the work of Prendl and Hofmann [20], the idea is to model the condenser and evaporator capacities for the individual hot and cold process streams separately as individual virtual HPs which yields more accurate linear approximations. For the hot process streams this means that the heat loads supplied to the evaporator Q^e are modelled directly whereas on the hot side of the HP, a virtual condenser heat load $Q^{c,v}$ is derived using a linearized Carnot HP model. Similarly, the heat loads supplied to the cold streams from the condenser are modelled directly and the corresponding virtual evaporator loads are calculated. Ideally, the sum of virtual evaporator heat loads and the sum of actual evaporator heat loads should be equal. The same is true for virtual and condenser heat loads. In general, this is not the case due to the error made by linearizing the Carnot model. A schematic drawing of this concept is presented in Figure 3.

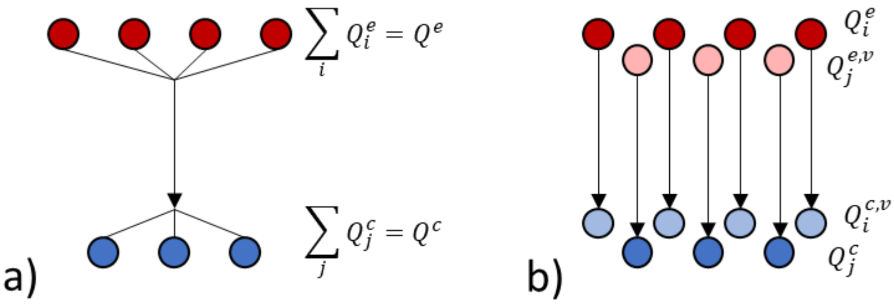

Figure 3: Schematic representations of (a) the nonlinear Carnot model and (b) the linearized version using virtual heat loads

The correlation between the evaporator heat loads $\dot{Q}_i^e$ and the corresponding virtual condenser heat load $\dot{Q}_i^{c,v}$ is modelled as a function of dT using the coefficients c_i. The term including the slack variable s_i is used to (de)activate the constraint.

$$dT * c_{i,0,0} + \dot{Q}_i^e * c_{i,1,0} + z_i^e * c_{i,2,0} + s_i\left(dT^{max} * c_{i,0,0}\right) = \dot{Q}_i^{c,v}$$

The correlation between virtual evaporator heat loads and actual condenser heat loads is modelled with the same concept.

$$dT * c_{j,0,0} + \dot{Q}_j^{e,v} * c_{j,1,0} + z_j^c * c_{j,2,0} + s_j\left(dT^{max} * c_{j,0,0}\right) = \dot{Q}_j^c$$

Virtual and actual condenser heat loads are set to be equal

$$\sum_j \dot{Q}_j^c = \sum_i \dot{Q}_i^{c,v}$$

whereas in contrast to the actual Carnot model, the electricity consumption P^{el} is larger than both the difference of actual condenser and evaporator heat loads and the difference between actual condenser heat loads and virtual evaporator heat loads.

$$P^{el} \geq \sum_j \dot{Q}_j^c - \sum_i \dot{Q}_i^e$$

$$P^{el} \geq \sum_j \dot{Q}_j^c - \sum_j \dot{Q}_j^{e,v}$$

The slack variables are constrained by logical constraints activating or deactivating stream connections.

$$s_i \leq 0$$

$$s_i \geq -(1 - z_i^e)$$
$$s_j \leq 0$$
$$s_j \geq -(1 - z_j^c)$$

Insights from the Pinch Analysis are used to restrict the domain for minimum and maximum HP temperatures, temperature lift and heat loads. Costs for the considered industrial HP's are divided into costs for the HEXs (condenser and evaporator) and the residual HP costs. The residual HP costs are heat load specific and are based on a rough estimate of 300 €/kW$_{th}$.

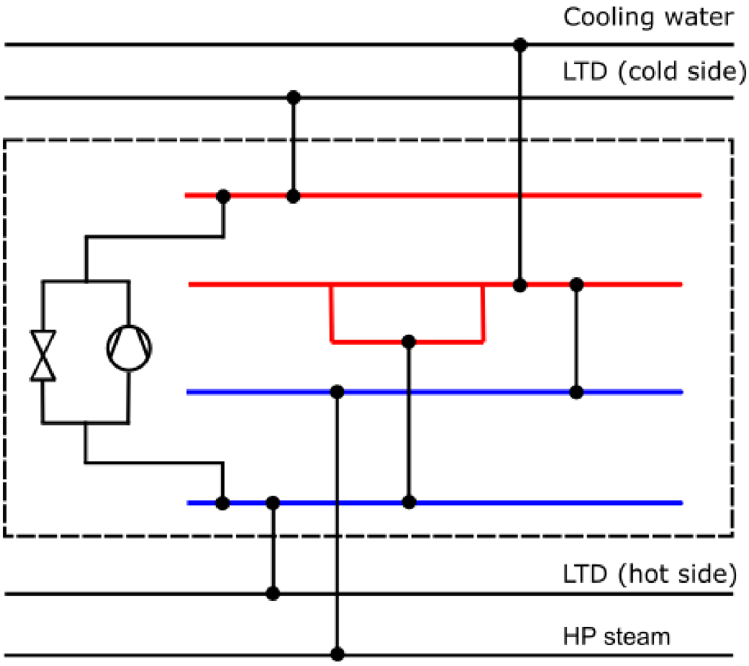

Figure 4: Heat Exchanger Network Synthesis including low temperature distribution (LTD) and a heat pump (HP)

The **LTD system** is modelled as an external utility that can be used to heat or cool process streams. The piping network capital cost is based on the diameter and the total length of the pipes. Since the length of the required piping systems for potential inter-facility connections are discrete values, depending on the facilities involved, combinatorial fixed and variable piping costs can be identified prior to optimization.

The diameter of the LTD system is a function of the amount of heat transferred. The average flow velocities were limited to avoid significant pressure losses in the pipes. For condensates, the range of allowed velocities was set to 2.5-4 m/s whereas for steam velocities are considered to be between 15-30 m/s. The capital cost of the pipe network was estimated following the methodology suggested by Smith [11] who proposed a factorial technique, where a general equation for calculating the equipment costs is corrected by introducing cost factors for materials of construction, design pressure and design temperature, as well as standard installation cost factors. The assumptions made that impact the cost function are detailed below:

- Only equipment and installation costs are considered;
- ASME B 16.9 A106 [12] Schedules 40 (standard) pipes were selected for low pressure heat distribution.

- The equation proposed by Ulrich and Vasudevan for complex networks was used that considers one fitting (elbow or tee) every 3 m and one valve every 7.5 m (the investment purchase of fittings is not considered in this study since the prices vary widely) [13].
- Heat losses were neglected but costs of purchasing and installing for appropriate insulation were included in the cost function.
- The inflation of the equipment prices has been measured by the CEPCI (Chemical Engineering Plant Cost Index) since the costs given by Ulrich and Vasudevan are on mid 2003 basis and in US$.

The cost function for the LTD piping system can be written as

$$C_{CAP,PIP} = (F_{BM} \cdot C_{p,CS} + C_{INS}) \cdot CEPCI \cdot USDtoEUR \cdot L$$

where F_{BM} is the installation factor, $C_{p,CS}$ is the piping base cost in USD/m, C_{INS} are the costs for insulation in USD/m, $CEPCI$ is the Chemical Engineering Plant Cost Index, $USDtoEUR$ is the currency conversion rate from USD to Euro and L is the distance for the piping. The installation factor F_{BM} is determined by

$$F_{BM} = 3.22 - 0.05D_{nom} - 0.001D_{nom}^2$$

with the nominal pipe diameter D_{nom} in cm. The piping base costs are calculated by

$$C_{P,CS} = 0.4199D_{nom}^2 + 1.9675D_{nom} + 25.97.$$

Cost of purchasing and installing insulation is calculated as

$$C_{INS} = 1.13 \cdot t_{opt} \cdot (D_{act} + t_{opt})$$

where D_{act} is the actual outer bare-pipe diameter in cm and t_{opt} is the insulation thickness which is obtained by

$$t_{opt} = 0.085 \cdot D_{nom}^{0.20} \cdot \Delta T^{0.65}$$

where ΔT is the temperature difference between the bulk fluid and the ambient in °C.

Case-Study

The presented methodology is used to analyze a steel production site in Europe. Figure 5 shows a rough overview about the plant distribution and the general product flows and steam supply. There are four individual facilities (A, B, C, D) within the range of 1 km which are further processing raw material from the steel shop to semi-finished products. The distances between these facilities can be seen in Table 1. Values in Table 1 include direct distance and additional 20 % in order to consider that realizable pipe length is usually greater than the direct distance. The high pressure (HPr) steam production efficiency is assumed to be 95 %. As the blast furnace and the steel shop are too far away for heat integration with the other facilities (> 5 km) and they do not use the same steam supply system, they are not considered in the present study.

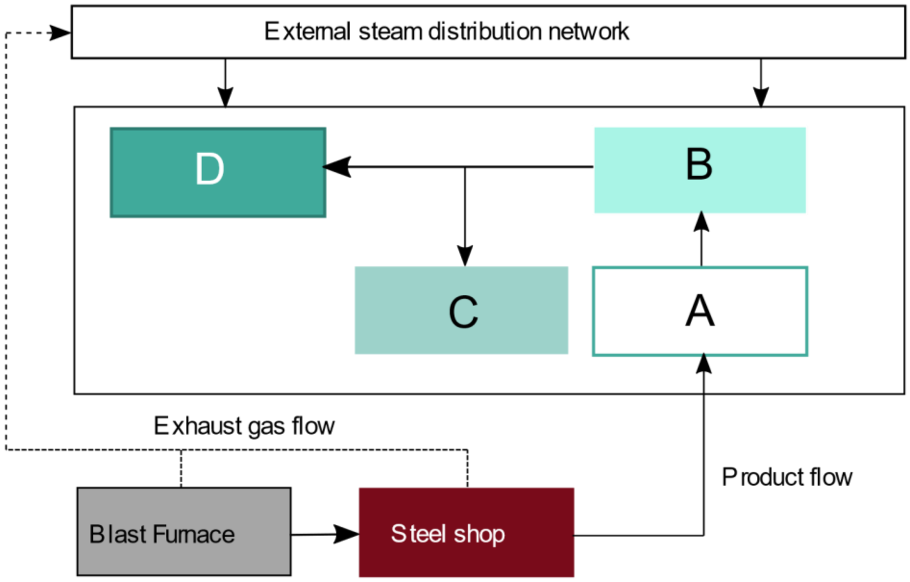

Figure 5: Part of the considered integrated steel production site

Table 1:Distances between facilities

Facility 1	Facility 2	Distance
A	B	60 m
A	C	120 m
A	D	360 m

The heating demands for the four considered facilities are covered by HPr steam provided by an external company. Currently these facilities are supplied with steam at 5 bar_a which is mainly used to preheat cleaning water, air for drying and for combustion and for heat supply in lubrication systems. The most prominent sources for excess heat are flue gases from furnaces and warm cleaning water, which yield large quantities of relatively low temperature heat. The considered changes to the existing system are depicted in Figure 6.

