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DECARBONISATION THROUGH INNOVATION

Decarbonization pathway development for industrial heating systems under CSRD requirements

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Abstract

The EU Corporate Sustainability Reporting Directive (CSRD) requires industrial companies not only to report on their current primary energy use and greenhouse gas emissions, but also to disclose decarbonization strategies across short-, medium-, and long-term horizons. This regulatory framework increases the need for transparent, robust pathways to industrial decarbonization.
In heating systems, CO_2 emissions stem from heat generation, distribution, and consumption. Effective decarbonization therefore depends on a combination of investments into new heating infrastructure and operational measures across all system levels. These include the integration of low-carbon heat generators, adaptation of temperature setpoints, network upgrades, and load management strategies.
However, conventional planning tools typically evaluate measures in isolation, failing to account for interdependencies and cumulative system effects. This limits their value for long-term strategy development and CSRD-aligned reporting.
This contribution introduces a framework for constructing and comparing interconnected decarbonization pathways in industrial heating networks. It links technical and operational measures into time-sequenced strategies, simulating their combined impact on emissions and energy costs at hourly resolution.
A case study of a pharmaceutical campus illustrates the approach. It demonstrates how the performance of a heat pump integration — in terms of coverage, efficiency, and primary energy savings — depends strongly on accompanying measures such as temperature reductions and enablers such as the expansion of low-temperature networks. The heat pump acts as a central, but not isolated component in a broader transformation strategy.
The results highlight the importance of considering the timing, interaction, and cumulative effect of decarbonization measures. The proposed framework enables companies to develop more realistic and effective decarbonization pathways — improving both regulatory compliance and strategic decision-making in industrial energy systems.

Keywords: Decarbonization; Industrial Heating Systems; Corporate Sustainability Reporting Directive

1. Introduction

To enable a more effective way of policy making with regards to the effects climate change policies have on commercial undertakings in the European Union, the EU introduced the Corporate Sustainability Reporting Directive (CSRD). One of the main aims of this regulation is to gather concrete data on the status quo of alignment of companies with the EU's 2050 net zero target as well as detailed information on how companies plan to achieve the decarbonization of their operations.

The industrial sector, especially the manufacturing industry, plays a significant role in the efforts for decarbonization. Due to the nature of the manufacturing industry (taking input materials, refining them, selling the refined goods), significant amounts of energy are necessary for the sector's operation.

Faced with the obligation to report detailed information on how their production processes and facilities will be decarbonized until 2050, industrial companies operating in the European Union need to focus on the existing heating systems present at their production sites. A detailed analysis of the pathways to a decarbonized operation is required to not only comply with the recently introduced regulation, but to stay competitive in the race to net zero.

2. Regulatory Background: Corporate Sustainability Reporting Directive

The Corporate Sustainability Reporting Directive (CSRD; Directive (EU) 2022/2464) expands the existing EU Accounting Directive by introducing mandatory, standardized sustainability disclosure obligations for large and listed companies. Under the CSRD, firms must report a Sustainability Statement that includes (i) quantified indicators describing their environmental impacts, (ii) strategies and actions contributing to sustainability goals, and (iii) decarbonization targets for short-, medium-, and long-term horizons. The European Sustainability Reporting Standards (ESRS) further specify the required metrics, including annual primary energy use disaggregated by energy carrier and annual Scope 1–3 greenhouse gas emissions.

For operators of Industrial Heating Systems (IHS), the CSRD implies that long-term GHG reduction trajectories must be documented and supported by transparent technical evidence. Because process heat often dominates industrial energy use, future compliance requires companies to forecast how modifications to generation, distribution, and consumption infrastructure will affect energy consumption and CO_2 emissions up to 2050. This necessitates a systematic understanding of how decarbonization measures such as heat pump integration, temperature-level reduction, waste heat recovery, or fuel switching affect system performance over multi-decadal time horizons. In the context of this work, a *decarbonization pathway* describes the chronological sequence of measures transforming a system from its current state toward a low-carbon or net-zero configuration, including the timing, interactions, and cumulative effects of each measure.

2.1. Modelling approaches for long-term decarbonization of Industrial Heating Systems

While CSRD provides the regulatory motivation, the methodological challenge of forecasting future sustainability performance of industrial heating systems has been addressed in the scientific literature through several modelling paradigms.

