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District heating in 100% renewable energy systems: Combining industrial excess heat and heat pumps

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ABSTRACT

The literature emphasizes the important role of industrial excess heat (IEH) and heat pumps (HP) in future 4th generation district heating and smart energy systems. However, they can potentially have negative or positive effects on the integration of renewable energy sources (RES). It is necessary to find a trade-off between IEH and HP in the transition towards a 100% renewable energy system yet has not been discussed in the literature. This paper presents a comprehensive techno-economic analysis for the optimal district heating (DH) strategy in a 100% renewable energy system. It is conducted based on a novel hybrid methodology framework that couples hourly smart energy system simulation, multi-objective optimization, and multiple-criteria decision making. The optimal share between IEH and HP and associated RES capacity can be determined considering the preferences of policymakers. A scenario for 2050 for Aalborg Municipality in Denmark is used as a case study. Results show that an appropriate mix of IEH and HP, 40% and 20% respectively in the DH supply, should be employed to obtain a balanced near carbon–neutral system with the least cost. Also, the cross-sector effective interactivities between the DH network, power grid, and gas grid are revealed in the smart energy system context. The proposed framework is designed in a general way that can be used in other cities, regions, or countries.

1. Introduction

1.1. Background

Heat is the largest energy end-use worldwide accounting for around half of the total energy consumption in 2018. About 46% of total heat was consumed in buildings for space and water [1]. The decarbonization of the heating sector is expected to play a key role in the transformation into future 100% renewable smart energy systems, which aim to provide more achievable and affordable solutions by utilizing the synergies across energy sub-sectors. In Europe, district heating (DH) can cost-effectively provide at least 50% of the heat demands in 2050 from the current level of 10% [2]. The development of 4th generation district heating (4GDH) is essential to the implementation of smart energy systems. Heating demands can be largely covered by DH from a variety of available low-temperature sources in 4GDH, for instance, excess heat from processes in industry and commercial buildings (e.g. supermarkets), heat pumps, power generation, waste incineration, geothermal, solar thermal, and conversion losses from the production of electrofuels [3].

This paper focuses on two critical technologies in 4GDH, i.e., industrial excess heat (IEH) and heat pumps (HP) [4,5]. IEH refers to the heat losses from industrial processes which can be in the form of exhausts, effluents, etc [6]. The part that can be recovered and utilized for multiple applications is considered to be IEH, while which cannot be recovered is considered waste [7]. About 3974 TWh of the primary energy supply in EU28 was lost in the transformation process in 2018, which takes up 30% of the final energy consumption [8]. Integrating IEH in the existing DH system is a potentially effective means to reusing these transformation losses. However, challenges exist in utilizing IEH, e.g. different occurrence forms, non-continuous availability, the need for heat transfer, and the lack of control by the heat demand, making it an under-utilized heat source in DH systems [6,9]. As for the large-scale HP, it is a power-to-heat technology that helps provide flexible electricity demands [10] and promotes integrating and balancing renewable power production [11–15]. Without affecting the overall system efficiency, the integration of large-scale HP in combined heat and power

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Nomenclature

3GDH	3rd generation district heating
4GDH	4th generation district heating
BAU	Business as usual scenario
CEEP	Critical excess electricity production
CHP	Combined heat and power
CO_2	Carbon dioxide
DH	District heating
HP	Heat pump
IEH	Industrial excess heat
MCDM	Multiple-criteria decision making
MOPSO	Multi-objective particle swarm optimization algorithm
MU	Mutation rate in MOPSO
POP	Population size in MOPSO
PSO	Particle swarm optimization
PV	Photovoltaic
REP	Repository size in MOPSO
RES	Renewable energy source
TOPSIS	Technique for order of preference by similarity to ideal solution
ω	Inertia weight in the velocity update equation of PSO
ϖ	Comprehensive weight in TOPSIS
ϖ^{sub}	Subjective weight in TOPSIS
ϖ^{obj}	Objective weight in TOPSIS
c_1	Personal confidence factor in
c_2	Global confidence factor in the
r_1	Uniformly distributed random numbers between 0 and 1
r_2	Uniformly distributed random numbers between 0 and 1

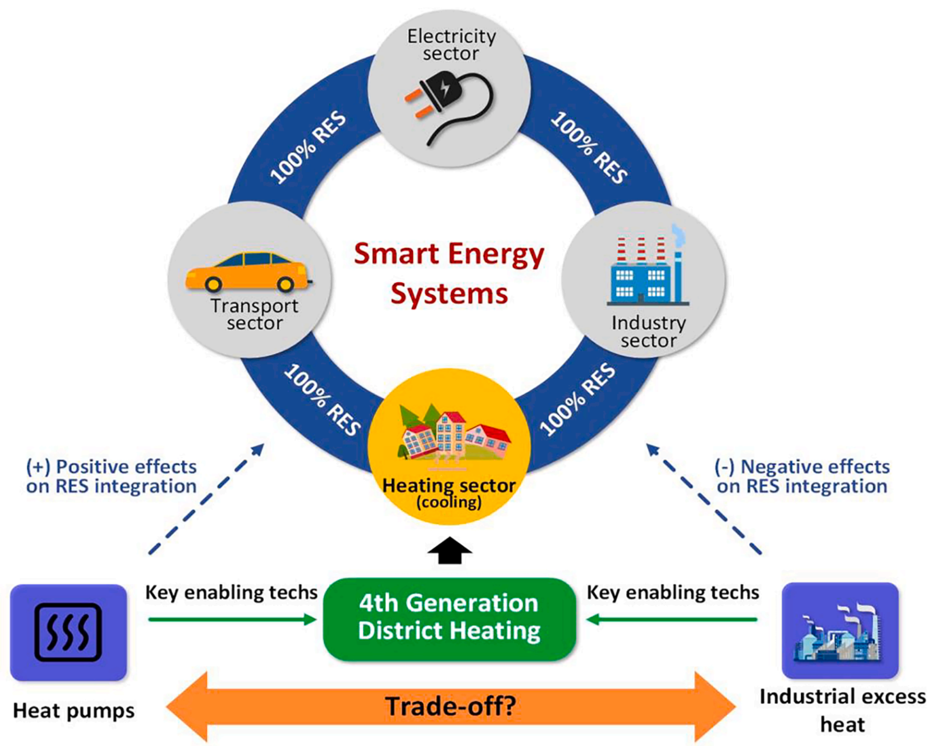

Fig. 1. Trade-off between heat pumps and industrial excess heat in the context of 100% renewable smart energy systems.

(CHP) plants can bring up to 40% integration of fluctuating renewable energy sources (RES) into the power supply [9].

Despite many desirable advantages of IEH and HP, there can be a dilemma when introducing IEH and HP into the DH system, as demonstrated in Fig. 1. On one hand, increasing the integration of IEH in the DH system may hinder the penetration of renewables on a greater scale and prevent the opportunity of creating a more flexible system, which potentially can be the benefit of installing HP. On the other hand, increasing HP installation may result in a more expensive system than the IEH-based energy system, in general, caused by higher initial investment. In light of these problems, determining the shares of these two technologies in the heat generation mix can be a complicated and difficult decision. It is necessary to conduct a detailed and thorough techno–economic analysis of a given energy system to reach a trade-off between HP and IEH, so as to help the policymakers devise a suitable future energy development plan towards carbon neutrality.