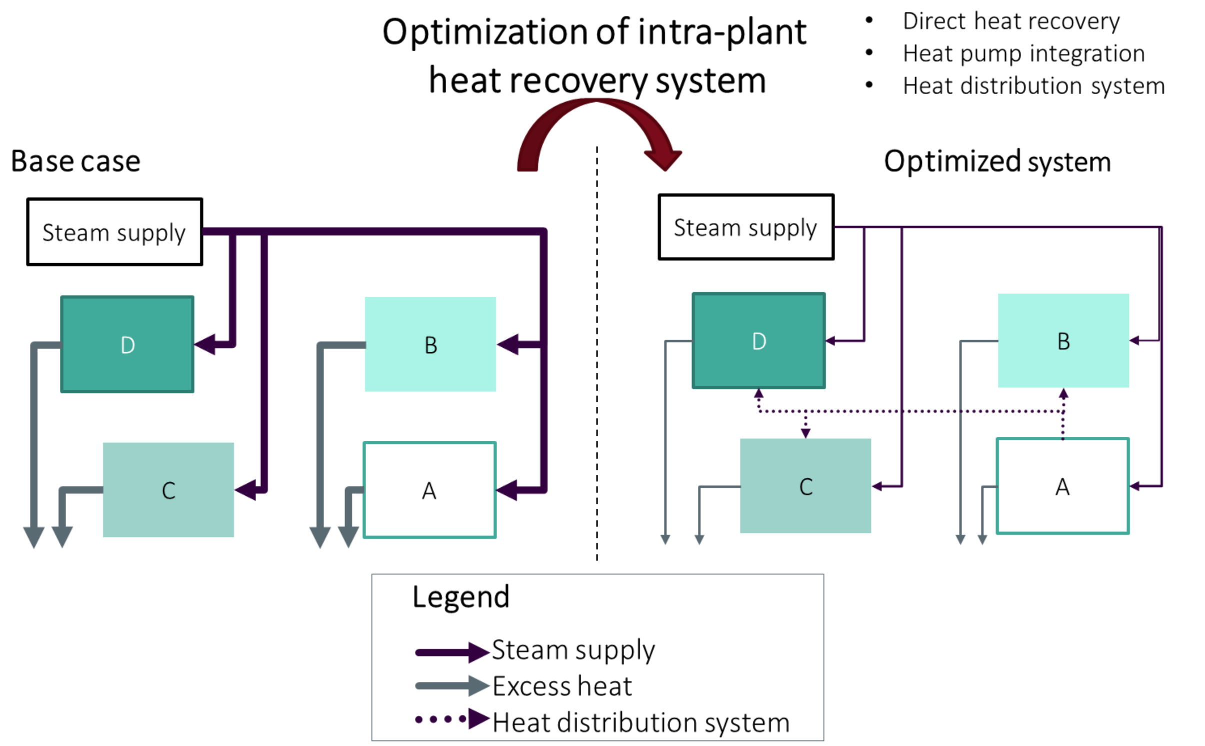

Figure 6: Schematic of the considered changes to the existing system (reduction of steam supply, heat distribution system, excess heat usage)