Several studies investigate how energy systems evolve under long-term policy or economic constraints. Rolling-horizon or multi-period investment models [1] simulate the sequential adoption of technologies under uncertainties such as fluctuating electricity prices or future market conditions. These models highlight that decarbonization cannot be evaluated as a single end-state optimization but must reflect the order and timing of measure implementation.

At the company level, [2] emphasizes that decarbonization strategies depend on the prioritization of internal versus external measures, investment timing, and stakeholder preferences. These frameworks align structurally with CSRD requirements: companies must not only select technical measures but must articulate their contribution to GHG reduction over several time horizons. However, these works do not quantify changes in system-level energy flows or heat generation performance.

A large body of research focuses on modelling specific technologies relevant for industrial heating decarbonization in specific sectors or processes. These include high-temperature heat pumps, waste heat recovery systems, and hybrid heat supply configurations [3–5]. These studies typically use MILP, dynamic simulation, or steady-state thermodynamic tools to quantify energy savings and emission reductions of individual measures. While they demonstrate the technical feasibility and potential environmental benefits of alternative heat generation options, they generally address neither multi-decade system transformation pathways nor their alignment with reporting standards.

Advanced simulation environments such as Modelica, Dymola, and TRNSYS have been widely applied to district heating and multi-energy systems [6–9]. These tools can represent hourly operational dynamics, interactions between technologies, thermal storage, and varying boundary conditions—features necessary for modelling IHS transformations. However, existing studies typically analyse single-year performance or technology integration scenarios, not sequential decarbonization pathways across several time horizons.

Despite substantial research in individual components, long-term optimization, and district energy modelling, no existing framework links multi-decade system transformation of industrial heating systems to the concrete reporting requirements of the CSRD. Specifically, the literature lacks:

- A method to quantify annual primary energy use and CO_2 emissions for different stages of future system configurations,
- A simulation-based representation of sequential measure implementation (short-, mid-, and long-term),
- An approach that integrates operational dynamics with pathway-level investment planning,
- A tool tailored to the reporting logic and KPI requirements defined in the ESRS.

This gap motivates the development of the simulation-based evaluation framework presented in this work.

3. The Decarbonization Pathway Analysis Model

3.1. Framework design

To enable the structured analysis of one given decarbonization pathway, the developed framework consists of two distinct sub-models: The simulation-based "IHS simulation model" and the "Decarbonization pathway model". The two components of the framework are closely connected to each other via inputs from one model to the other and vice versa. In addition to that, both are dependent on user input with regards to the relevant input data described in the following chapters.

Different stakeholders are interested in different levels of detail about the output of the models. Whereas a decision maker ("management") may only be interested in "superficial" KPI's in the form of numerical aggregates and investment/energy costs associated with the measures, an energy engineer must consider technical constraints and feasibility limits at not only a yearly, but an hourly or even sub-hourly timescale. Based on this more detailed analysis, additional effects of the proposed integration of measures, such as changing peak demands in primary energy or required maximum capacities for different heat generators can be reviewed.

3.1.1. IHS simulation model

The IHS simulation model describes a simulation-based model which describes a real-world IHS with all its relevant components. The aim of the model is to enable a yearly simulation of the system, with a detailed performance representation of the individual components of the system. The IHS model receives changes of its technical, economical, or environmental input parameters from the high-level decarbonization pathway model and feeds back its output data to the same model.

3.1.2. Decarbonization pathway model

The decarbonization pathway model encompasses the tasks necessary for the initial setting of the decarbonization pathway measures and timelines, management of input, output, and intermediary files as well as evaluation and graphical representation of the respective results. It is responsible for handling the user input (files with load, weather, CO_2 intensity, energy costs data; definition of measures and their years of implementation). In addition, the model handles the setting and re-setting of parameters of the IHS model. It also reads in the simulation results provided by the IHS model and performs QA as well as evaluation calculations. Lastly, it provides graphical and tabular results data to the user.

The workflow for analyzing a specific decarbonization pathway using the Decarbonization Pathway Analysis Model is shown in Fig. 1.