2. Research questions

This paper aims to reveal the trade-off problem between IEH and HP in the context of 100% renewable smart energy systems by providing the optimal district heating strategy. Specifically, this paper addresses the following three key questions:

(1) How to determine the optimal share of IEH and HP in a given DH system and associated RES capacity in the integrated energy system;
(2) What is the techno–economic impact on the integrated energy system caused by the integration of IEH and HP in the local DH system considering sector synergy;
(3) How can the preferences of the policymakers have an impact on the technical choices.

Based on a hybrid approach of simulation-based multi-objective optimization, we propose a comprehensive techno–economic analysis framework, which aims to quantify the consequences of combining different heating technologies on the cross-sector interactivity of the integrated smart energy system, including electricity, heating and cooling, transportation, and industry.

The 2050 Energy Vision for Aalborg Municipality in Denmark [16] is chosen as a case study to illustrate the proposed framework as it has the following characteristics: (1) the current DH network of Aalborg largely depends on industrial excess heat with a more than 20% share in 2018, mostly from the local cement plant Aalborg Portland; (2) the technical potential of excess heat from various sources has been investigated in detail in our previous research which is a good data foundation; and (3) Aalborg Municipality follows the long-term national goal of Denmark's switch to 100% renewable energy in 2050 [17], making this study important.

2.1. Related work

Here, we first review the existing studies on IEH and HP, then move into research on the DH system-level planning with a focus on the application of multi-objective optimization, and summarize the research adopt a simulation-based optimization approach for smart energy system-level planning. The corresponding research gaps are discussed in respective subsections.

2.1.1. Existing studies on IEH and HP in DH system

A variety of studies on respective IEH and HP and their application in the DH system have been found in the scientific literature. Research on IEH in the DH network mainly focus on the technical analysis of excess heat recovery [18,19], technical potential estimation for different regions and countries such as Switzerland [6], Denmark[20], Milano in Italy [21], and the benefits of the IEH integration in DH system from economic-environmental aspects [22,23]. As for research on large-scale HP, the hot points lay on the socioeconomic potential analysis [24], feasibility study on its integration in DH system [25], technical analysis [26], policy issues such as tax incentives [27], and planning scheme design of integrating HPs in existing DH systems of different geographic scale from region[13], country [28] to Heat Roadmap Europe [29].

Besides, a number of studies on 4GDH include IEH and HP as key elements in the system analysis. For instance, Sorknæs et al. [30] analyzed the effects of going to 4GDH from 3GDH for Aalborg, the IEH plays a key role. Abokersh et al. [4] investigated various flexible control strategies for the HP operation to support the transition towards 4GDH. Averfalk and Werner [31] estimated the economic benefits of lower distribution temperatures in 4GDH systems, in which the high-cost sensitivity for IEH and HP were identified.

To our best knowledge, there is no evidence and study has been found that explores the trade-off problem and the technology choices between IEH and HP in the DH system, and which however is the main gap filled by this paper. Detailed techno–economic analysis for a 100% renewable energy system is carried out in this paper to compare the role of HP and IEH in the DH system.

2.1.2. Multi-objective optimal planning of the DH system

The optimal planning of the DH system has been widely studied in the literature, which can be divided into simplified single-objective optimization problems (such as cost minimum) [32] and multi-objective optimization problems [33] according to the number of optimization objectives. This review focuses on the studies targeting multi-objective problem due to the complex characteristics of DH planning in a 100% renewable energy system.

The DH planning is constrained by various factors, to support the long-term regional sustainable development for the defined area, the decision-makers need to find environmentally friendly, technically feasible, institutionally sound, cost-effective, and socially acceptable solutions of the best mix of energy supply and demand options. A set of efficient (non-dominated) solutions named Pareto front[1] [34] will be generated in the multi-objective optimization, which represents the optimal configurations of the designed system.

The most common approaches for the multi-objective optimization of DH systems are mathematical programming theory and various intelligent algorithms. For instance, Dorotić et al. [35] developed an hourly-based linear programming model for district heating and cooling systems to minimize system cost and CO_2 emission. Arabkoohsar et al. [36] employed a rigorous multi-objective genetic algorithm for sizing the components of a DH system to address the summer-supply challenges and provided corresponding techno-economic analysis. Casisi et al. [37] carried out a two-level hierarchical multi-objective optimization for the design and operation of a DH system, in which the genetic algorithm and mixed-integer linear programming were adopted.

Despite the aforementioned multi-objective works are able to obtain the optimal planning within the scope of the DH system itself under technological limits, they do not take into account the potential greater benefits and system improvement brought by the synergies with other sectors in the context of the smart energy system. Also, the technical operation details of the energy system were commonly simplified in these models to a certain extent.

For the future 100% renewable energy systems studied in this paper, we incorporate the DH system in the smart energy system model, which consists of all sectors of energy systems including heat, electricity, industry, and transportation. A hybrid method of hourly system simulation-based multi-objective optimization is employed for the entire energy system, which addresses the limitations of the traditional pure optimization approach.

2.1.3. Simulation-based optimization of smart energy systems

Despite the simulation-based optimization approach is not common in the literature on DH system planning, which has been applied in some studies targeting future smart energy systems. One widely used simulation tool is EnergyPLAN [38–42], which is an advanced energy system simulation software for assisting the planning of the future 100% renewable smart energy system in different geographic scales. EnergyPLAN provides the hourly operation of a user-defined energy system across a year [43]. A detailed illustration of EnergyPLAN and its applications can be found in [44].

This paper adopts EnergyPLAN-based multi-objective optimization for energy system-level techno–economic analysis. Some previous studies also developed similar approach. Bjelić and Rajaković [45] established a soft-linking of EnergyPLAN with the generic optimization program to develop the optimal national energy master plan of Serbia, in which a single objective of minimum total system cost is adopted. Besides, there were also studies that adopted multi-objective optimization. For instance, Mahbub et al. [46] developed a model for designing future energy scenarios by combining a multi-objective evolutionary algorithm and EnergyPLAN. Similarly to this approach, Prina et al. developed two optimization models, EPLANopt [47] and EPLANoptTP [48], by coupling EnergyPLAN to the multi-objective NGSA-II algorithm, which was designed respectively for the optimal energy planning of a specific year and the transition pathways of the long-term energy planning.

The above research provides insight, but limitations still exist. On one hand, none of them considered the preferences of the policymakers. They commonly provide all solutions in the Pareto front, but it is overlooked that the acceptability and feasibility of each solution differ under various policy contexts. The selection of the optimal planning scheme should be customized to the system characteristics. To fill this

[1] The non-dominated solution presents solutions that are not dominated by any other solution. None of the solutions in the Pareto front can bring a single optimal result in all objectives, i.e., no objective can be improved without sacrificing at least one other objective.

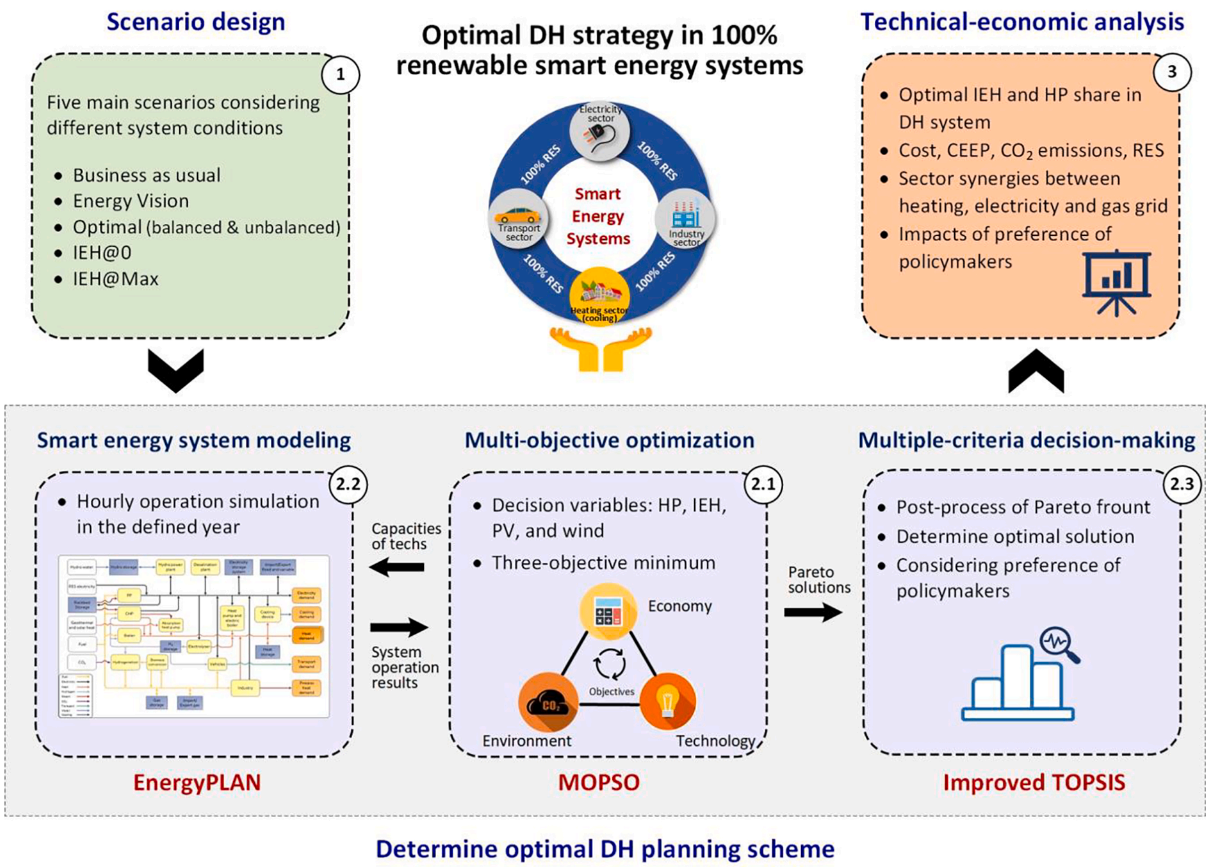

Fig. 2. Framework of methodology.

gap, this paper conducts post-processing for the Pareto front by carrying out the prioritization and filtering operations, which is able to determine the order of preference of all solutions. Preferable solutions will be recommended in this paper according to the requirements of the policymaker of the studied energy system.

On the other hand, despite the optimization objectives of economic and environment were fully studied in the aforementioned models, the technical objective that reflects the balance of the electricity system was not directly considered, which however is important in this study. In the 100% renewable energy system, the high penetration of intermittent RES will increase the need for balancing the electricity system [49]. The choice of optimization criteria has a significant impact on the result of the energy system design [50]. To achieve a more practical planning scheme, this paper adopts a critical indicator of electricity system balance, i.e., critical excess electricity production (CEEP), together with cost and CO_2 emissions as the optimization objectives.

2.2. Research contributions

This paper proposes a novel methodology framework for optimal heating strategy planning based on the trade-off between economy, environment, and technology in the context of the 100% renewable smart energy systems. Developed in a hybrid way, the framework couples the simulation of the smart energy system, the multi-objective optimization for the heating technology choices, and the multiple-criteria decision making (MCDM) for the post-processing of the Pareto front. This is realized by employing the EnergyPLAN software [51], multi-objective particle swarm optimization algorithm (MOPSO) [52], and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [53], respectively. By implementing the proposed method, the optimal heat generation structure in the DH system with a focus on the share of IEH and HP as well as the optimal RES installation configuration can be determined.

This paper contributes to the literature in the following four aspects:

(1) Detailed techno–economic comparison analysis between HP and IEH is carried out in the context of 100% renewable energy systems for the first time through a real case study;
(2) A novel hybrid methodology framework is proposed for the optimal DH system planning in the context of smart energy systems, which coupling simulation, optimization and MCDM;
(3) The preference of policymakers is taken into account so as to provide more adaptable development plans for DH system;
(4) The advantages of sector synergy are revealed in the results through the interactivities of the power grid, DH network, and gas grid.

3. Methodology

3.1. Framework of methodology

To identify the optimal DH strategy in the context of 100% renewable energy system, a framework of methodology is proposed in this paper, as shown in Fig. 2. It is comprised of three parts, including (1) scenario design; (2) determination of the optimal DH planning scheme; and (3) the techno–economic analysis. The following sections describe each part in detail.

Different DH planning schemes will be optimized respectively for different scenarios, and comprehensive techno–economic analysis will be made based on the results obtained. The second part of the framework is consisting of three sub-steps (purple boxes in Fig. 2), i.e., smart energy system modeling based on EnergyPLAN, multi-objective

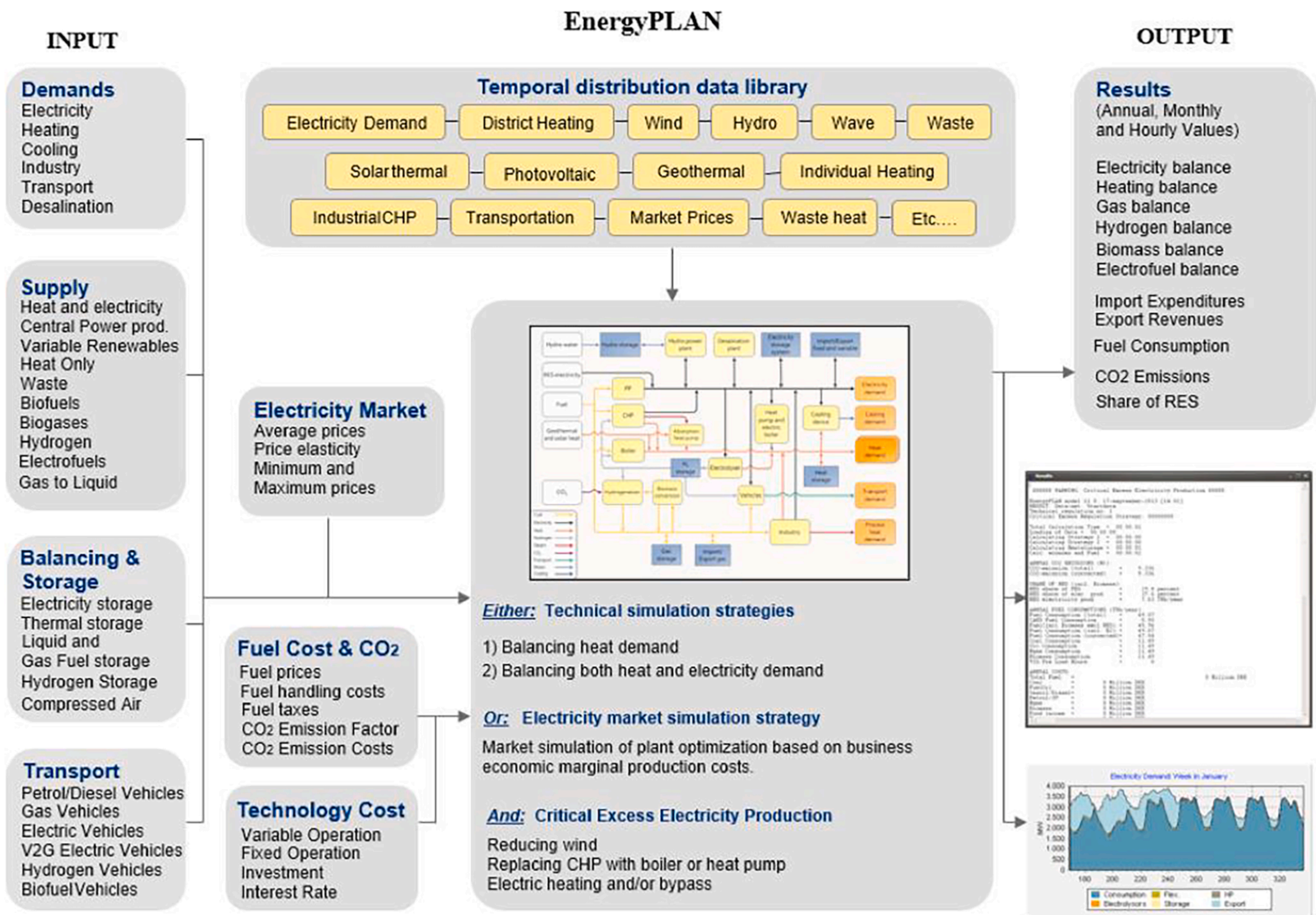

Fig. 3. Overview of EnergyPLAN software [44].

optimization based on MOPSO, and MCDM based on TOPSIS. The optimization calculation starts with MOPSO and ends with TOPSIS. A coupling relationship exists between EnergyPLAN and MOPSO. In each iteration of MOPSO, a set of decision variables is generated and serves as inputs to EnergyPLAN. The latter will execute an hour-by-hour energy system simulation for a whole year and then output the results of objectives and pass them to the MOPSO again for further update of the next iteration. After the optimization calculation is complete, a set of Pareto solutions will be output and transferred to the TOPSIS for further filtering and ranking so as to obtain the optimal planning scheme considering the preference of the policymakers.

3.2. *Smart energy system modeling based on EnergyPLAN*

3.2.1. *EnergyPLAN*

EnergyPLAN is an advanced energy system analysis computer software based on analytical programming, which simulates the yearly operation of energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. One of the key objectives with the EnergyPLAN tool is to aid in the design of 100% renewable energy systems where synergies across all energy sectors are utilized to the largest extent.

EnergyPLAN is based on a series of endogenous pre-defined procedures for simulating the operation of units. The underlying computational approach can be found in [44]. Fig. 3 shows an overview of EnergyPLAN software, which is designed with a graphical user interface. The users can input a number of deterministic parameters (including energy demands, technical parameters of the energy supply facilities, and costs) and select the different regulation strategies emphasizing electricity production. The outputs are the resulting detailed hourly and annual energy balance, fuel consumptions, CO_2 emissions, import/export of electricity, and total costs, which can be used to analyze the energy, environmental, and economic impact of various energy strategies.

EnergyPLAN features a very fast calculation speed (few seconds) which makes it feasible to execute an external call and couples EnergyPLAN computing with an optimization algorithm. This paper adopts the EnergyPLAN MATLAB toolbox version 1.2e to perform the external call which is designed to call and manage EnergyPLAN from MATLAB. The toolbox can be downloaded from Ref. [54] and detailed instructions of the toolbox can be found in Ref. [55].

3.2.2. *Studied energy system and reference scenario*

The 2050 energy system of Aalborg Municipality in Denmark is modeled in EnergyPLAN and taken as a case study. This section provides an overview of the studied energy system and the reference scenario. The detailed descriptions of the reference energy system and the variant scenarios are provided in Section 3.

The studied energy system is based on the research of “Smart Energy Aalborg” [16], which was conducted by the Energy Planning Research Group at Aalborg University at the request of the city council of Aalborg Municipality and the local municipality-owned utilities and authorities. The intent was to design a 100% renewable energy system for Aalborg Municipality. The design of the scenarios took its starting point in the current energy system of Aalborg Municipality in 2018 and through a number of steps and simulations in the tool EnergyPLAN it was possible to lower CO_2 emissions and reach 100% renewable energy in 2050 [38].

For the year 2050, the business as usual (BAU) scenario and the Energy Vision scenario in the Smart Energy Aalborg study were selected as the reference scenarios. The BAU scenario assumes that the energy

Table 1
Constraints for decision variables and objectives.

Items		Lower bound	Upper bound	Unit
Decision variables	Onshore wind capacity	95	1000	MW
	PV capacity	25	1000	MW
	HP capacity	0	300	MW
	IEH quantity	0	1023	GWh
Objectives	CO_2 emission	–	0.1	Mton
	CEEP	–	0.47	TWh

Table 2
Scenarios employed in this paper.

No.	Scenarios		Definition
1	Business as usual (BAU)		Maintain the status quo of the energy system of 2018 in the year 2050.
2	Energy Vision		The 100% renewable energy system defined in Smart Energy Aalborg project.
3	Optimal	3–1 balanced	The optimal 100% renewable energy system was obtained by using the proposed methodology, which has two sub-scenarios. The balanced has a CEEP less than 0.1TWh, while the unbalanced has a CEEP greater than 0.1TWh. The balanced optimal scenario is set as the main scenario in the subsequent analysis.
		3–2 unbalanced	
4	IEH@0		The 100% renewable energy system that doesn't utilize IEH in the DH system. The HP and RES capacity are determined by using the proposed methodology.
5	IEH@Max		In contrast to the IEH@0 scenario, the 100% renewable energy system with utilizing the maximum technical potential of IEH in the DH system.

system in 2050 will be the same as in 2018, however with increased energy demands and a larger district heating area. The Energy Vision scenario is designed for a 100% RES-based system in 2050, in which the energy consumption towards the year 2050 is characterized by massive electricity and heat savings as well as fuel savings in the industry compared to 2018. Based on three sub-scenarios of the Energy Vision described in [16], the balanced main scenario was chosen for analysis in this paper, i.e., the option of increased hydrogen production, which utilizes more electrolysers to generate gas for the single-cycle gas turbine to balance the excess electricity production.

3.3. Multi-objective optimization based on MOPSO

The particle swarm optimization (PSO) is a nature-inspired single-objective optimization algorithm proposed in 1995, which has been widely applied in various fields for its good performances in robustness and global astringency [56,57]. MOPSO is a multi-objective optimization version developed by Coello et al. in 2004, which allows the original algorithm to handle problems with several objective functions [52]. The algorithm flowchart and corresponding parameter setting of MOPSO employed in this paper are provided in Appendix A and B, respectively. The Pareto front will be outputted after the optimization calculation, which accomplishes an acceptable trade-off between conflicting objectives [34].

For achieving the optimal DH planning, MOPSO is adopted to optimize the technology choice in the DH system and the RES installation by finding a trade-off between three objectives, i.e., economy, environment, and technology. To be clear, the studied three-objective optimization problem can be described as Eq. (4). It aims to minimize the total annual cost, CO_2 emission, and CEEP. x_i is the i-th decision variable. To explore the quantitative impacts of the amount of IEH and HP on the interactivity with the intermittent RES and the rest of the components in the integrated energy system, four decision variables are selected, i.e., $x =$ [onshore wind capacity, PV capacity, HP capacity, IEH quantity]. L_i and U_i are the lower bound and upper bound of the i-th decision variable. The offshore wind capacity is assumed the same as the energy vision scenario as Aalborg is an inland city lacking offshore wind.

$$\text{Objective function } \min_{x} \begin{bmatrix} Cost \\ CO_2 \\ CEEP \end{bmatrix} \quad (1)$$

$$\text{Subject to } L_i \leqslant x_i \leqslant U_i$$

Table 1 shows the lower and upper bound of the decision variables and objectives of the Aalborg case. The lower bounds for RES capacity are assumed the same as the BAU scenario at the 2018 level. The quantity of IEH should not exceed the maximum technical potential. To obtain acceptable and practical results, the approach of penalty functions is adopted in the calculation to avoid the objectives exceed the bounds. To reach a near carbon–neutral system, the environmental objective of annual CO_2 emission is limited to not exceed 0.1 Mton. Also, it is expected that the CEEP should at least be better than that in the BAU scenario, so which is set as the upper bound of CEEP.

3.4. Multiple-criteria decision-making based on TOPSIS

3.4.1. Improved TOPSIS technique

TOPSIS is a practical MCDC method for ranking and selecting a number of possible alternatives. It is based on the concept that the chosen alternative should feature the shortest Euclidean distance from the positive ideal solution and the longest Euclidean distance from the negative ideal solution [58]. The TOPSIS method is adopted in this paper to evaluate the Pareto optimal solutions according to the preference of the policymakers so as to provide adapted and practical DH planning schemes.

A typical TOPSIS consists of four sections, including data generation, data normalization, weight determination, and best alternative selection. To appropriately reflect the preference of the policymaker, an improved TOPSIS technique with an entropy weighted method is adopted in this paper, [59]. The corresponding calculation process is depicted in the right box of Fig. A1.

The weights reflect the importance of all indexes which is directly related to the accuracy of the evaluation results [60]. A comprehensive weight ϖ is employed in this paper, as shown in Eq. (2), which incorporates both subjective weight ϖ^{sub} and objective weight ϖ^{obj} and thus can encompass reasonable allocation of weights. The objective weight is determined by the entropy method by following Ref. [61]. The subjective weight here is used to take the preference of the policymaker into the decision process.

$$\varpi = \varpi_j^{sub}\varpi_j^{obj} / \sum_{j=1}^{n} \varpi_j^{sub}\varpi_j^{obj} \quad (2)$$

3.4.2. Post-evaluation on the Pareto solutions

The resulting Pareto optimal solutions of the three objectives obtained by MOPSO are used to construct the performance matrix in the TOPSIS analysis. The Pareto solution with a CEEP no greater than 0.1 TWh is regarded as the balanced solution in the electricity system, and any higher as the unbalanced solution. In practice, a relatively balanced electricity system is normally preferable to avoid bottlenecks.

Table 3
Summary of industrial excess heat sources in Aalborg Municipality [30].

No.	Industry types	Sources[a]	Heat types	Potential [GWh]	Annualized costs [MEUR]	Accumulated potential [GWh]	Accumulated costs [MEUR]
1	Aalborg Portland	Output from existing units	Direct	466	0.3	466	0.3
2	Aalborg Portland	Optimization of existing units	Direct	108	0.73	574	1.03
3	Aalborg Portland	Heat recovery from grey cement kiln	Direct	97	0.73	671	1.76
4	Other industries	Arla Foods	HP	12	0.11	683	1.87
5	Supermarket	Supermarket	Direct	12	0.12	695	1.99
6	Other industries	Industries at the commercial harbors	HP	3	0.03	698	2.02
7	Other industries	Other industries	HP	21	0.22	719	2.24
8	Other industries	Wastewater treatment plants	HP	98	1.17	817	3.41
9	Aalborg Portland	HP reducing return temperature to existing units	HP	34	0.48	851	3.89
10	Aalborg Portland	Collecting radiant heat from the white cement kiln with heat shields	Direct	160	2.32	1011	6.21
11	Aalborg Portland	Exploiting heat from filtrate water using HP	HP	12	0.37	1023	6.58

[a] In the Energy Vision scenario, only the first nine sources were used in the DH system, while the last two sources were not included. Because there are considerable uncertainties associated with source No. 10, both in terms of investment cost and the technical consequences for cement production at Aalborg Portland. Further, the marginal cost of source No. 11 is too high to be economically feasible.

In the main evaluation process, we assume that the policymakers have equal preference for the three objectives of cost, CO_2 emissions and CEEP, and the subjective weights of them are set as equal, i.e., [1,1,1]. Then, the first ranked solution is chosen as the optimal DH planning scheme. Considering different policymakers may have different preferences, the subjective weights can be changed depending on the situations of the different energy systems.

3.5. Scenarios and sensitivity analysis

For a comprehensive analysis, three scenarios are designed to compare with the reference scenarios (BAU and Energy Vision), as listed in Table 2. The economic and technical aspects of these scenarios will be investigated in terms of total annual costs, CEEP, CO_2 emissions, RES share, structure of electricity and heat supply, and so on.

In addition, two sensitivity analyses are carried out. The first aims to investigate the impact of the preference of policymakers on the technology choice and the design of energy systems. This is been conducted by applying different subjective weights in the TOPSIS technique to change the influences of the three objectives of cost, CO_2 and CEEP. As mentioned earlier, the three objectives are set equally important in the main evaluation process, i.e., [1,1,1]. Here in the sensitivity analyses, we decrease the weight of any one of the three objectives at one time, i.e., [1,2,2,2,1,2], and [2,2,1], respectively.

The second sensitivity analysis aims to investigate the cross-sector interactions between the gas grid, power grid, and DH network, which is studied by applying different gas prices in EnergyPLAN. The gas price will have a direct impact on the production of power-to-gas technologies which further have an indirect impact on the RES penetration and the electricity market. Four levels of gas prices are adopted: (1) unchanged price, which is the normal price used in the Energy Vison scenario; (2) zero gas price, which is an extreme case assuming the gas price is zero; (3) 50% lower than normal; (4) 50% higher than normal.

4. Descriptions of the energy sysetem

Since the entire BAU and Energy Vision scenarios, including the detailed modeling process, the corresponding principals, and the technical and economic data, are clearly illustrated in our previous research Ref. [38] and [16], this section only provides the overall description of the energy system in the Energy Vision scenario with a focus on the heating sector. Some key data are attached in Appendix C.

4.1. Overview of the Aalborg energy system

Aalborg's 100% renewable energy system in the 2050 Energy Vision scenario is based on onshore and offshore wind, solar energy, biomass, waste, and excess heat from both industries and electrolysers. The detailed energy demand for electricity, heating, transport, and industry sectors is provided in Table C1. The detailed capacities and corresponding costs of energy supply technologies are listed in Table C2. And the normalized hourly distributions of the annual electricity and heating demand of Aalborg Municipality are shown in Fig. C1. A Sankey diagram of the Energy Vison scenario is shown in Fig. C2, which shows the yearly input of primary energy and how it is utilized in various conversion technologies to supply the energy demands [38].

4.2. District heating system

In 2050, Aalborg Municipality will be upgraded from the current 3GDH to 4GDH technology. The annual DH demand reaches 1.56 TWh, which is estimated on the basis of a detailed building level heat atlas developed by Aalborg University [62].

The central DH network is primarily supplied with IEH (0.85TWh), with the cement plant Aalborg Portland accounting for a significant share and the rest of the IEH comes from other industries and supermarkets [63]. The remaining part of the central DH is produced by central CHP plants, waste incineration CHP, industrial CHP, compression HPs, excess heat from electrolysers and for a smaller part solar thermal and peak load boilers. A 40 GWh seasonal thermal storage is also installed. Here, the central CHP unit can operate in back pressure mode, producing both electricity and heat, and in condensing mode, producing only electricity. The waste incineration CHP and industrial CHP are fixed operation units, that throughout the year produce the same amount of heat and electricity. The industrial CHP is mainly used for its own consumption, but some electricity is delivered to the grid. In the decentral DH systems, small gas CHP plants, boilers, solar thermal, and HPs are employed.

The heat pumps in the district heating system can operate flexibly with partial loads. Based on the more or less constant temperature of the

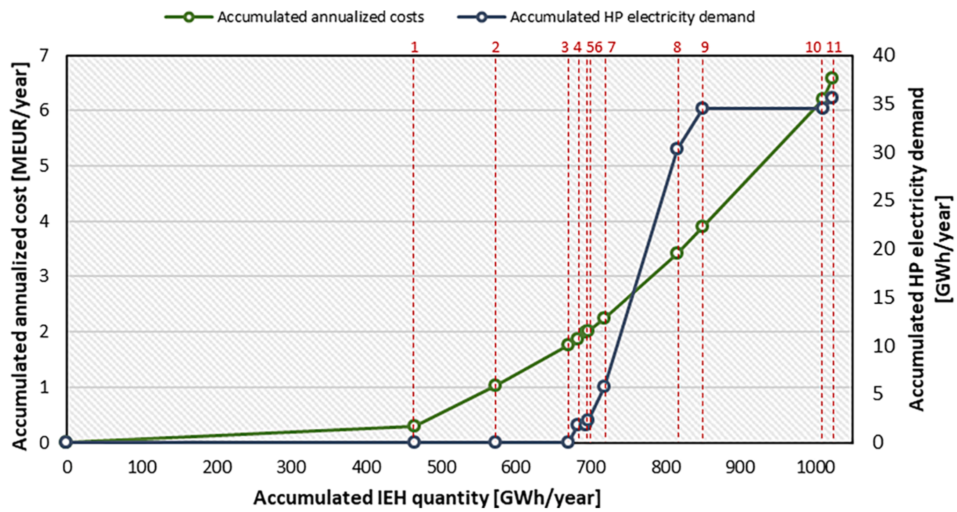

Fig. 4. The relationship between the accumulated IEH quantity and the accumulated annualized costs and the accumulated additional electricity demands from HP.

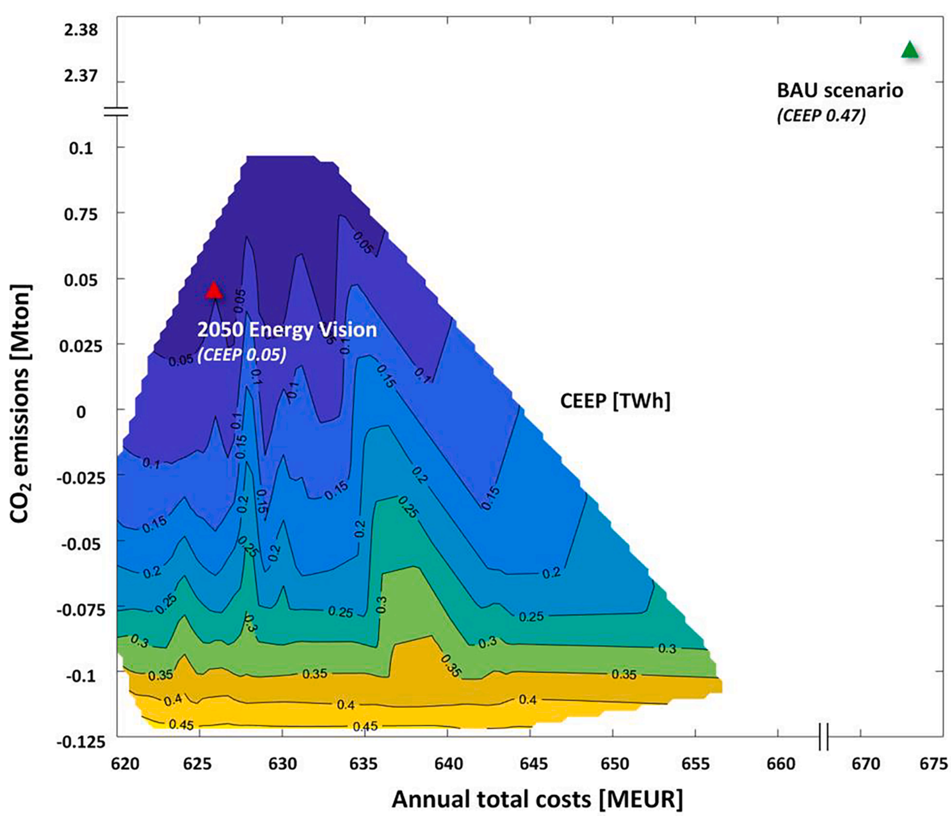

Fig. 5. Pareto front of the three-objective optimization.

seawater, geothermal source and the district heating network, the average COP of 3.9 is assumed to be reasonably constant over the year. The assumption is a district heating network is at the requirement of 4GDH temperature levels, i.e., 55 °C for the forward temperature and 25 °C for the return temperature [30]. The evaporator operates at a temperature of 5 °C.

4.3. Technical potential of excess heat

Identifying by local stakeholders, there is a total of 11 potential IEH sources available in Aalborg, which are from Aalborg Portland, other industries, and the refrigeration systems of local supermarkets. The detailed information of each heat source has been described in our previous study Ref. [30].

Table 3 summarizes the technical potential, types and the annualized costs of the IEH sources, which are sorted by the marginal costs from low to high. These IEH sources can be utilized in the DH system either directly or indirectly through HPs at the requirement of 4GDH temperature levels, i.e., 55 ~ 65 °C for the forward temperature and 25 °C for the return temperature. The annualized costs include the yearly investment cost and the O&M cost, but the purchase of electricity for operating the HPs is excluded. The technical specifics (temperature, capacity and COP) of indirectly utilized IEH through HPs are provided in Table C3. Constant yearly COPs for HPs utilizing excess heat are still

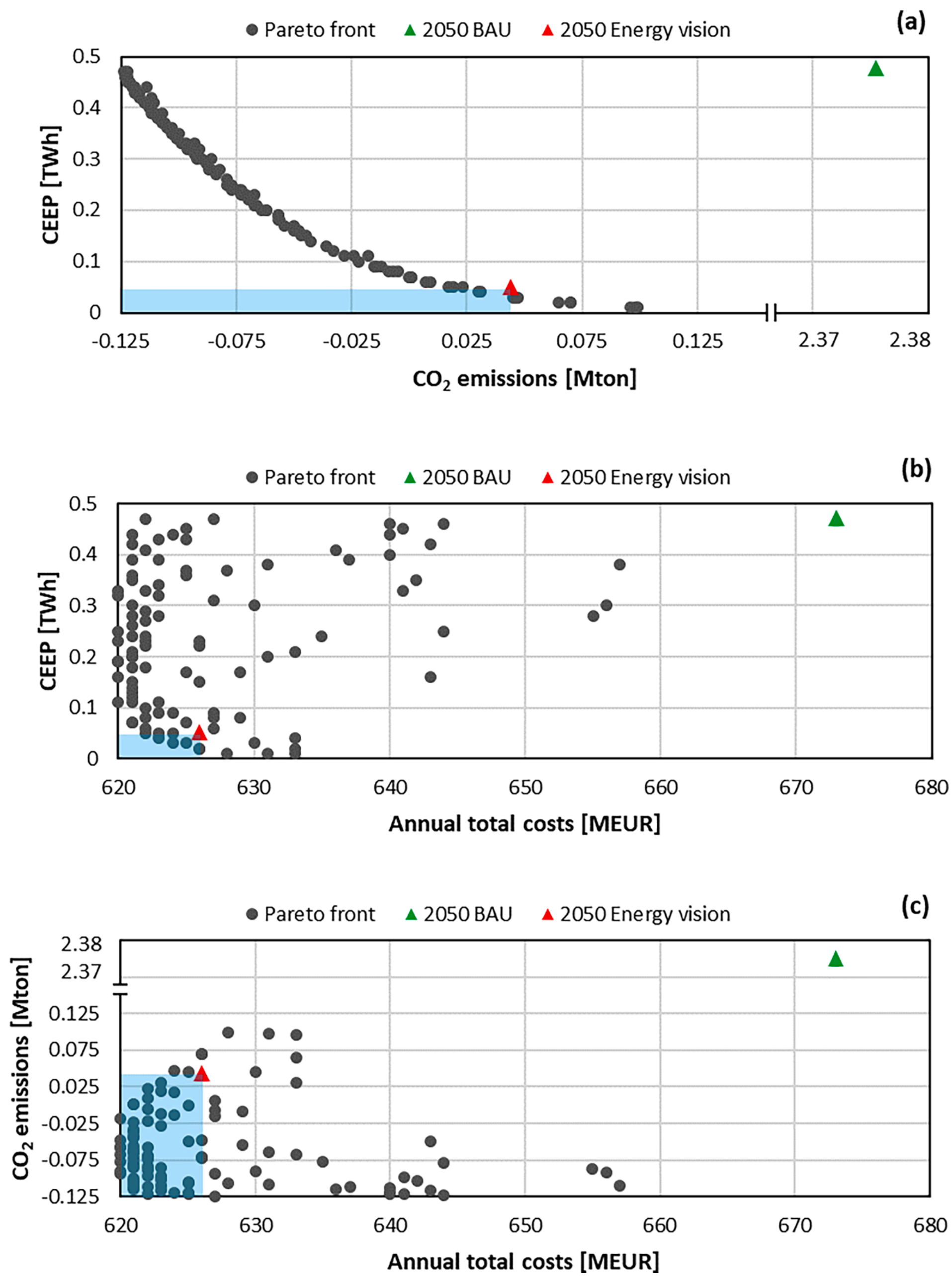

Fig. 6. Pareto front of the three-objective optimization in two-dimensional form (blue area: solutions outperform 2050 Energy Vision in corresponding two objectives).

used, because it is assumed that an unchanged relationship between the temperature of the excess heat sources and the district heating forward temperature throughout the year. The lifetime of each investment is assumed to be 20 years for all options.

The quantity of IEH is one of the important decision variables in MOPSO. To identify the quantitative relationship between the quantity of IEH and the corresponding cost and additional electricity demand (only for the indirect sources using HPs) in the process of optimization calculation, a piecewise curve fitting is employed for the accumulated IEH quantity of the 11 heat sources and the other two corresponding accumulated parameters, which is shown in Fig. 4. The red dashed lines mark the numbers of IEH sources. Each dot on the curves denotes the accumulated costs and the additional electricity demands of the IEH sources. In MOPSO calculation, we assume that IEH can be obtained on the piecewise continuous function. The quantity of IEH will be generated randomly and within the limitations (on the lines of Fig. 4) in the initialization phase of the optimization, and the Pareto solutions will be determined after a series of iterations.

5. Results and discussion

5.1. Results of the optimal district heating planning

This section provides the results of the optimal DH planning in different scenarios obtained based on the proposed methodology framework.

5.1.1. Results of the Pareto front

Fig. 5. visualizes the Pareto front of the proposed three-objective optimization problem in the way of a shaded contour plot. The x-axis represents the total annual costs, the y-axis represents the CO_2 emissions, and the lines indicate the CEEP. Fig. 6 provides the results of any

Table 4
Results of the planning scheme of the Aalborg energy system in different scenarios.

Scenarios	Objective functions			Decision variables			
	Cost [MEUR]	CO_2 [Mton]	CEEP [TWh]	Wind [MW]	PV [MW]	HP [MW]	IEH [GWh]
BAU	673	2.374	0.47	95	25	0	340
Energy Vision	626	0.044	0.05	285	458	26	850
IEH@0	628	0.001	0.09	409	404	56	0
IEH@Max	624	0	0.07	382	349	24	1023
Optimal (Balanced)	621	0.001	0.07	375	374	32	665
Optimal (Unbalanced)	620	−0.077	0.25	495	470	35	712

Table 5
Results of single-objective optimal cases.

Cases	Note	Value of objective functions			Value of decision variables			
		Cost [MEUR]	CO_2 [Mton]	CEEP [TWh]	Wind [MW]	PV [MW]	HP [MW]	IEH [GWh]
Minimum cost	Ignore CO_2 and CEEP	620	-0.018	0.11	418	395	25	575
Minimum CO_2	Ignore cost and CEEP	627	-0.124	0.47	600	545	51	913
Minimum CEEP	Ignore cost and CO_2	628	0.099	0.01	292	221	25	653

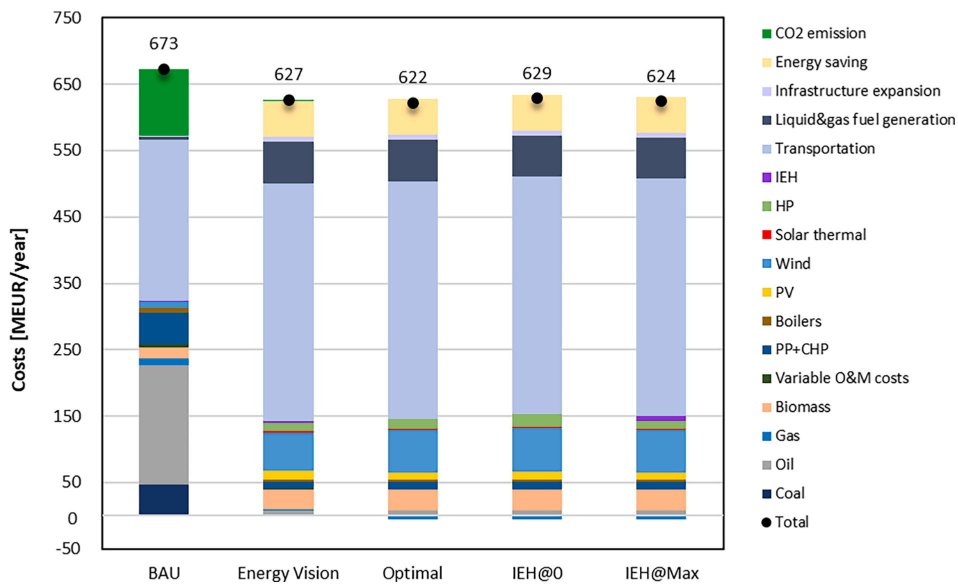

Fig. 7. Cost division of different scenarios.

two of the three objectives of the Pareto front, where the black dots represent the 100 Pareto solutions.

It is found that all solutions in the Pareto front calculated by MOPSO are outperformed the BAU scenario in all three objectives. The relationship between annual total costs, CO_2 emissions and CEEP can be seen clearly. CEEP and CO_2 emissions have a strong correlation that higher CEEP tends to have lower CO_2 emissions because of more wind and PV installation. Such conflict indicates the necessity of multi-objective optimization. The costs and the other two objectives do not show apparent correlation as different system configurations lead to different results.

In Fig. 6 (a), only few dots fall into the blue area where is the advantage area of Pareto solutions compared to Energy Vision, which indicates that the Energy Vision scenario already has a good balance in CEEP and CO_2. However, a number of solutions with lower CEEP and costs or lower CO_2 and costs can be found in the blue area in Fig. 6 (b) and (c) respectively, which represents the room for system improvement and better configurations for the Aalborg energy system are underneath these solutions. The identified optimal energy system will be present and discussed in next section.

5.1.2. *Results of the optimal energy system*

Table 4 provides the specifics of the Aalborg 100% renewable energy system in different scenarios. The inputs and outputs of the BAU and Energy Vision scenarios are from the previously established EnergyPLAN model [16], while the results of the other scenarios are obtained by using the proposed methodology. As seen in scenario IEH@0, more HPs need to be installed in the DH system if no IEH can be used, while at the same time more variable RES will be integrated to meet the increased electricity demand from HPs. In the opposite scenario, IEH@Max, the HP capacity and RES capacity decline due to access to more excess heat. The cost decreases as well due to less investment.

The balanced and unbalanced results of the Optimal scenario are both provided. Even though the unbalanced result has lower cost and CO_2 emissions than the balanced scheme, the differences are quite small and the CEEP of 0.25 TWh is greater, which has to be exported or curtailed. The balanced optimal result is used for further analysis from a practical perspective. A near carbon–neutral system can be reached in the balanced optimal scenario together with a 7.7% lower total annual cost and an 85.7% CEEP curtailment compared to the BAU scenario. The balanced optimal result places the use of IEH at 665 GWh, which is in between the quantity of the BAU scenario (340 GWh) and the Energy Vision scenario (850 GWh).

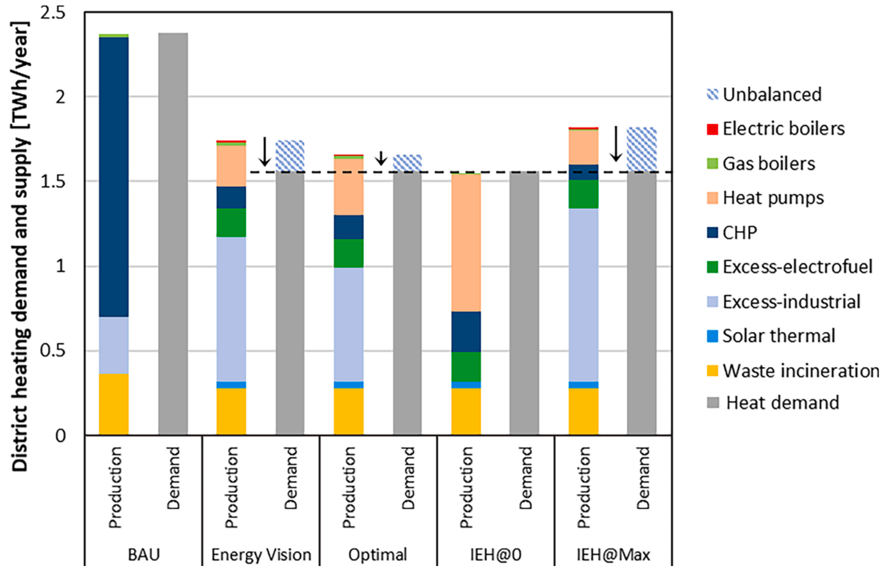

Fig. 8. Structure of district heating of different scenarios.

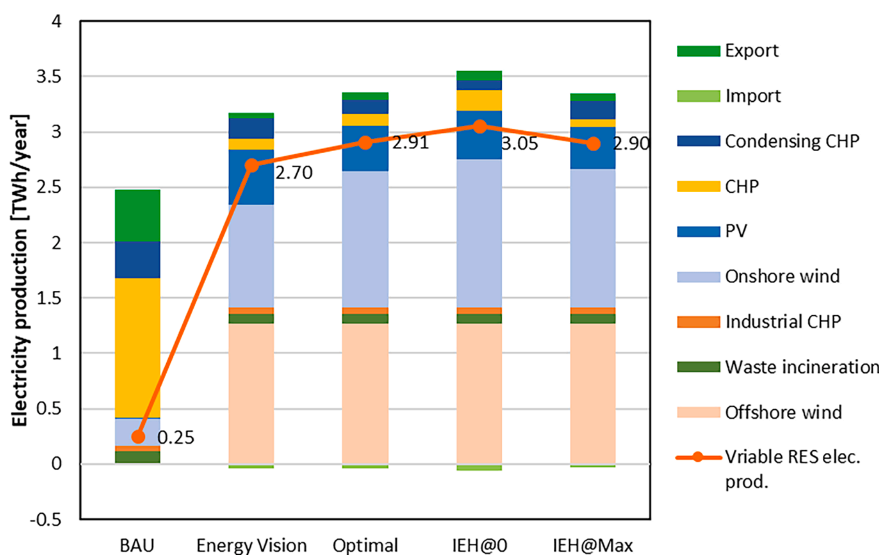

Fig. 9. