Sector-Coupled Decarbonisation of High-Temperature Industrial Heat in Kazakhstan: A Thermodynamic and Techno-Economic Model for Steel, Cement, and Chemical Manufacturing

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Abstract: Industrial heat above moderate temperatures is hard to decarbonise due to constraints of energy carriers with regard to temperature quality, operational continuity, process integration and economic costs. We build an hourly sector-integrated optimization model for an industrial cluster in Kazakhstan that comprises the production of steel, cement, ammonia, and equivalent chemicals in terms of energy requirement. Our analysis accounts for low-, medium- and high-temperature heat requirements and integrates the procurement of renewable electricity, direct electricity heating, electrolysis, hydrogen storage, hydrogen combustion, heat recovery, and thermal storage. We compare four configurations of energy systems: one based on fossil fuels, one relying on direct electrification only, a mixed strategy involving hydrogen and electricity, and finally a fully sector-integrated configuration featuring cascading of waste-heat and multi-level thermal storage. The fully sector-integrated system leads to a drop in annual CO_2 emissions from 5.94 to 0.19 Mt/year (96.8% reduction), and to a 16.5% decline in costs compared to the fossil baseline, and 8.7% compared to the direct electrification scenario. Hydrogen is reserved for reductant, feedstock and high-temperature heat, with recovered heat covering low-temperature heat service and electricity supplying medium-temperature heat service in the optimal solution. Thermal storage helps increase the effective usage of waste heat from 39% to 71%, and decreases the hydrogen consumption for combustion by 18.4% in comparison to the hybrid case. The results show that Kazakhstan's industrial-heat transition is most credible when designed as a cluster-level thermodynamic integration problem rather than as isolated plant-level fuel substitution.

Keywords: industrial decarbonisation; high-temperature heat; sector coupling; hydrogen; thermal energy storage; waste-heat recovery; Kazakhstan; techno-economic optimisation

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1. Introduction

The need to find solutions to decarbonise industrial heat has emerged as a key issue in the transition towards greener industries. The problem is not merely linked to the amount of energy needed by heavy industry but to the quality of the heat, the chemistry of the fuels used in production flows, the longevity of the kilns and furnaces, and the tight operation continuity of continuous processes. Processes in industries like steel, cement, ammonia, and methanol production are complex and involve heat exchange, chemical reactions, material transformations, and production scheduling. They cannot be decarbonised solely by substituting a traditional fuel with an alternative one. A recently published assessment of industrial decarbonisation pathways stresses the importance of efficiency, electrification, hydrogen, carbon management, material efficiency, and fuel/feedstock change in order to transition away from fossil fuels and achieve emissions reductions [1–3].

Kazakhstan poses unique challenges to this issue due to its energy profile based on cheap coal, fossil resources, energy-intensive industry, and strong seasonality of energy demand. While the country aims to decarbonise, these characteristics make industrial heat decarbonisation a technological problem as much as a climate one. A transition to low-carbon heat must be designed in such a way that steel, cement, and chemical outputs are guaranteed, while the heat supply system is transformed. Thus, the main question is not whether low-carbon heat technologies are available in isolation but whether a coherent technological design exists for a whole industrial cluster to be powered by them.

The classification of heat by temperature class plays a central role in this paper. Low-temperature needs can be covered by heat recovery technologies, electric boilers, heat pumps, and utilities integration. Intermediate temperatures may also be met with direct electrification, such as through resistance heating, induction heating, electrode boilers, or similar electrotechnologies. High-temperatures duties, defined here as heat above approximately 800°C, pose additional challenges. The combination of flame temperature, heat flux density, residence times, atmosphere control, refractory materials behaviour, and chemical transformation is what makes this temperature range particularly challenging. Direct electrification is thermodynamically appealing and has great emissions-reduction potential when coupled with low-carbon electricity but cannot be applied to all heat processes [4,5]. Heat recovery, internal recycling, and hydrogen play crucial roles in covering high-temperature duties.

Hydrogen is treated as an integrated resource here instead of a fuel substitute. The use of hydrogen in an industrial cluster includes both as a reducing agent and an energy source. In a steel production system, it can be employed as a reducing agent during hydrogen direct reduction, followed by electric steelmaking. In ammonia and methanol production, hydrogen is a key raw material, whereas in cement and process heating, hydrogen may serve as a combustion fuel. The importance of hydrogen and how it is used in a given industrial process depend on electrolyser utilisation, renewable electricity purchase timing, storage times, compressors' efficiency, and hydrogen demand pooling across processes [6–8]. This time aspect plays a crucial role in the case of Kazakhstan due to the irregularity of renewable electricity generation.

The recovery and reuse of waste heat and thermal energy storage constitute a third component of integrated industrial heat. Heavy industry plants generate exhausts, clinker coolers, hot solid flows, syntheses circuits, condensers, and cooling systems that can release considerable amounts of heat, depending on the temperature level and heat-recovery possibility. Although the theoretical potential is very high, actual opportunities are constrained by heat recovery matching temperature, simultaneous availability of source and sink for the heat, and efficient storage and transportation [9–11]. Thus, an integrated industrial cluster can convert stranded heat to valuable heat by combining heat recovery, storage capacity, and heat demands according to temperatures.

This paper addresses the question *how a sector-coupled design incorporating renewable electricity, flexible electrolysis, hydrogen storage, heat recovery, and thermal storage can change the cost, residual emissions, heat supply distribution, and system flexibility of high-temperature heat decarbonisation in a Kazakh steel–cement–chemical cluster?* An hourly optimisation framework is employed in this study to explore the differences between four types of systems: a reference-case based on fossil fuels, a direct electrification scenario, a hydrogen-electricity hybrid, and the sector-coupling scenario. The contributions of this study are threefold. First, temperature-specific heat demand is considered. Second, hydrogen and waste heat are represented as cluster-wide resources. Finally, the paper explains how integration lowers both emissions and costs by providing temporal flexibility to electrolysers, safeguarding process continuity through hydrogen storage, and enhancing the recoverability of waste heat through thermal energy storage.

2. Literature background and modelling position

The growing consensus among studies about heavy industries is that steel, cement, and chemicals will require specific strategies for decarbonisation. As shown by the review by Bataille et al. and Rissman et al., emissions reductions in heavy industries will have to follow a portfolio of mitigation options since basic materials' production involves high-temperature energy requirements, process emissions, capital lock-in, and product quality considerations. The same conclusions can be found in the sixth report of the Intergovernmental Panel on Climate Change on the role of industries in mitigating climate change. The IPCC report identifies high-temperature heat and process-emission intensive materials as particularly challenging due to capital intensity and long-lived equipment [1].