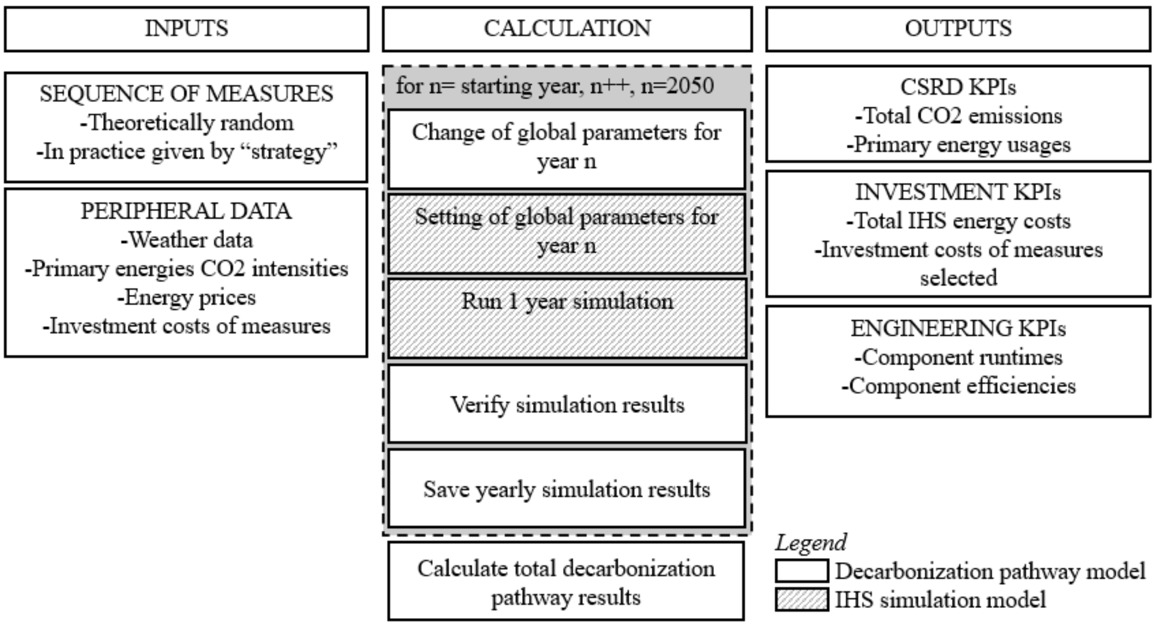

Figure 1: Workflow of the Decarbonization Pathway Analysis Model

3.2. Framework implementation

To implement the developed framework, both for the IHS simulation model and the decarbonization pathway model, a suitable tool or software must be chosen. As the interface to and feedback from the IHS simulation model depends on its specific software design, the selection of the programming language for the decarbonization pathway model is highly specific to each individual software.

3.2.1. IHS simulation model implementation: TRNSYS

For the IHS simulation model, the simulation software TRNSYS is chosen. TRNSYS has been used to study heating systems as well as coupled heating, cooling, and electricity generation systems (CHP) in various cases, especially in district heating as well as industrial heating systems. In TRNSYS, a model of a given physical system is generated through linking different components with specific parameters. Combined with read-in input data, the model can be given to a mathematical solver to run the simulation. Outputs from the model can be defined freely and displayed both as a graph as well as written into output files.

To accurately represent the IHS which should be studied, the TRNSYS model must be constructed in a way which represents the real-world system at least to sufficient accuracy. In addition, all decarbonization measures which should be studied must be available in the TRNSYS model. They must be integrated in such a way as they may be "switched on or off" via one or a set of input parameters. This is achieved through the parametrization of all necessary component data (e.g. capacities, mass flows; but also digital inputs for control strategies) via user-defined variables in TRNSYS.

To enable running the TRNSYS model in combination with an overarching decarbonization pathway model, the model is saved as a .dck-file, which encompasses the complete model data. This dck-file can be used as a parameter when running TRNSYS through calling the TRNSYS.exe. To enable the setting and re-setting of parameters, the user-defined parameter variable names are replaced manually in a text editor to be set by the overarching decarbonization pathway model.

To extract the output data from one year of IHS simulation, the printer component in TRNSYS is set up to save all relevant output data in an hourly frequency in an output file.

3.2.2. Decarbonization pathway model implementation: Python

To enable efficient overarching data management as well as calculation of KPI's, the decarbonization pathway model is implemented in Python code. The decarbonization pathway model handles the following subtasks:

- Description of code structure to generate decarbonization pathway
- Handling of sequencing of measures
- Handling of modelling Quality Assurance (QA)
- Handling of evaluation of simulation outputs
- Cost calculation of complete IHS system
- CO_2 emissions calculation of complete IHS system
- Plotting and saving data
- Evaluation of single measures (e.g. electricity usage of heat pumps)

The decarbonization pathway model is built in the programming language Python. Python is a versatile programming language which can handle both basic and advanced mathematical functions and manage files (inputs/intermediary/outputs).

The main workflow of the decarbonization pathway model consists of a loop calling the IHS simulation model for each year of the complete decarbonization pathway (default: 2025 to 2050). For each year, the model parameters are changed according to the changing peripheral data (energy prices and CO_2 intensities) as well as the implementation of decarbonization measures as given by the user input. For each year of simulation, the simulation results are post-processed both for QA and for calculation of environmental and economic performance. The results for each year are stored. After the main loop has finished running, an evaluation of the overall pathway is performed.

4. Application

To demonstrate the application of the Decarbonization Pathway Analysis Model to a real-world system, an example application on a case study system is presented.

The facility studied is a pharmaceutical R&D and production campus located in South-West Germany (see Fig. 2). It consists of various buildings, some of which are typical office buildings, others are laboratories or production buildings. With all secondary buildings and storage areas, the site takes up about 155.000 m^2 of space.

The processes which are present at the site are mainly packaging as well as filling of various medical equipment and devices. The process temperatures necessary to power these processes can be defined as max. 110 °C. The process with the maximum temperature requirement is superheating of hot water and steam to create pure steam and process water as well as sterilization. To supply the different processes and to provide general heating and cooling of the site's buildings, steam and chilled water is produced at centralized generation hubs and distributed throughout the site via pipelines. The presence of chilled water generation is significant to this analysis, as the heat rejected from the electrical chillers may be used as a form of waste heat to be recovered by water-sourced heat pumps. The main energies consumed at the facility are steam (4 bar, ~180 °C), heat (at 90 °C for ~85 % of the total heat demand, not constant throughout the year), electricity and chilled water (at 6 °C).

The heating load of this production campus varies throughout the year, with a thermal peak in the winter season of 14.29 MW, and a summer load of around 7 MW. The chilled water demand of the site follows a typical load pattern of low demand in the winter season (approx. 1.5 MW) and significantly higher demand in the summer (6.3 MW peak).

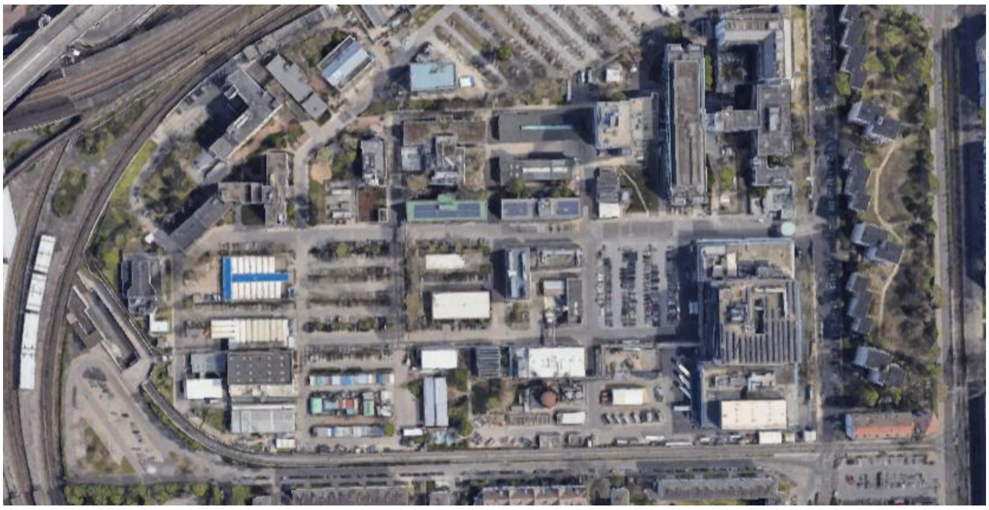

Figure 2: Satellite Image of Case Study Industrial Production Campus

4.1. IHS simulation model setup

The simulation model is designed to represent the generation, distribution, and consumption of heat within the industrial heating system (IHS). It consists of several interconnected thermal subsystems operated on an hourly basis over a full year.

The main heating network supplies the primary heating load and comprises a gas-fired boiler, hot water circulation pumps, the connected load components, and thermal inertia represented by supply and return water volumes. Cooling demand is served by a chilled water loop consisting of an electrically driven chiller and a corresponding circulation pump. Heat rejection is modelled through a recooling circuit including a recooling pump and cooling tower. Two optional heat pump integrations are predefined within the model: an air-source heat pump (AWHP) and a water-source heat pump (WWHP). These can be activated depending on the selected decarbonization pathway and interact with the existing heating and recooling systems.

In addition, auxiliary components are implemented to enable control strategies that respond to external conditions such as ambient temperature, primary energy prices, and CO_2 emission intensities. Generator capacities, efficiencies, and operating priorities are parameterized using engineering-based assumptions. Temperature-dependent and part-load effects are considered where relevant, particularly for heat pumps and chillers, while conventional boilers and network components are represented using constant nominal efficiencies typical for industrial applications.

All parameters affected by individual decarbonization measures are defined in a modular manner, allowing automated modification of the model input data without structural changes to the simulation framework.

4.2. Decarbonization pathway model setup

In the decarbonization pathway model, the following default parameters are set as initial conditions: The heating network is supplied by the gas boiler only with a constant supply temperature setpoint of 90 °C. All heat pump integrations are switched off. The chilled water network is supplied by the electrical chiller with a constant supply temperature setpoint of 6 °C. The recooling circuit runs according to the rejected heat from the electrical chiller and recooling takes place only in the closed-circuit cooling tower. The control logic of the complete IHS is thermodynamical only. No additional constraints or operational strategies are applied. The following decarbonization measures can be implemented:

- Heating network supply temperature change
- Implementation of a weather-dependent supply temperature setpoint
- Heating network load reduction
- Gas boiler efficiency upgrade
- Heating network pipe insulation increase
- Implementation of a water-sourced heat pump with a price-optimal control strategy
- Implementation of a water-sourced heat pump with a CO_2-emission-optimal control strategy
- Implementation of an air-sourced heat pump with a price-optimal control strategy
- Implementation of an air-sourced heat pump with a CO_2-emission-optimal control strategy

As peripheral data, primary energy costs have been used based on constant prices for natural gas, district heating, and hydrogen. The electricity prices are taken from the spot market prices in Germany for the reference year of 2023 [10]. The CO_2 emission factors for electricity is taken from the actual German electricity grid CO_2 intensity in the year 2023 [11]. The following appreciation/depreciation factors are given in Table 1.

Table 1: Appreciation/Depreciation factors for primary energy CO_2 emission intensities and energy prices

	Natural Gas (NG)	Electricity (E)	District Heating (DH)	Hydrogen (HY)
CO_2 emission intensity appreciation	-1%*	-5%	-3%	0%
Energy cost appreciation	3%	-2%	2%	0%

* Some hydrogen/renewable gas injection into the natural gas grid is assumed to take place.

4.3. Reference case performance

As peripheral data (mainly primary energy prices and CO_2 intensities) are changing over time, a reference performance is calculated for the starting year setup of the model. This scenario is described as the “do nothing” scenario. The performance of the reference case IHS with respect to CO_2 emissions is shown in Fig. 3.

Figure 3: Yearly CO_2 emissions for reference case IHS

As per the price increases and CO_2 intensity developments, the IHS will produce 17.938 t/a of CO_2 emissions. Without changing anything in the IHS, the yearly CO_2 emissions from the IHS fall by 25,7 % due to the lowering of CO_2 intensity in the electrical grid until the year 2050.

4.4. Decarbonization pathways assessment

In the following chapters, 3 different decarbonization pathways and their results are discussed. Each decarbonization pathway consists of the reference IHS, which is changed through the implementation of 3 measures. For clarity reasons, the years of implementation for each measure have been aligned to match the year 2030, 2035 and 2040.

4.4.1. Decarbonization pathway 1: Conservative operation

In this pathway, a set of measures is presented which should represent a “conservative” approach to decarbonization. The user assumes to take defensive measures which don’t require large capital investments: A setpoint change for the heating supply temperature, the implementation of weather-dependent control, and an efficiency upgrade of the gas boiler. Fig. 4 shows the performance of this decarbonization pathway IHS.

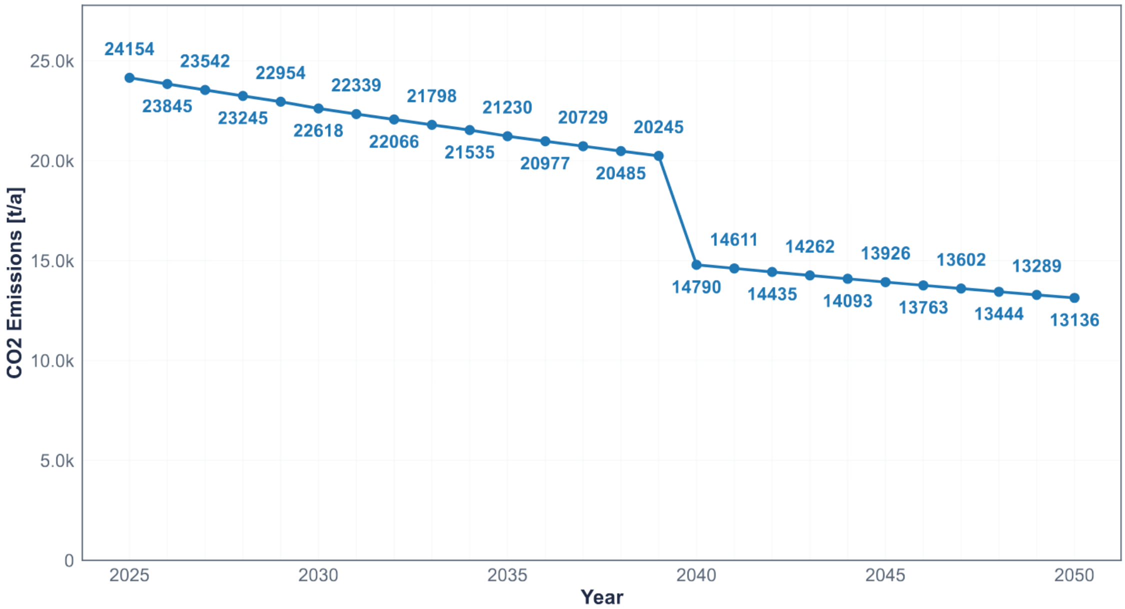

Figure 4: Yearly CO_2 emissions for decarbonization pathway 1 IHS

The results for the performance of decarbonization pathway 1 show each of the measures implemented have some effect, which is visible in the form of a reduction in primary energy demand. However, the configuration of the first two measures (setpoint change and weather-dependent control) only comes with a small reduction, and thus their CO_2 emissions reduction is barely visible compared to the overall changes in CO_2 emissions. This is due to the changing CO_2 emissions intensity in the electrical grid. The gas boiler efficiency upgrade produces significant reductions in CO_2 emissions.

4.4.2. Decarbonization pathway 2: Progressive operation

In this pathway, a more ambitious set of measures is implemented: Weather-dependent control, improvement of insulation, and AWHP integration with price-optimal controls. The performance of this decarbonization pathway is demonstrated in Fig. 5.

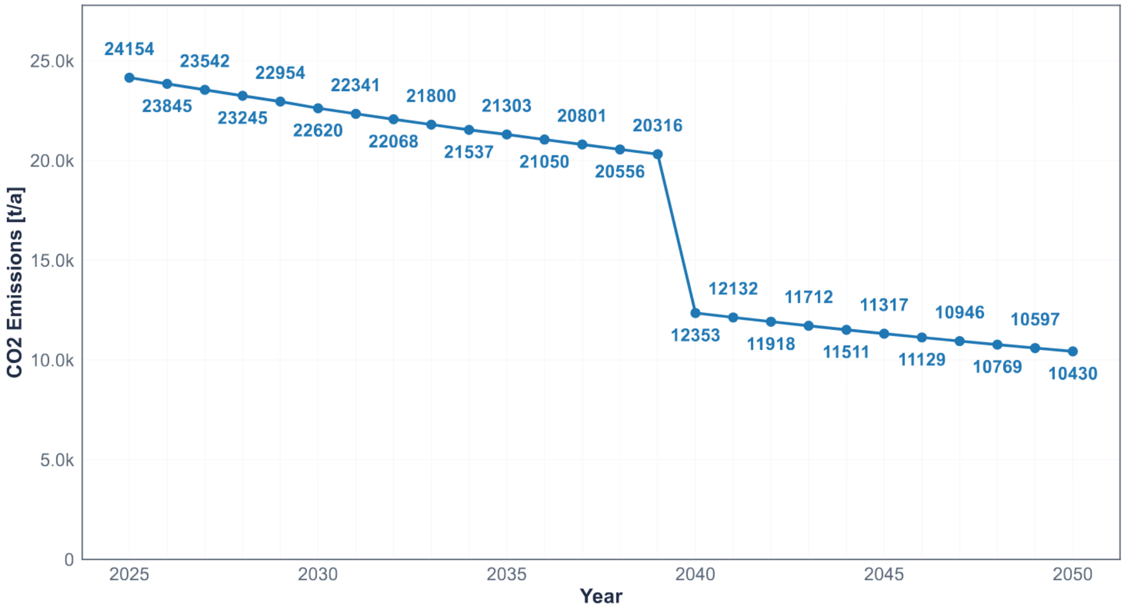

Figure 5: Yearly CO_2 emissions of decarbonization pathway 2 IHS

In decarbonization pathway 2, the effect of switching to a weather-dependent control has a similar effect as in decarbonization pathway 1 (DP1: -258 MWh/a, DP2: -259 MWh/a). Increasing the insulation on the heat distribution network has an adverse effect. While not initially expected, this can be explained by the gain in surface in contact with ambient air being greater than the additional insulation thickness. The operational-cost-optimal integration of the AWHP in 2040 leads to a significant reduction in CO_2 emissions of the IHS.

4.4.3. Decarbonization pathway 3: Heat Pump implementation

In this pathway, an early adopter of WWHP technology is assumed to be a key decision maker. The modelled pathway is therefore given as: Implementation of WWHP with CO_2-optimal control, supply temperature setpoint change, and load reduction. In Fig. 6 the performance of this decarbonization pathway is demonstrated.