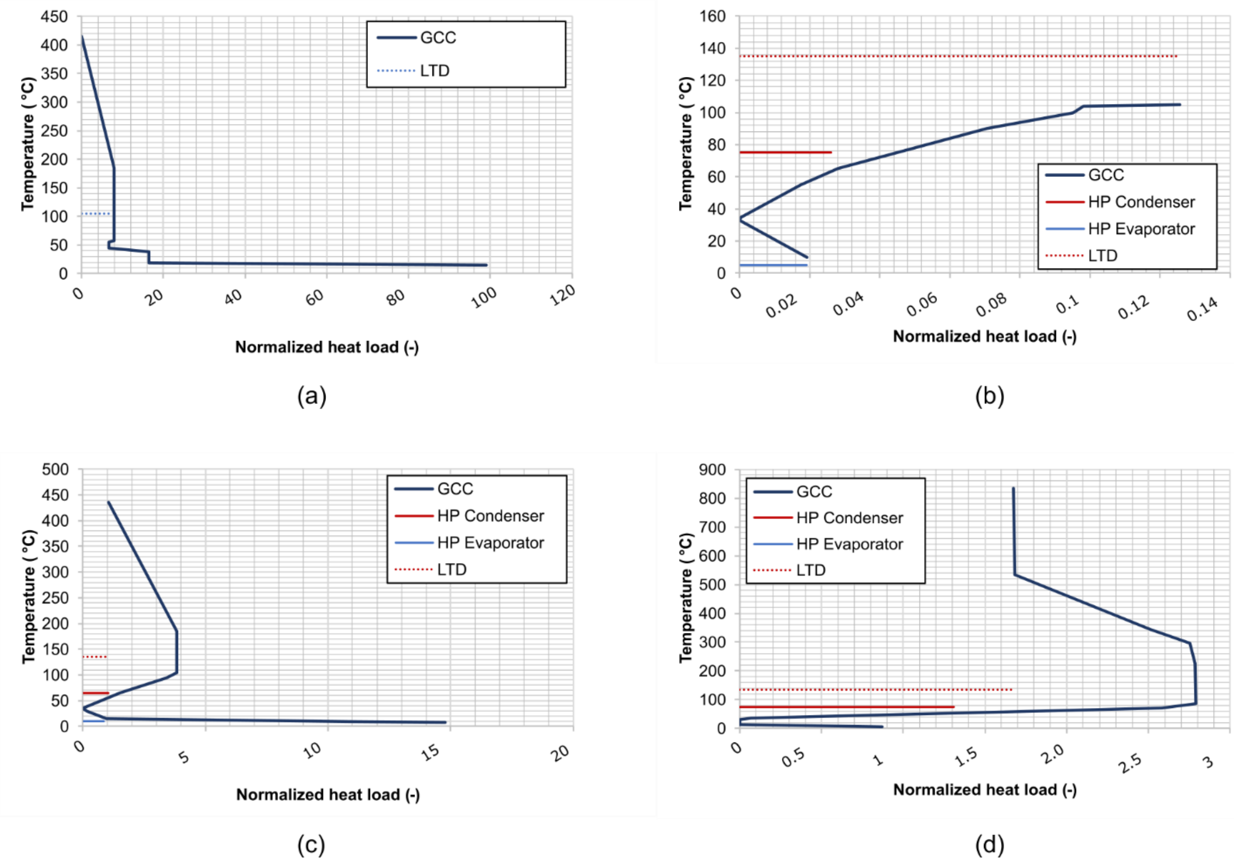

Figure 7: Grand Composite Curves (GCCs) for (a) Facility A (b) Facility B (c) Facility C and (d) Facility D including potentials of an intermediate heating cycle as well as heat pumps

The composite curves for all facilities are shown in Figure 7. These curves show that in facility A, after DHR, there is no demand for external heating, but large quantities of excess heat could be used elsewhere. Facilities B to D show potentials for HR and for HP integration at relatively low temperature levels. The pinch point for these facilities lies in the range of 30-60°C. Considering a second law efficiency η of 0.45, which lies in the usual range of 0.4-0.6 [21], to determine the COP_{real} for potential HPs, heating requirements of facilities B and D could be covered.

$$COP_{real} = \eta \cdot COP_{Carnot} = \eta \cdot \frac{T_{hot}}{T_{hot} - T_{cold}}$$

Analysis of the potentials for LTD between facilities shows that the excess heat from facility A could be sufficient to cover residual heating demands of facilities B-D. Considering ideal heat transport without losses, the analysis depicted in Figure 8 shows that within a temperature range for the heat transfer fluid of 120°C up to 284°C, demands could be fully covered. This in turn would eliminate the need for the existing gas-powered HPr steam system.

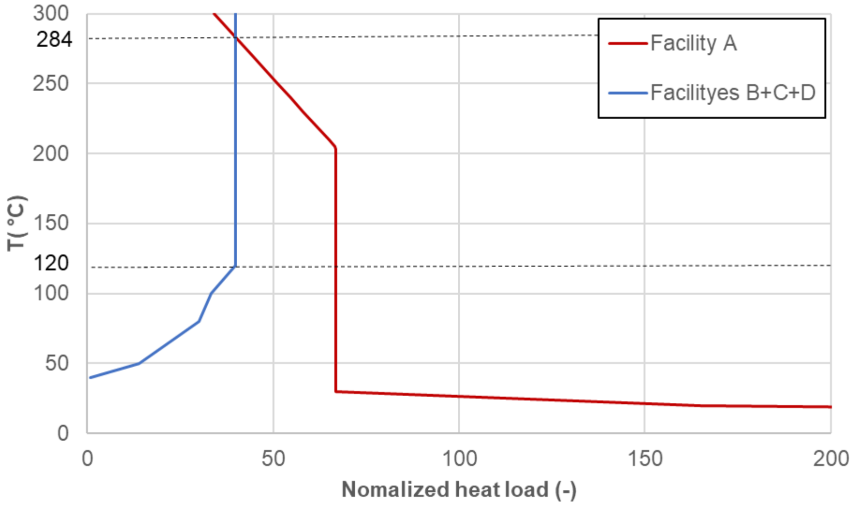

Figure 8: Potential of an intermediate cycle for low temperature heat distribution

In order to analyze the economic feasibility of the respective measures, costs for the individual components such as HEX, HPs and the LTD system were elaborated and implemented in the optimization model. For applicable LTD systems using thermal oil, pressurized water and low-pressure steam were considered at first. However, based on the temperature levels steam is advantageous and further elaborated in this work.

For the optimization model minimum approach temperatures of 5°C for evaporators and condensers of the HPs and 30°C for all other HEXs were selected. Cooling water was considered as cold utility. The optimization model was parameterized for different scenarios, which are shown in Table 2:

- A base scenario, which was derived from both historic price data on Central European energy spot markets and with costs provided by a worldwide steelmaking company
- A scenario with current (July 2021) energy and CO_2 costs for Central Europe
- A progressive future scenario with increased costs for CO_2 emissions compared to current values.

In the latter, HP investment costs are reduced to 90% due to assumed learning curves.

Table 2: Scenario definition

Scenario	Electricity price (€/MWh)	Natural gas price (€/MWh)	CO_2 price (€/t)
Base	40	25	40
EU average	90	35	53.2
Prog. CO_2 prices	90	35	128

Results

For each of the scenarios the status quo and four different technology combinations for HR measures were considered:

- No heat recovery at all (NO HR);
- only direct heat recovery (DHR);
- direct heat recovery & heat pump integration (DHR HP);
- direct heat recovery & low temperature distribution system (DHR LTD);
- direct heat recovery, heat pumps & low temperature distribution system (DHR HP LTD).

In the optimization model an annualization period of 10 years was considered for CAPEX for minimization of total annual costs. The normalized heat loads for HR and for residual HPr steam and cooling water demands are presented in Table 3. Normalized HR is also shown in Figure 9.

Table 3: Overview of results – normalized heat recovery (highest values emphasized in bold) and utility loads

Scenario	Con-figuration	DHR	LTD	HP sink	HR total	HPr Steam	Cooling water
Status quo	NO HR	-	-	-	-	9.71	23.37
Base	DHR	5.72	-	-	5.72	3.99	23.37
Base	DHR LTD	5.00	4.70	-	**9.71**	-	23.37
Base	DHR HP	5.71	-	1.25	6.96	2.74	23.36
Base	DHR HP LTD	5.00	4.70	-	**9.71**	-	23.37
EU average	DHR	5.72	-	-	5.72	3.99	23.37
EU average	DHR LTD	5.00	4.70	-	**9.71**	-	23.37
EU average	DHR HP	5.72	-	0.49	6.21	3.50	23.36
EU average	DHR HP LTD	5.00	4.70	-	**9.71**	-	23.37
Prog. CO_2 price	DHR	5.72	-	-	5.72	3.99	23.37
Prog. CO_2 price	DHR LTD	5.00	4.70	-	**9.71**	-	23.37
Prog. CO_2 price	DHR HP	5.72	-	1.26	6.98	2.72	23.36
Prog. CO_2 price	DHR HP LTD	5.00	4.70	-	**9.71**	-	23.37

Results show that introduction of an LTD system is favorable compared to only DHR and HPs. In all cases where LTD was available for the solver, it was selected to cover all residual heating requirements after DHR leaving costs for cooling water (0.01 €/kWh) as the only remaining OPEX. Thus, in terms of costs, all scenarios yield the same results for configurations including LTD. However, depending on the scenario, cost savings vary significantly as costs for HPr steam range from 40 to 90 €/MWh and CO_2 prices range from 40 €/t to 128 €/t.

The energy price differences between the individual scenarios does not impact the costs for systems with LTD since there are no residual energy costs for heating. Depending on the energy prices, HP normalized nominal powers range from 0.49 to 1.26. Especially the EU average scenario with relatively high electricity costs reduces HP utilization.

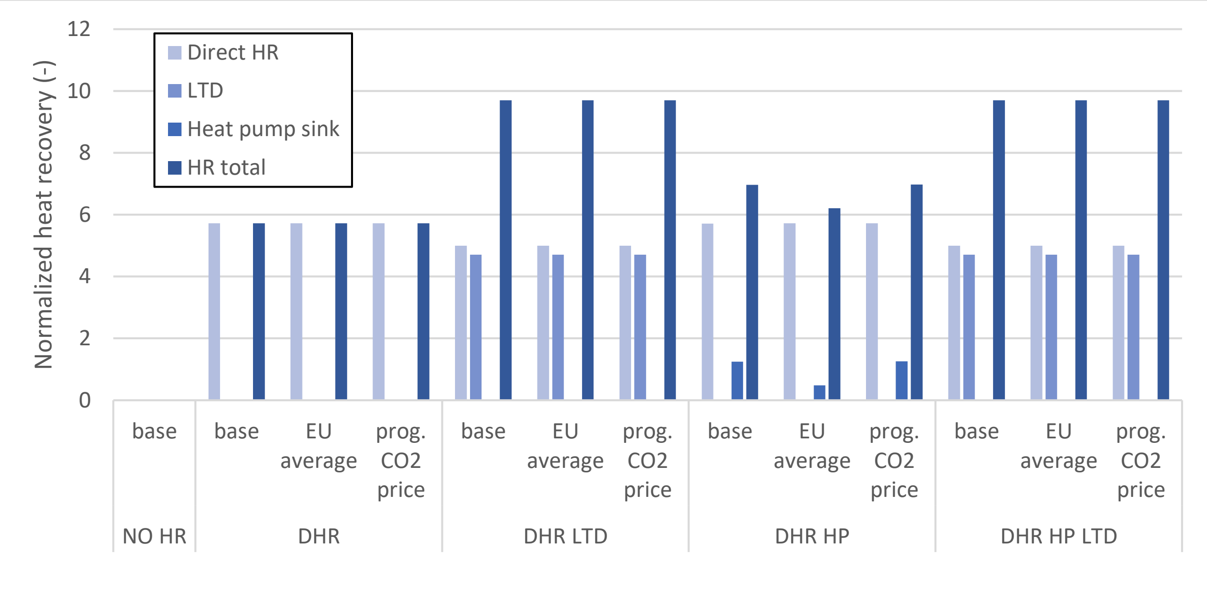

Figure 9: Normalized heat recovery for all scenarios and combinations of heat recovery measures

Energy flows for the individual configurations are presented in Figure 10. Figure 10 (a) shows the status quo without any additional HR measures. All facilities require HPr steam. Figure 10 (b) introduces DHR in all facilities represented by loops. In Figure 10 (c), HPs are integrated in facilities C and D eliminating HPr steam demands for facility C. In facility B no HP is considered, even though pinch analysis would suggest potentials at relatively low temperatures. Figure 10 (d) shows heat flows including the LTD system. The resulting heat exchanger network for all cases considering LTD is shown in Figure 11. The LTD is extensively used and heats all cold streams in facilities B to D. HEX for DHR are placed in facilities A, B and C. Hot streams without any HEX do not have a cooling requirement but are rather potential heat sources that in this case have not been used.

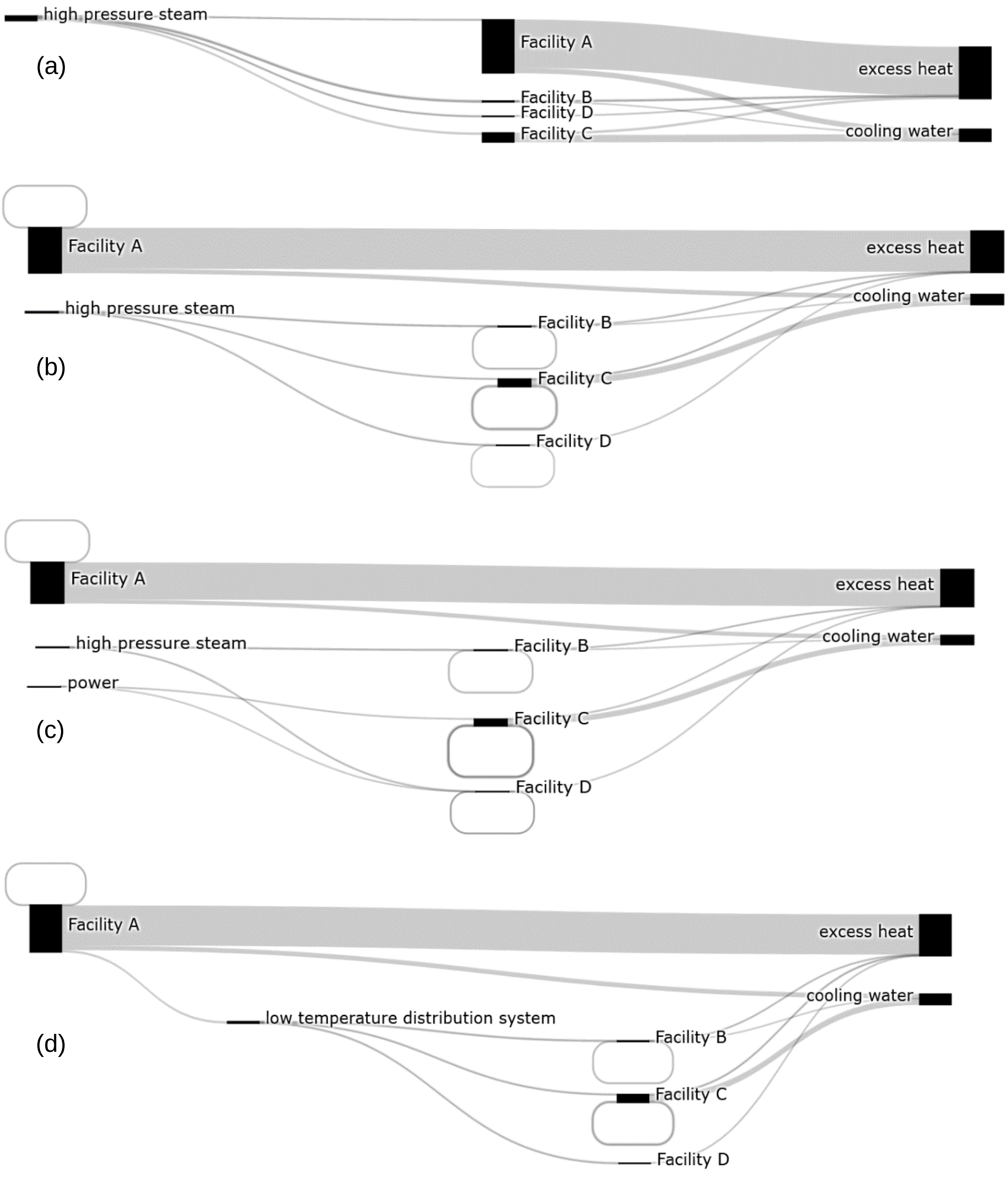

Figure 10: Sankey diagrams for the base case scenario (a) without HR, (b) with DHR, (c) with DHR and HP, (d) with DHR and LTD

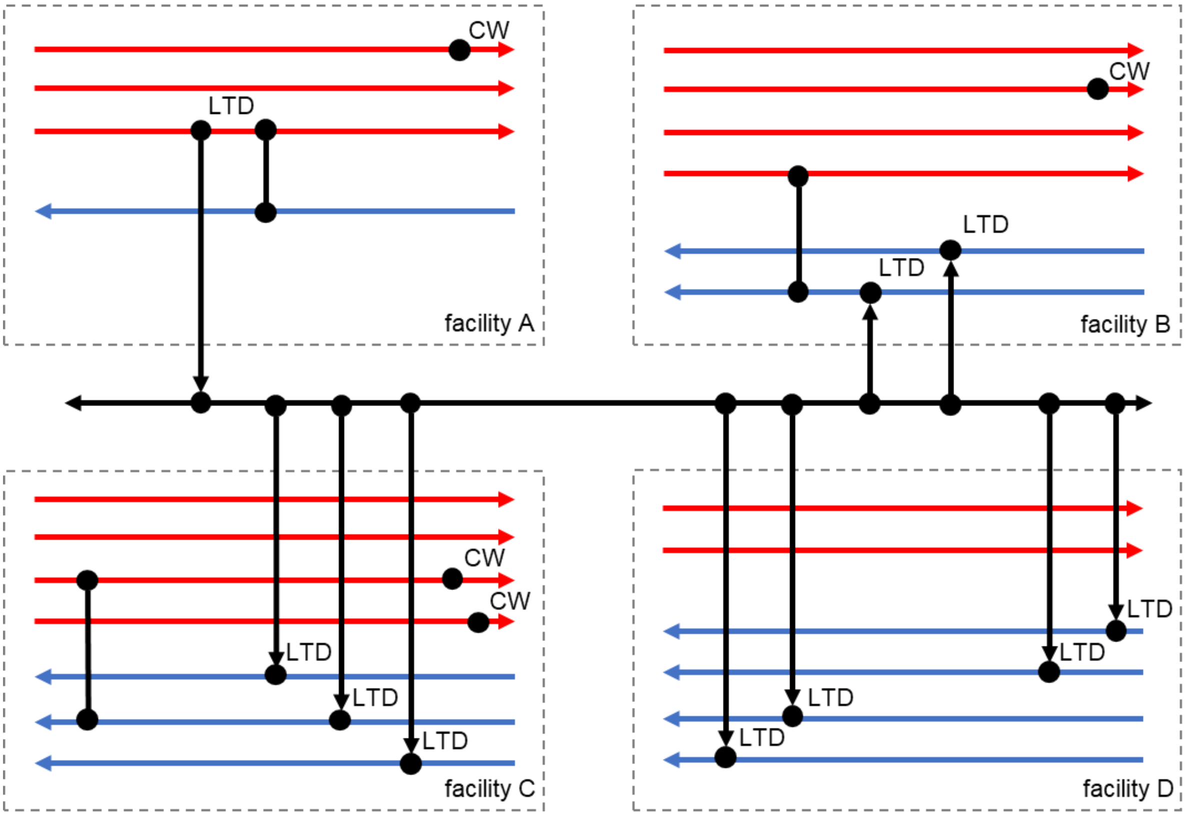

Figure 11: Heat exchanger networks including LTD (CW means cooling water)

Figure 12 summarizes OPEX and CAPEX for all scenarios and configurations. It shows that for all measures, drastic reductions in OPEX can be obtained. As mentioned before, integration of an LTD reduces OPEX to costs for cooling water, but CAPEX for the entire HR system account for approximately 7 M€. In these cases, the original HPr steam distribution system is not used any longer. Reuse of the already existing HPr steam distribution system for the LTD was not considered in this work but could potentially reduce CAPEX for LTD systems. In the cost-optimized system with LTD DHR is reduced compared to pinch analysis targets leading to increased usage of the LTD (4.7 vs. 3.9 from the pinch analysis target).

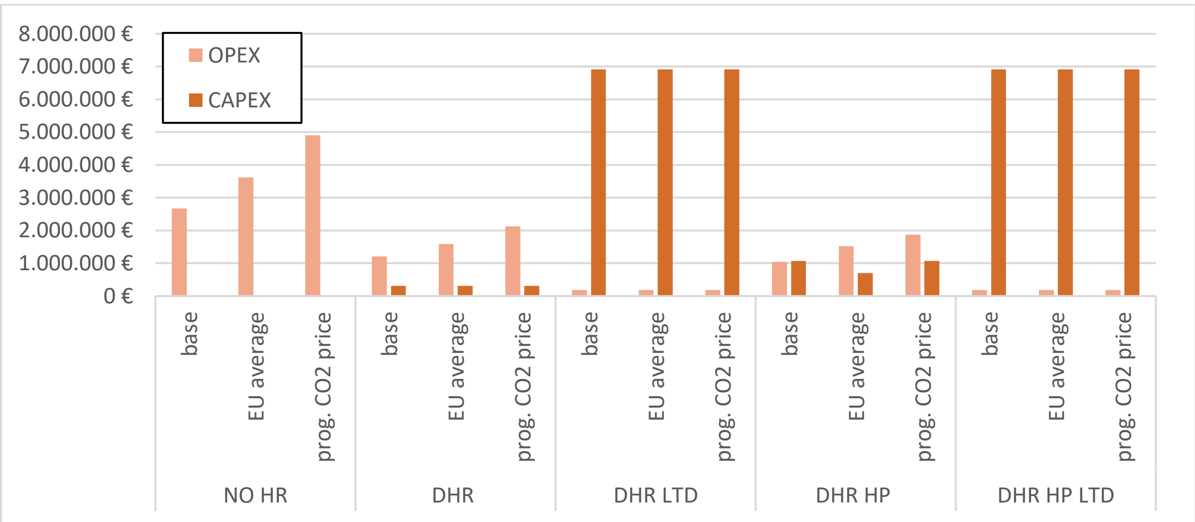

Figure 12: CAPEX and OPEX for all scenarios and combinations of heat recovery measures

In order to facilitate evaluation of the costs for the different configurations, the net present value (NPV) was calculated for 10 years starting from the implementation of the recovery measures and is shown in Figure 13.

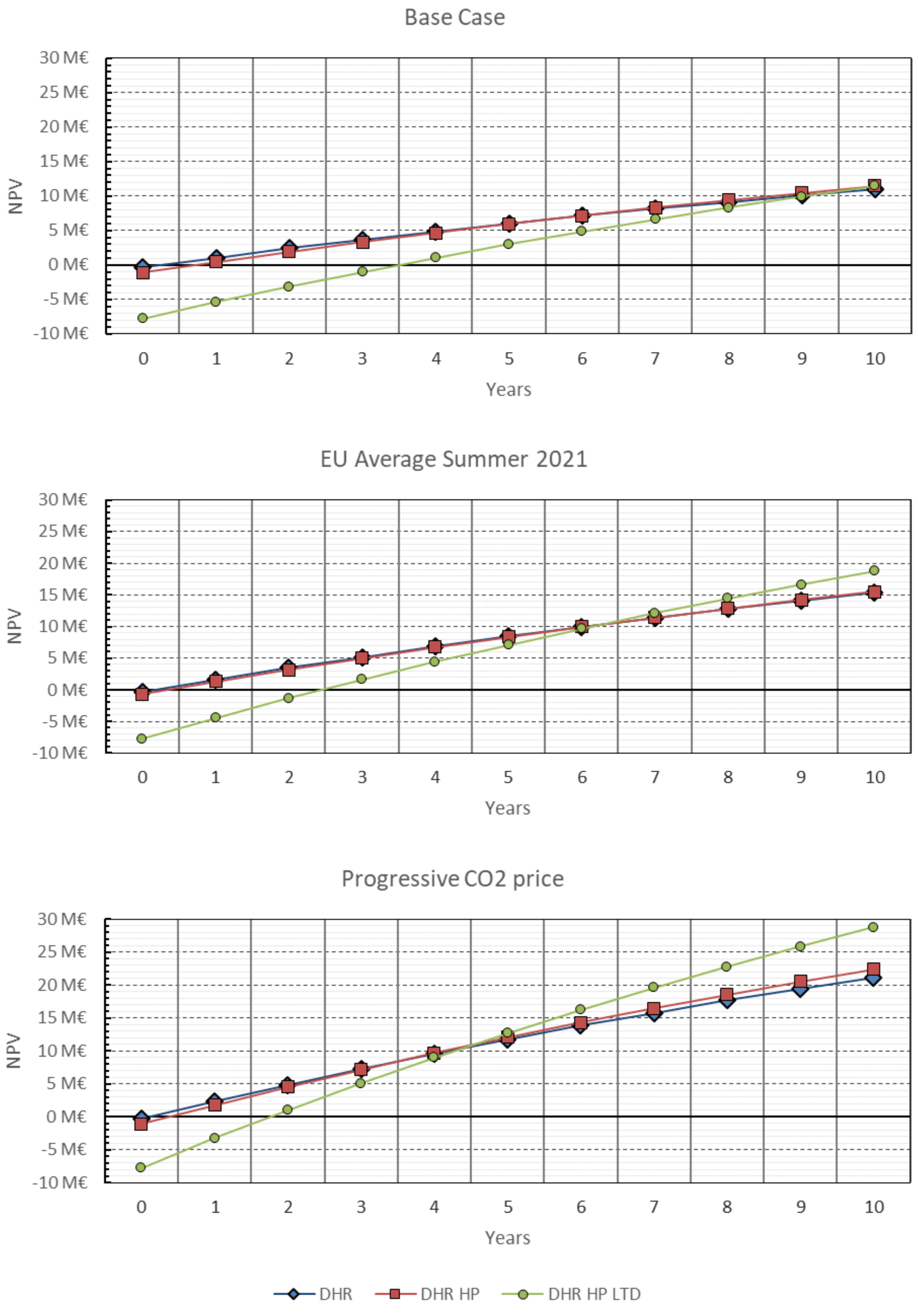

Figure 13: Net present value for all combinations of heat recovery measures for all scenarios with an assumed discount rate of 5%

The figure clearly shows that introduction of LTD is the most expensive in terms of investment costs and has the longest payback period but after approximately 5-10 years (depending on the scenario and according prices), the NPV exceeds DHR alone and HP integration. After 10 years, overall savings from LTD integration are between 10 and 30 M€ whereas integration of DHR measures alone and DHR combined with HPs yield approximately 10 to 20 M€ in NPV after 10 years.

Conclusion & Outlook

A steel production site with four individual facilities was analyzed using Pinch Analysis and mathematical programming regarding cost efficient heat recovery by means of direct heat recovery, heat pumps and inter-facility heat transfer. For economic evaluation, three different scenarios including a base case, the status quo of the energy market in Central Europe and a futured scenario were considered. The results show that introduction of an LTD system might be the most promising solution since using excess heat from flue gas in one facility could potentially supply the other facilities with enough heat so that the existing HPr steam system would not be necessary any longer. Within the considered timeframe of 10 years the LTD system is the most favorable. Especially in the future case scenario the integration of the DHR HP LTD system yields the highest potential as the NVP shows overall savings of almost 30 M€ after 10 years. Moreover, analysis showed that DHR alone bears a potential of at least approximately 10 M€ referring to the base case. However, NPV analysis also shows that depending on the scenario for energy costs, potential revenues from energy savings with the LTD system only exceed DHR and HP integration only after 5 to 10 years.

It has to be noticed that the costs considered in this work do not include integration, which adds a high degree of uncertain additional costs which could jeopardize economic viability. Furthermore, analysis is based on a so-called rough pinch-analysis which yields some uncertainties due to inaccessible stream data. Therefore, to confirm the results from this study, more detailed analyses including site measurements are needed.

Acknowledgement

This work was conducted within the BAMBOO project which has received funding from the European Union’s Horizon 2020 research and Innovation programme under grant agreement N°820771.

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