In the case of steel production, it becomes obvious why the process and electricity consumption are tightly intertwined. In particular, Vogl et al. have shown that fossil-free steel production through hydrogen reduction combined with electric steelmaking can be made technically feasible if supported by renewable electricity but that the route becomes highly sensitive to costs. further confirmed this finding by demonstrating that power-to-steel routes required integrated planning of hydrogen production and utilisation through steelmaking [12]. Therefore, it justifies considering steel as both an electricity and hydrogen consumer.

Cement poses another challenge by making process emissions a relevant factor to consider. While kiln emissions related to fossil fuel use may be lowered using electrification or hydrogen heat sources, process emissions caused by calcination cannot be avoided without changes to clinker chemistry or carbon capture technologies. Earlier studies had already quantified cement's carbon burden, whereas more recent assessments highlighted cement's importance for industrial emissions through calcination processes [13–15]. Cement production is taken into account in this paper, not as a sector that can be completely decarbonised via substitution, but as a producer of a heat demand and waste heat potential.

Finally, the chemical sector adds hydrogen utilisation to the equation. In the green-ammonia sector, several studies have shown that the performance of green ammonia and renewable methanol production relies heavily on electricity prices, electrolysers usage, hydrogen storage, carbon source selection, and process integration [16–18]. Therefore, industrial chemical production contributes to the need of having hydrogen infrastructure, as it provides relatively stable demand for the hydrogen produced.

Electrification plays an essential role in emissions reduction due to its cost-effectiveness and large emissions-reduction potential. Madeddu et al. have quantified the opportunity of using power-to-heat to reduce emissions in Europe, whereas recent assessments of industrial electrification identified electric boilers, resistance heating, induction heating, plasma heating, and electric arc furnaces as promising electrotechnologies [4,5]. What matters here is not that the technologies do not exist but rather the lack of flexibility caused by their inability to cope with volatile hourly prices.

Hydrogen is another relevant topic, with studies focusing on various hydrogen-related issues. Buttler and Spliethoff reviewed the role of electrolysis in energy storage, grid balancing, and energy system integration, stressing the importance of part-loading capacity [7]. In addition, Staffell et al. put hydrogen in the perspective of a larger energy system that would involve not only power, but also heat, transport, and industry applications [8]. Finally, Glenk and Reichelstein showed that the performance of renewable hydrogen relies heavily on electricity prices and operating conditions [19]. In terms of models, this means that the evaluation of electrolysis potential should not only cover annual hydrogen output but also allow for time-shifting capabilities.

Finally, waste heat recovery and industrial symbiosis provide a fourth field of literature for the purpose of the current study. On the one hand, Forman et al. provided estimates of global potential of waste heat recovery, whereas Jouhara et al. discussed the state-of-the-art in recovering technologies and constraints. More specifically, the importance of thermal energy storage was highlighted by Miró et al. and Gil et al. as increasing the usefulness of industrial waste heat by relaxing simultaneity constraints between the heat source and sinks [20]. On the other hand, industrial symbiosis is also a relevant concept as it enables heat and utilities sharing and exchange [21–23].

Thus, the existing modelling gap lies in the combination of these strands, as they usually address either one of the sectors alone, a particular heat source or technology, an annual perspective, and/or a standalone hydrogen solution. By contrast, this study considers four factors in one modelling exercise: high-temperature heat demand classified by temperature, integrated electricity and hydrogen infrastructure, waste heat cascading with thermal energy storage, and hourly renewable electricity purchase. This position gives the paper a clear analytical role: it tests whether integrated cluster design changes the cost and emissions ranking of industrial heat-transition options in Kazakhstan.

3. Cluster representation and mathematical formulation

3.1. System boundary and heat-service configuration

The model covers an industrial cluster producing four products per year: steel (2.0 Mt/year), cement (4.5 Mt/year), ammonia (0.35 Mt/year), and methanol equivalent chemicals (0.25 Mt/year). Steel production consists of hydrogen-based direct reduction, and electric arc furnace operations. Cement production includes preheating, calcination, and clinker burning operations. Ammonia and methanol synthesis uses electrolysis-produced hydrogen. Cluster electricity consumption is covered by hourly profiles linked to renewables and residual power and, if possible according to the transition scenario, the residual grid, and fossil fuels.

Figure 1 shows the boundary around the cluster's energy and materials flows. It is intended to define the utility network through which the electricity, hydrogen, recovered heat, and thermal energy storage are exchanged between the production units.

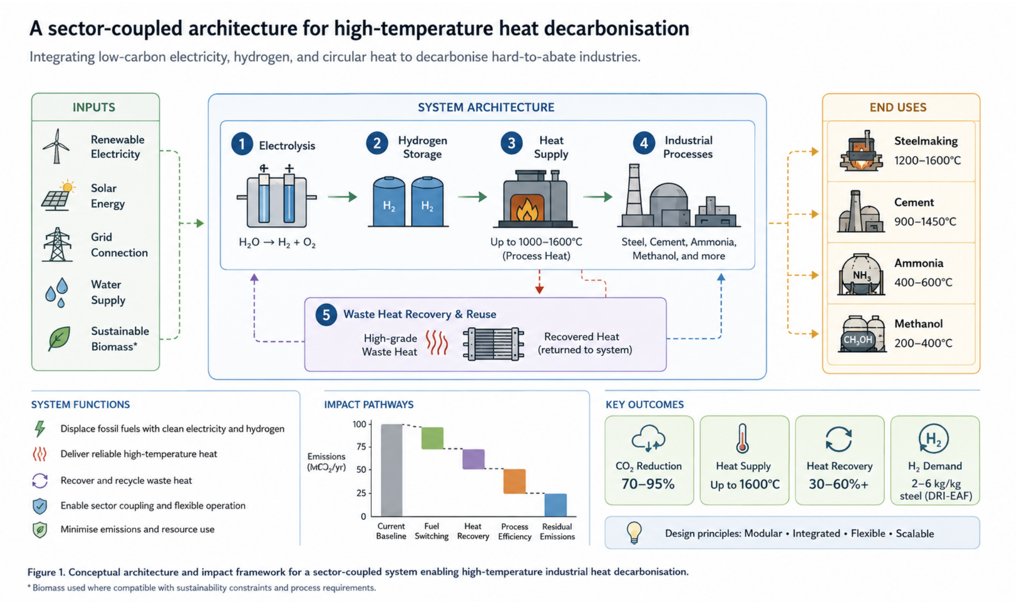
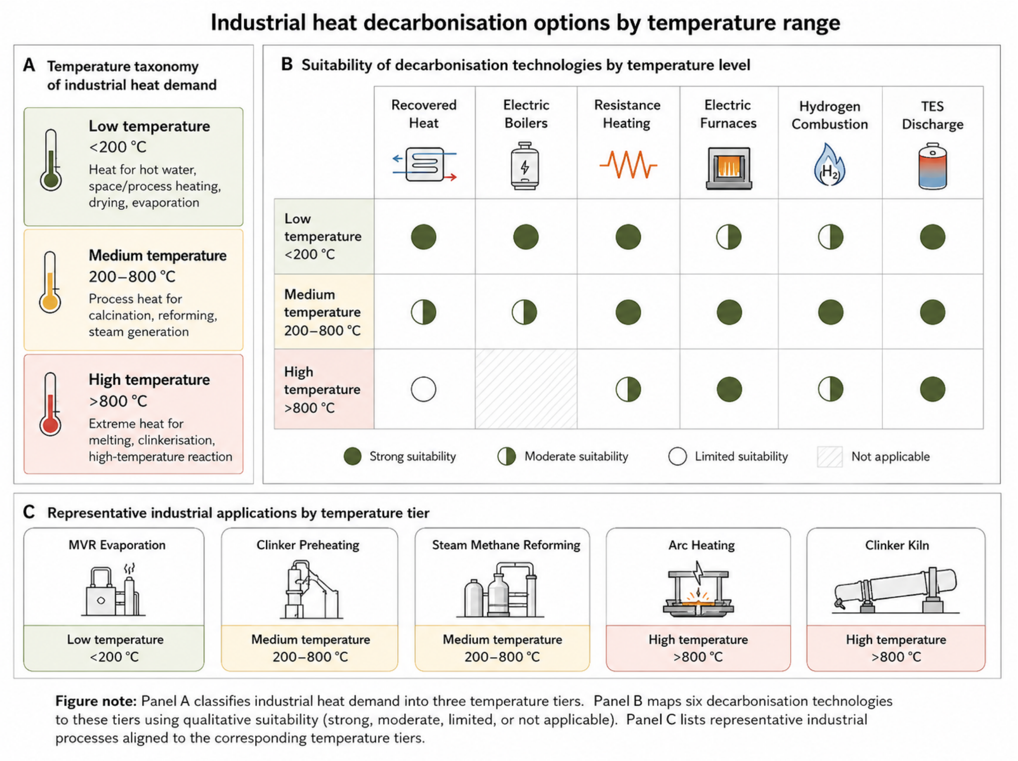


Figure 1. Coupled industrial utility system boundary.

As Figure 1 shows, the system's components cannot be assumed to correspond one-to-one to individual processes or plants. Electrolysis, hydrogen storage, burners, electric heaters, and thermal energy stores are facilities that serve multiple processes. Consequently, decisions on capacity for one process affect costs and emissions incurred by other processes. For instance, excess electrolysis capacity may lower hydrogen-combustion costs in cement production, help with feedstock provision in chemical production, and, indirectly, limit peak electricity consumption in steel production.

Industrial heat duties are divided into three types: low-temperature ($< 200°\text{C}$) heat, medium-temperature heat ($200° - 800°\text{C}$), and high-temperature heat ($> 800°\text{C}$). The temperature class is a modelling constraint rather than an aid to visualization. The low-temperature heat class excludes substitution with recovered heat and hydrogen to avoid counting low-grade recovered heat as an alternative source of heat to a kiln, and avoiding arbitrary assignment of hydrogen as the source of heat to an industrial duty where direct electricity use or recovered heat is cheaper.

Figure 2 shows the temperature ladder that is assumed in the optimization problem. All low-temperature duties are supplied using recovered heat and electric utility heat, medium-temperature duties by resistance heating, recovered heat upgraded to medium temperature, hydrogen combustion, and thermal energy store discharge, and all high-temperature duties by electric furnace or arc processes, hydrogen combustion, or thermal recovery. Eligibility criteria are required to account for the fact that the engineering feasibility of meeting an industrial heat demand depends on the temperature of that duty.



	Recovered Heat	Electric Boilers	Resistance Heating	Electric Furnaces	Hydrogen Combustion	TES Discharge
Low temperature <200 °C	●	●	●	◑	◑	●
Medium temperature 200–800 °C	◑	◑	●	●	●	●
High temperature >800 °C	○	▨	◑	●	◑	●

● Strong suitability ◑ Moderate suitability ○ Limited suitability ▨ Not applicable

Figure note: Panel A classifies industrial heat demand into three temperature tiers. Panel B maps six decarbonisation technologies to these tiers using qualitative suitability (strong, moderate, limited, or not applicable). Panel C lists representative industrial processes aligned to the corresponding temperature tiers.

Figure 2. Heat service temperatures and eligible heat sources.

3.2. *Objective function and annualised capacity cost*

The optimisation problem is set up as an hour-based linear cost-minimisation programme with $t \in T$, $k \in K$, $m \in \{L, M, H\}$, and $p \in P$. The objective function is thus

$$\min Z = C^{\mathrm{cap}} + C^{\mathrm{fix}} + C^{\mathrm{var}} + C^{\mathrm{el}} + C^{\mathrm{fuel}} + C^{\mathrm{CO_2}} - R^{\mathrm{co}}, \tag{1}$$

where Z is the total annualised cost, C^{cap} is the annualised cost of capital investment, C^{fix} and C^{var} are the respective fixed and variable cost terms, C^{el} is the cost of purchased electricity, C^{fuel} is residual external fuel cost, $C^{\mathrm{CO_2}}$ is the cost allocated to residual CO_2 emissions, and R^{co} is co-product revenue.

Eq. (1) supplies economic meaning to the formulation. The optimal solution will not be the least-costly individual heater component, but the most economically efficient blend of capital investment and operational effort capable of satisfying industrial demand at the specified heat quality and emissions standard. The co-product revenue term is included to facilitate economic assessment of oxygen or other by-products in a future phase of research, but in this baseline model it equals zero so that any economic benefits from integration are not predicated on auxiliary income.

Capital cost is expressed as

$$C^{\mathrm{cap}} = \sum_{k \in K} \alpha_k I_k x_k, \tag{2}$$

where

$$\alpha_k = \frac{r(1+r)^{n_k}}{(1+r)^{n_k}-1}. \tag{3}$$

In this notation, x_k is the capacity of the heat supply technology, I_k is the corresponding specific investment cost, r is the discount rate, n_k is the technology lifetime, and α_k is the capital recovery factor.

Eqs. (2) and (3) take into account the different economic lives of various technologies in their calculation of annual costs. This is vital to the current situation since the electrolysis equipment, heat reservoirs, furnaces, heat exchange systems, and holding tanks will all have different lifespans. Without annualisation, a capital-intensive heat recovery system would unjustly suffer against those with lesser capital investment but different economic lifespans.

3.3. Hourly electricity, hydrogen, and heat balances

Hourly electricity balance is imposed as

$$P_t^{\text{grid}} + P_t^{\text{ren}} + P_t^{\text{dis,b}} = P_t^{\text{ely}} + P_t^{\text{eh}} + P_t^{\text{proc}} + P_t^{\text{ch,b}} + P_t^{\text{aux}} + P_t^{\text{curt}}, \tag{4}$$

where grid power, renewable power linked to supply, and power from batteries can meet demands for electrolysis, heating, process power, battery charging, auxiliary power, and curtailment.

Eq. (4) represents how variability in hourly electricity prices affects the problem of industrial heat supply. Electrolyzers and heaters compete for inexpensive electricity, while curtailment happens due to excess renewable power linked to supply that cannot find productive use. Hydrogen and heat storage help address such curtailment by turning the surplus electricity into inventory.

Hydrogen balance is defined as

$$H_t^{\text{ely}} + H_t^{\text{dis,h}} = H_t^{\text{DRI}} + H_t^{\text{burn}} + H_t^{\text{chem}} + H_t^{\text{ch,h}}, \tag{5}$$

where electrolytic hydrogen and hydrogen produced by discharging storage units satisfy direct reduction, hydrogen combustion, chemical synthesis, and storage charging.

Eq. (5) reflects differences between three industrial roles hydrogen plays. In steelmaking industry, hydrogen is a key substance used to reduce ore, in chemistry industries, hydrogen is a raw material, and in high temperature processes, hydrogen becomes a fuel. Such distinctions are important as any effort to minimize hydrogen consumption in one industry does not affect electrolysis capacity if other services are using the same hydrogen.

Useful heat balance equations have different temperatures:

$$Q_{t,m}^{\text{el}} + Q_{t,m}^{\text{H}_2} + Q_{t,m}^{\text{rec}} + Q_{t,m}^{\text{dis,tes}} = D_{t,m}^{\text{heat}} + Q_{t,m}^{\text{ch,tes}}. \tag{6}$$

Eq. (6) is the thermodynamic heart of the model. It guarantees that eligible heat sources must be provided to each temperature class rather than obscuring an infeasible substitution by allowing the sum of the yearly heat energy. The term at the right-hand side of the equation also emphasizes that thermal storage cannot serve as a source of free heat; instead, it competes with the recovered or produced energy during charge periods and becomes a source of energy once stored energy is deducted.

Technology eligibility is ensured by the binary parameter $\chi_{k,m}$:

$$0 \le Q_{t,k,m} \le \chi_{k,m}\,\overline{Q}_{k,m} \qquad \forall t,k,m. \tag{7}$$

Eq. (7) serves to protect physical realism. For $\chi_{k,m} = 0$, no technology k could be assigned to temperature class m regardless of the reduction of cost associated with such action. This constraint prevents the misallocation of low-temperature waste heat for high-temperature kiln duty and ensures that no non-suitable technologies enter the system just because they offer a numerical solution.

Thermal storage is defined by

$$SOC_t^{\text{tes}} = SOC_{t-1}^{\text{tes}}(1-\lambda^{\text{tes}}) + \eta^{\text{ch}} Q_t^{\text{ch,tes}} - \frac{Q_t^{\text{dis,tes}}}{\eta^{\text{dis}}}, \tag{8}$$

and

$$0 \leq SOC_t^{\text{tes}} \leq \overline{SOC}^{\text{tes}}. \tag{9}$$

The above equations define thermal storage as an inventory-based resource. State of charge establishes the continuity in time of the resource, while the loss parameter accounts for the losses due to heat leakage. Consequently, the thermal storage acts as a resource with temporal flexibility, yet the feasibility of its use depends on the availability of storage capacity and charging opportunities.

Hydrogen storage behaves similarly:

$$SOC_t^{\text{h}} = SOC_{t-1}^{\text{h}} + \eta^{\text{h,ch}} H_t^{\text{ch,h}} - \frac{H_t^{\text{dis,h}}}{\eta^{\text{h,dis}}}, \tag{10}$$

$$0 \leq SOC_t^{\text{h}} \leq \overline{SOC}^{\text{h}}. \tag{11}$$

Eqs. (10) and (11) give hydrogen its role as a long-term energy carrier. Unlike electricity storage, which has been found economically inefficient for longer periods in this study, gaseous hydrogen storage allows for the preservation of industrial fuel/feedstock availability over longer renewable deficits. The latter is particularly significant for winter conditions characterized by low renewable production and high heat demand.

Constraints on production volumes are

$$\sum_{t \in T} y_{t,p} \geq \overline{Y}_p \qquad \forall p \in \{\text{steel, cement, ammonia, methanol}\}. \tag{12}$$

Eq. (12) ensures that the optimiser does not reduce cost by decreasing the amount of product. All transitions cases must produce the same amount of product annually; hence the difference in cost and emissions will correspond to energy-system design and not any change in industrial activity.

Residual emissions are

$$E^{\text{CO}_2} = \sum_t \left(\phi_t^{\text{grid}} P_t^{\text{grid}} + \sum_f \phi_f F_{t,f} + \sum_p \phi_p^{\text{proc}} y_{t,p} \right), \tag{13}$$

where ϕ_t^{grid} is hourly CO_2 grid emission factor, ϕ_f is fuel emission coefficient, and ϕ_p^{proc} is process emission coefficient.

The Eq. (13) distinguishes energy emissions from process emissions. It is vital in this context for cement, because despite the absence of fossil fuel as an energy carrier, calcination emissions would be accounted for. Therefore, the formula makes sure not to underestimate the impact of heat substitution on decarbonisation.

A measure for the useful fraction of waste heat is estimated through

$$\eta^{\text{rec}} = \frac{\sum_{t,m} Q_{t,m}^{\text{rec}}}{\sum_{t,s} Q_{t,s}^{\text{avail}}}, \tag{14}$$

where $Q_{t,s}^{\text{avail}}$ represents the heat available from a specific source stream s.

The Eq. (14) provides a straightforward metric for assessing quality of thermal integration. Higher numbers do not necessarily imply larger amounts of heat, but rather indicate sufficient sink capacity and appropriate transfer paths and storages to utilise available heat efficiently. This indicator is therefore used to interpret the difference between isolated heat recovery and integrated thermal management.

3.4. Technology set and case assumptions

Table 1 outlines the technologies considered within the optimisation model. The technology portfolio is limited to mature or near-commercial technologies that would be relevant to industrial applications by mid-century.

Table 1. Technology portfolio employed in the model.