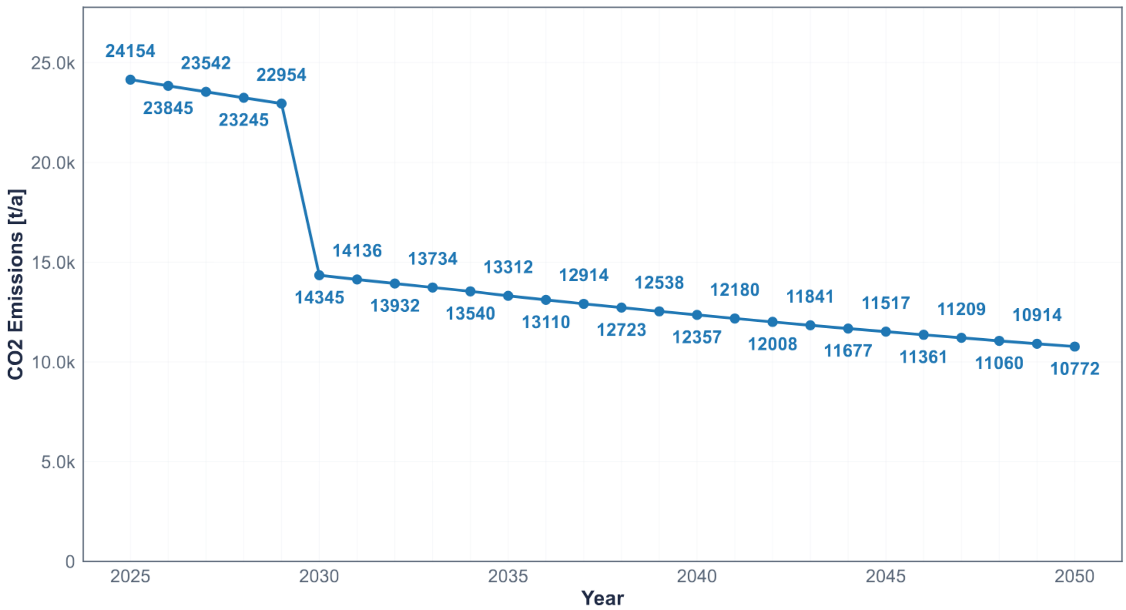

Figure 6: Yearly CO_2 emissions for decarbonization pathway 3 IHS

This decarbonization pathway demonstrates the impact the implementation of the WWHP with the CO_2-optimal control strategy has, significantly reducing CO_2 emissions as well as energy costs. Changing the setpoint supply temperature seems to not have a significant positive effect. Even though natural gas consumption is reduced by approx. 2.700 MWh/a by this measure implementation, it also increases electricity demand by 2.175 MWh/a, seemingly forcing an economically unfavourable operation of the WWHP. The load reduction measure is clearly visible as a reduction of CO_2 emissions.

5. Results and Discussion

All investigated decarbonization pathways lead to a reduction in CO_2 emissions compared to the reference case, but with notable differences in magnitude and timing. These differences highlight the importance of sequencing and system interactions rather than the isolated evaluation of individual measures. In all pathways, early emission reductions are partly driven by the assumed decrease in grid electricity CO_2 intensity. As a result, efficiency-oriented measures show limited direct impact on annual emissions despite reducing energy demand. Their role should therefore be understood primarily as enabling steps for subsequent structural changes.

Pathway 1, which focuses on operational and incremental efficiency measures within the given heating infrastructure, achieves moderate emission reductions but does not deliver deep decarbonization within the investigated timeframe. This confirms that such measures alone are insufficient to meet long-term climate targets. Pathway 2 shows a pronounced emission reduction once an air-source heat pump is introduced. The results confirm electrification of heat supply as a key decarbonization lever, while secondary effects such as changes in distribution losses remain of minor relevance for overall performance. Pathway 3 achieves the strongest and most consistent emission reductions by prioritizing an early integration of a water-source heat pump combined with CO_2-emission-oriented operational control. Although electricity demand increases, this is compatible with the assumed long-term decarbonization of the power sector and results in the lowest overall emissions.

Comparing the pathways demonstrates that similar end states can lead to significantly different emission trajectories depending on implementation order. This finding underlines the relevance of pathway-based assessments for CSRD-aligned reporting, where intermediate performance and cumulative emissions are increasingly important.

6. Conclusions

This work addressed the previously identified gaps in modelling the long-term sustainability performance of Industrial Heating Systems, specifically the lack of CSRD-aligned KPI forecasting, the absence of pathway-based transformation modelling, and the limited use of detailed simulation tools for industrial systems. To close these gaps, a simulation-based framework was developed that integrates a TRNSYS model of the heating and cooling networks with a Python-based pathway model for scenario sequencing and KPI evaluation.

The case study demonstrates three central findings aligned with these gaps.

- Pathway sequencing is critical: The order and timing of measures strongly affect primary energy use and cumulative CO_2 emissions, confirming that CSRD-compliant assessments cannot rely on static end-state scenarios.
- System adaptations are essential for heat pump integration: The results show that enabling measures such as supply temperature reductions are necessary to unlock the expected emission reductions, addressing the gap in understanding measure interdependencies.
- CSRD-relevant KPIs diverge significantly across pathways with similar end states: This highlights the need for dynamic, simulation-based multi-year assessments rather than extrapolation of current measured data, directly responding to the methodological gap identified at the outset.

Overall, the framework provides a structured method for evaluating industrial decarbonization pathways in a manner consistent with CSRD requirements and fills the methodological gaps related to long-term forecasting, measure interaction analysis, and transparent KPI derivation. Future work will extend the framework with optimization-based pathway generation and uncertainty treatment to further support least-regret and flexibility-oriented decision making.

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