Tech category	Technologies	Technology use
Electrical heating	Electric arc furnace, resistance heater, electrode boiler	Direct useful heat and process electricity when applicable based on temperature and process conditions
Hydrogen system	PEM electrolyser, compression, gaseous H_2 storage, H_2 burner	Flexible hydrogen generation, feedstock provision, reduction duty, and high-temperature combustion
Thermal energy storage	Medium-T thermal energy storage (TES), High-T TES	Energy shifting via heat storage or electric heat as function of hourly price and demand variations
Waste heat recovery	Heat exchanger, exhaust gas recovery, clinker cooler recovery, synthesis loop recovery	Energy shifting via cascading of waste heat from high/medium temperature sources to suitable sinks
Processes	Hydrometallurgical direct reduction, electric arc furnace, dry-process cement kiln, ammonia synthesis, methanol synthesis	Conversion of raw materials into final products under annual output limitations
Grid interface	Grid power, wind energy-driven power purchase, solar energy-driven power purchase, battery buffer	Access to renewable electricity sources along with balancing buffer

It can be seen from Table 1 that none of the technologies are considered universal. In cases where electric heating will lead to the highest conversion efficiency and is compatible with the process, it is selected. Hydrogen is selected for reduction, feedstock, and high-temperature processes. Waste heat recovery and TES are considered to change the temporal and temperature profiles of heat rather than simply reducing overall energy consumption.

The energy and production assumptions used are detailed in Table 2. The values have been chosen such that the combination represents a reasonable physical case for a realistically-sized industrial plant cluster.

Table 2. Annual output and energy per unit of output.

Process	Output	Electricity input	Heat input	Meaning for modelling
Steel (H-DRI + EAF mix)	2.0 Mt/year	3.20 MWh/t	2.65 MWh_{th}/t	Predominant demand for hydrogen and electricity for the two processes dominates the utility demand of the cluster
Cement	4.5 Mt/year	0.12 MWh/t	0.94 MWh_{th}/t	Persistent need for kiln heat and calcination results in high temperature demand
Ammonia	0.35 Mt/year	0.72 MWh/t	0.18 MWh_{th}/t	Continuous hydrogen demand as input for ammonia production
Methanol equivalent chemicals	0.25 Mt/year	0.54 MWh/t	0.21 MWh_{th}/t	Process requires hydrogen and carbon as inputs, and some heat can be recovered from the synthesis process

Table 2 explains why there is a need to model the load requirements of the cluster more carefully, as opposed to just treating it as an aggregate of isolated demands. For example, steel represents the highest electricity and hydrogen demand, cement has the highest high-temperature heat requirements, and chemicals provide stable hydrogen consumption. In addition, such a disparity creates opportunities for synergies between sectors, as equipment optimised for one process can help out the other sector in terms of reliability and/or efficiency.

In total four transition scenarios are considered. Scenario C0 is the reference scenario based on fossil fuel technologies with no electricity usage beyond the basic needs and some heat storage capabilities. In contrast, scenario C1 uses direct electrification and heat storage capabilities, while C2 adds hydrogen electrolysis, hydrogen storage, and hydrogen-powered high-temperature heat generators. Finally, C3 introduces the waste heat recovery possibilities and various levels of thermal energy storage into the hybrid system of hydrogen and electricity technologies. Production requirements remain the same in all scenarios.

Assumptions regarding the economy remain fixed for all the cases studied unless varied in sensitivity analysis. Assumptions used in the base scenario include a 7% WACC, 650 EUR/kW as capital cost of electrolyser, 28 EUR/kWh$_{th}$ and 46 EUR/kWh$_{th}$ for medium-temperature and high-temperature thermal energy storage, respectively, and finally, residual carbon price at 120 EUR/tCO$_2$. Annual mean costs for wind-tied and solar-tied power purchase scenarios

4. Results and interpretation

4.1. Transition outcome at the system level

The outcomes of the system optimisation exercise are summarised in Table 3. The shift from C0 to C3 is not merely an intensification of one specific technology, but rather a reconfiguration of the system architecture.

Table 3. Optimisation results for the four transition cases.

Indicators	C0	C1	C2	C3
Annualised total cost (M EUR/y)	1668	1524	1448	1392
Absolute savings over C0 (%)	0.0	-8.6	-13.2	-16.5
Annual CO$_2$ emissions (Mt/y)	5.94	1.36	0.48	0.19
Absolute savings over C0 (%)	0.0	77.1	91.9	96.8
Sustainable electricity fraction (%)	28.0	74.6	83.4	87.9
Electrolysis capacity (MW)	0	0	1210	1180
Hydrogen storage capacity (t)	0	0	11600	9800
TES capacity (MWh$_{th}$)	0	420	760	1820
Utilised recoverable waste heat (GWh$_{th}$/y)	118	196	238	612
Sustainable electricity curtailment (GWh/y)	0	184	129	74

Table 3 is the answer to the first part of the research question. Even though direct electrification results in an emission reduction of 77.1% compared to the base-case scenario, it comes with the disadvantage of the high residual cost due to the exposure to hourly price peaks and inefficient utilization of thermal energy that can be recovered. On the other hand, the addition of the chemical energy storage in case C2 makes the system more efficient. The hybrid case C3 achieves optimal performance thanks to hydrogen and thermal energy recovery.

Figure 3 highlights this point, illustrating that C3 cannot win by adding capacity only once. The electrolyser capacity is lower for C3 than for C2 due to heat recovery and TES, reducing the necessity of hydrogen combustion. At the same time, thermal storage is significantly higher; the recovered heat is increased to nearly double the amount in C2, while the renewable curtailment decreases to 74 GWh/year. Thus, Figure 3 illustrates the synergy between fuel substitution and energy quality management.

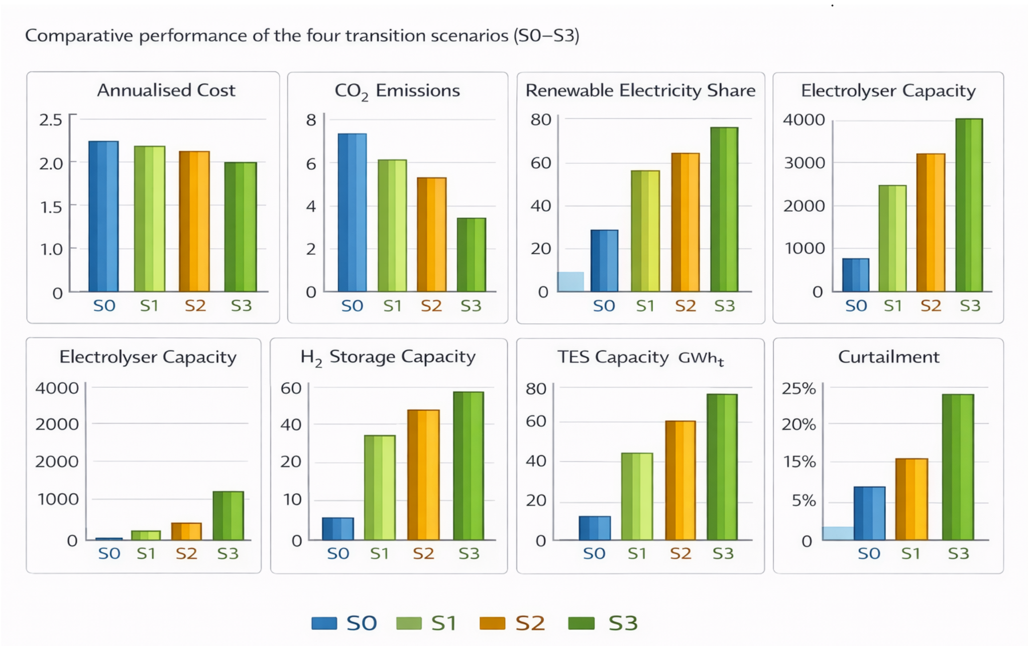


Figure 3. Cost, emission, storage, and curtailment at case level.

4.2. *Heat allocation according to temperatures*

The heat allocation of C3 makes the integrated scenario technologically feasible. Figure 4 shows the share of useful heat supply per temperature range.

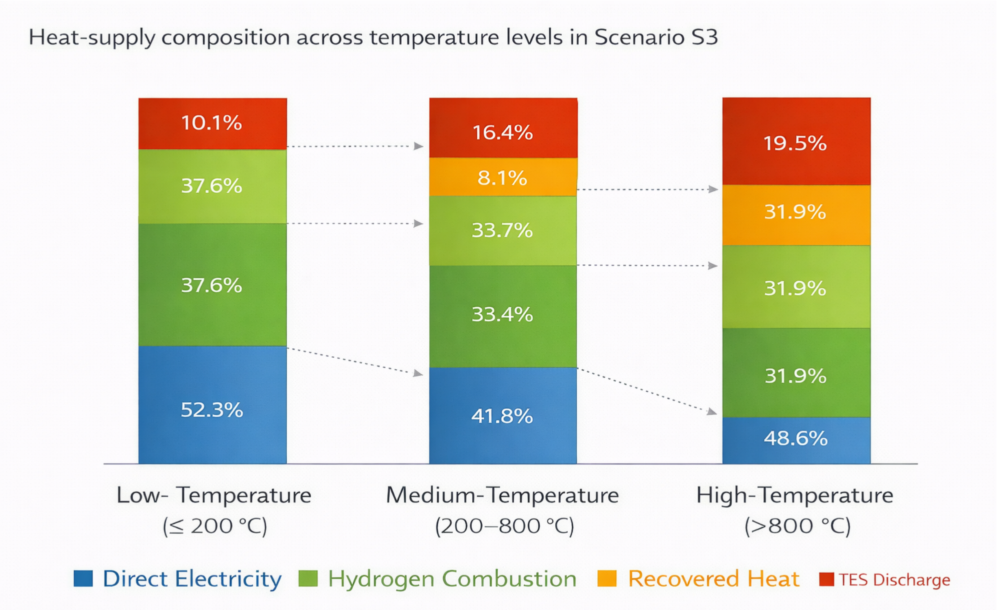


Figure 4. Heat-source allocation by temperature level in C3.

Low-temperature heat is provided by 52.3

The analysis is straightforward: the optimal system reserves hydrogen for more thermally intensive tasks rather than using it as a general-purpose energy source. Low-temperature heat consumption is dominated by recovered heat, since the level of exergy in this heat type is enough for these duties. High-temperature consumption is dominated by hydrogen, as certain kilns need more thermal intensity than electrical heating can provide in the given pricing regime.

Recovering and shifting heat at high temperatures should be noted as well. This does not imply that heat with low grade is used in kiln processes, as the system uses recovered heat and storage to reduce heat needs in lower temperatures, making space for other sources in more restrictive situations. This is the systems effect that is missed when each plant is analysed separately.

4.3. Hydrogen flexibility through electrolysers and storage

Apart from hydrogen production efficiency, the decision regarding the deployment of electrolysers is based on their capability of shifting industrial energy consumption away from periods of higher costs of electricity. In C2, average electrolyser usage rate amounts to 46.1%. It increases up to 49.7% in C3, despite being installed electrolyser capacity lower. Such improvement takes place due to thermal recovery and storage, which make the hydrogen demand downstream more smooth and allow electrolysers to avoid unfavorable periods of operation in terms of costs.

The way it operates is illustrated in Figure 5. The electrolyser load grows at low price periods, additional energy generated beyond current demand is stored, and hydrogen discharge happens whenever the price increases or there is insufficient renewable generation.

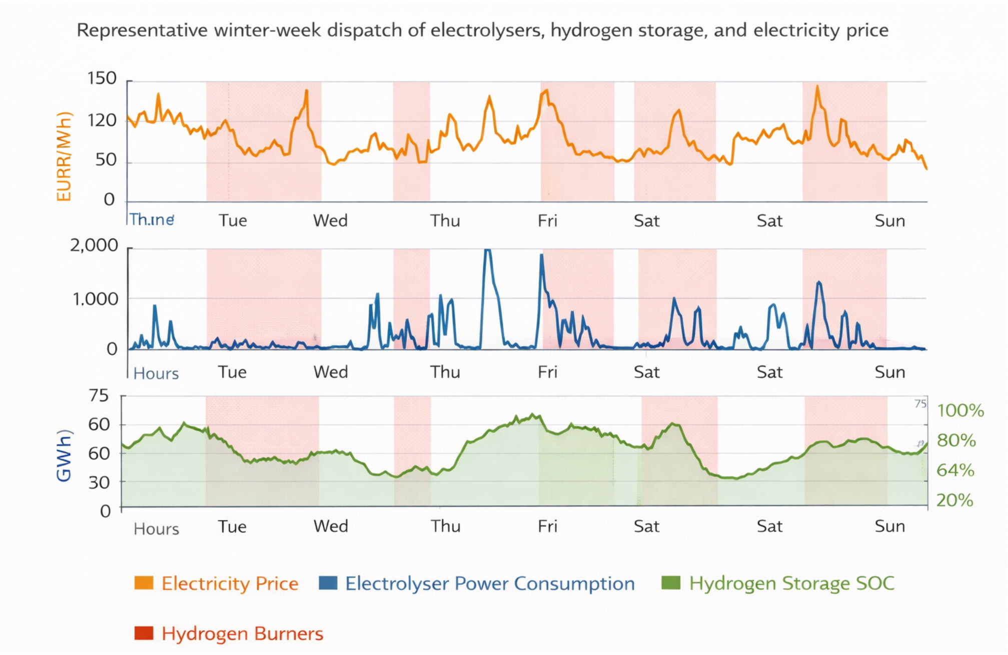


Figure 5. Hydrogen dispatch and prices during winter week.

Thus, the cluster uses hydrogen storage not as a mere energy storage solution, but as a resource that ensures industrial processes stability. The key aspect here is the opportunity to protect high-temperature heat generation and raw material supply while still keeping flexibility within the power side of the system.

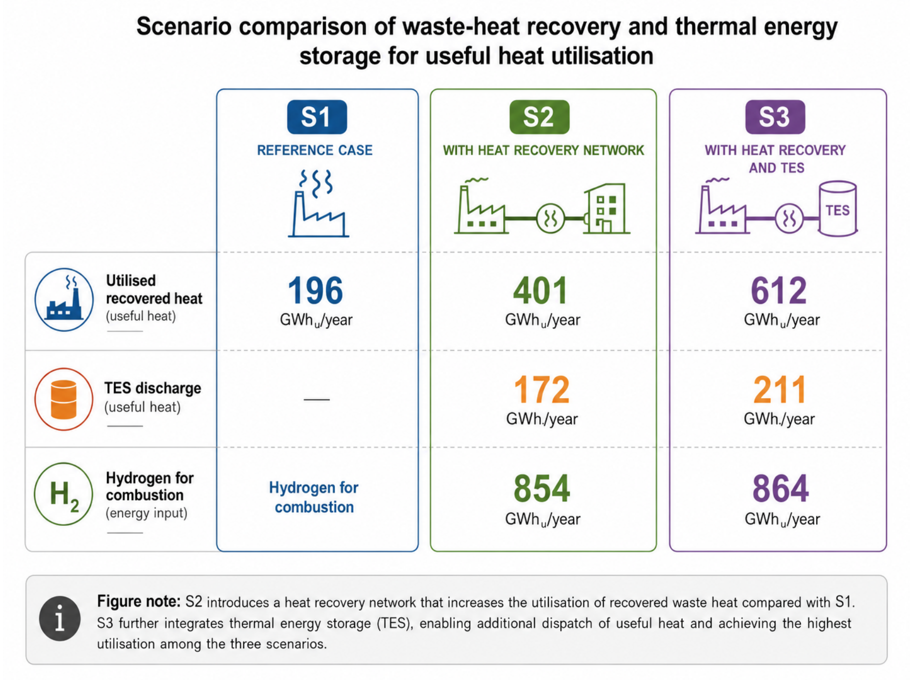
Median cycle duration of hydrogen storage operation in C3 is equal to 31 hours, and it reaches 116 hours during the winter season, which indicates the 95th percentile. It is longer than what is usually expected from batteries used within industrial plants. Thus, such hydrogen storage becomes justifiable despite higher capital costs of electrolysers because the benefits include not just cheaper electricity, but also the security of reduction, combustion, and chemical synthesis tasks completion.

Constrained dispatch test proves the interpretation given above. If electrolyses are required to work on close to constant levels, the total annualized cost will grow in C3 by 6.2%. At the same time, renewable curtailment will increase twice. It means that the economics of electrolysis heavily depends on its operational flexibility. Capacity alone is not enough; the production schedule must be able to respond to the hourly energy environment.

4.4. Waste heat recovery and its relationship to TES

Waste heat recovery provides only a moderate benefit in standalone analysis of individual plants; however, under cluster coordination, waste heat recovery becomes essential. The total benefit of waste heat recovery in C1 is 196 $\mathrm{GWh_{th}/yr}$. In C3, this value has increased to 612 $\mathrm{GWh_{th}/yr}$ due to exchanges facilitated by the presence of a suitable pathway and TES.

From Figure 6, it is observed that the role of TES transforms waste heat recovery from a supplementary technique to a dispatchable resource. Waste heat recovery requires synchronization in time and temperature level of the heat source and sink without storage. However, using TES, waste heat can be moved to times where the requirement is higher in terms of temperature level and overall energy content. The utilization rate of available waste heat has improved from 39% to 71%. The hydrogen demand has also decreased by 18.4% compared to C2 for meeting combustion heat requirements.



Scenario comparison of waste-heat recovery and thermal energy storage for useful heat utilisation

	S1 REFERENCE CASE	S2 WITH HEAT RECOVERY NETWORK	S3 WITH HEAT RECOVERY AND TES
Utilised recovered heat (useful heat)	196 $\mathrm{GWh_u}$/year	401 $\mathrm{GWh_u}$/year	612 $\mathrm{GWh_u}$/year
TES discharge (useful heat)	—	172 GWh./year	211 GWh./year
Hydrogen for combustion (energy input)	Hydrogen for combustion	854 $\mathrm{GWh_u}$/year	864 $\mathrm{GWh_u}$/year

Figure note: S2 introduces a heat recovery network that increases the utilisation of recovered waste heat compared with S1. S3 further integrates thermal energy storage (TES), enabling additional dispatch of useful heat and achieving the highest utilisation among the three scenarios.

Figure 6. Interaction between waste heat and TES.

In summary, waste heat recovery must be planned along with TES and process scheduling, right at the start of system design. Heat exchangers may not be able to utilize all the available waste heat due to lack of an appropriate sink. Furthermore, TES increases the likelihood of recovering waste heat for displacing marginal fuels.

4.5. Sensitivity and robustness

The sensitivity analysis assesses the sensitivity of electrolyser capital cost, renewable electricity price, carbon price, and recoverable waste-heat potential. These changes are summarized graphically in Figure 7 and numerically in Table 4.

Table 4 shows that the renewable electricity price dominates as the main cost factor. This is no surprise, as the direct electrification scenario depends entirely on it. Second to that comes the cost of an electrolyser plant, which determines hydrogen cost. The carbon price is less influential in C3 than in D3, since fossil heating is almost entirely replaced at this level. However, a lower carbon price leads to higher residual emissions in C3 due to increased fossil flexibility in marginal hours.

As for the impact of waste-heat potential, a 25% drop in recoverable waste-heat potential causes costs to increase by 3.8%, and emissions to increase by 6.5%. That proves that waste heat is no window-dressing for C3. This parameter plays a very material role in defining the resulting fuel mix and emissions profile. Conversely, higher recoverable waste-heat potential brings both cost and emission savings, with diminishing effects once all easily integrable heat sinks are used up.

It can also be seen from Figure 7 that the C3 hybrid solution retains its strength through the whole range of tested parameters. No scenario turns out to give priority to direct electrification over the other options. Rather, the proportions between the energy vectors get readjusted. This characteristic is particularly valuable for Kazakhstan in view of the likely heterogeneous development of renewables' cost, technology price, and climate policy dynamics in future.

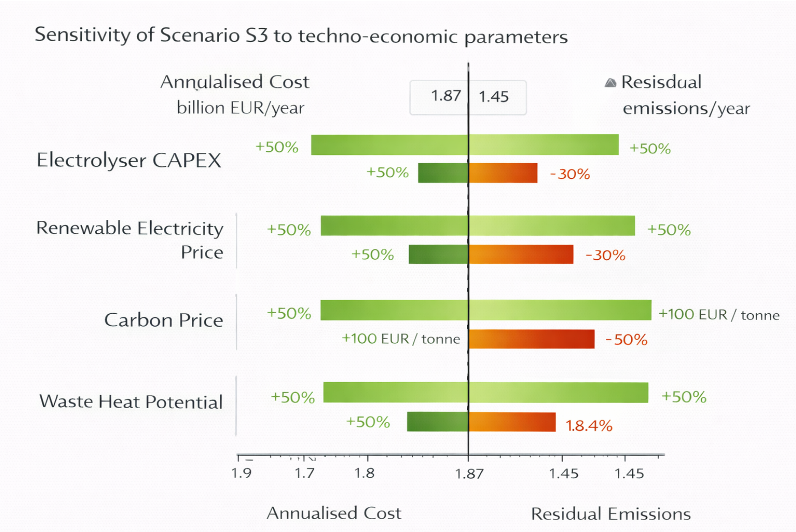


Figure 7. Cost and emissions sensitivity of C3.

Table 4. Sensitivity of C3 to uncertain parameters.

Parameter variation	Change in annualised cost	Change in residual emissions
Electrolyser CAPEX: -23%	-4.8%	-1.2%
Electrolyser CAPEX: +31%	+6.1%	+1.9%
Renewable electricity price: -15%	-7.4%	-0.8%
Renewable electricity price: +20%	+9.2%	+0.6%
Carbon price: 80 EUR/tCO_2	+1.7%	+8.4%
Carbon price: 180 EUR/tCO_2	-0.9%	-4.7%
Recoverable waste-heat potential: -25%	+3.8%	+6.5%
Recoverable waste-heat potential: +20%	-2.6%	-3.1%

4.6. Discussion (engineering)

These results directly address the research question posed at the beginning of the paper: sector coupling benefits high-temperature industrial decarbonisation because each technology is assigned to play a role in solving the thermal challenge in the place where its engineering value is greatest. Electrical heating applies process-compatible heat supply efficiently. Hydrogen covers reduction, feedstock, and high-thermal-intensity loads. Waste-heat recovery handles lower-temperature heat duties and intermediate thermal levels. Thermal energy storage turns the intermittent process of heat recovery into a service.

In other words, assigning technologies in this way alters the economics of the industrial transformation. While C1 operates largely with electricity at the moment of heat demand, such an approach decreases emissions but increases vulnerability to costly hours and renewable curtailment. C2 decreases that vulnerability by including hydrogen storage, but still uses too much available waste-heat recovery. C3 completes the picture by adding the thermal dimension. It provides a cheaper and cleaner operation despite having more infrastructure to connect processes together.

Secondly, the findings confirm the system-value of electrolysis. In isolation, a levelised cost analysis may make underutilisation look inefficient. The current approach suggests, however, that it is precisely utilisation flexibility that brings value to electrolysis. Electrolysers consume electricity in good periods, hydrogen storage transmits the power through several days, and then the cluster uses hydrogen when its process value is higher than the value of direct electricity use and waste-heat recovery. The proper engineering metric in this case should thus not be the maximum electrolyser capacity factor, but reduced cost, reduced renewable curtailment, and reliable production.

A similar argument applies to waste-heat recovery. If it occurs in the wrong hour or at the wrong temperature, heat recovery does not deliver significant value to a plant. In this example, TES and heat matching between multiple processes is precisely what increases the utility of the recovered waste-heat beyond merely reducing the need for primary heating. As a consequence, waste-heat recovery and associated systems such as heat exchange networks or thermal energy storage vessels should be an integral part of industrial park planning and design.

For the Kazakh industry specifically, the message is clear: to achieve industrial heat decarbonisation, cluster-level engineering and planning is required. Each plant has a unique heat profile and unique thermal challenges. Such uniqueness is far from being a hindrance to sector coupling. On the contrary, it is what allows such coupling to happen in the first place. Chemical production helps stabilise hydrogen demands, cement helps accommodate high-temperature flexibility, and steel production enables electrolysis scale-up. By leveraging these roles, the cluster can become more robust than its parts.

There are also limitations. The presented plant cluster is illustrative and representative of a real facility but is not based on any specific plant design. Further, the model does not consider detailed furnace geometry and related challenges such as refractory degradation and start-up costs. Moreover, it does not perform the unit commitment procedure and optimisation in the space of full process mass balances. Finally, it assumes aggregate cement process emission accounting and does not jointly optimise cement process emissions and kiln heat substitution. Renewable electricity profiles reflect one typical year.

These limitations do not affect the main conclusions, but point to the necessary subsequent steps. For instance, a cluster-level model could benefit from further plant-specific calibrations, inclusion of stochastic weather years, modelling detailed kilns and furnaces, joint optimisation of cement kiln emissions and heat substitution, and siting infrastructure for hydrogen and thermal networks.

5. Conclusions

In this work, we have examined how the impact of sector coupling on cost, emissions, heat allocation, and operational flexibility will change the dynamics of high-temperature industrial decarbonisation in a steel–cement–chemical cluster in Kazakhstan. We find that it changes the decarbonisation challenge from one primarily of substitution of the existing fuels to a problem of coordinated heat quality and energy storage. The case that achieves the highest performance does neither rely purely on direct electrification nor on hydrogen alone. The best-case scenario is where electricity, hydrogen, recovered heat, and TES are all allocated based on their relative value in different temperature bands and timescales.

The fully sector-coupled design achieves CO_2 emissions in the amount of 0.19 Mt CO_2/year compared to 5.94 Mt CO_2/year in the fossil reference case, which corresponds to the 96.8% emissions reduction. The total cost is 1392 M EUR/year, which is 16.5% lower than in the fossil reference case and 8.7% lower than in the electrification case. This means that cluster integration results in lower cost decarbonisation as compared to inflexible electrification-driven decarbonisation under the considered assumptions for Kazakhstan.

Heat supply is allocated according to a well-organised scheme. Most of the heat of the lowest temperature is supplied by the recovered heat, while direct electrical heaters are predominantly used for the supply of middle temperature classes. Hydrogen is applied exclusively for chemical purposes, reduction, and high-temperature combustion. Thermal storage contributes to higher utilisation of waste heat as well as reduces the demand on hydrogen burning. This leads to a 18.4% decrease in the hydrogen combustion compared to the hybrid hydrogen-electrical case. Storage of hydrogen increases energy-system resilience to intermittent nature of renewables, leading to 31-hour median cycle duration and up to 116 hours in winter seasons.

Our sensitivity analysis demonstrates that the renewable electricity and electrolyser CAPEX are dominant uncertainties in terms of cost. At the same time, waste heat availability has significant impacts on both cost and residual emissions. C3 architecture is still preferable over all the variations studied. Therefore, our main finding is robust: Kazakhstan's high-temperature industrial heat transition should incorporate cluster-level matching of temperatures, hydrogen flexibility provided by the electrolysers, multi-day hydrogen storage, recovery, and use of waste heat and thermal storage.

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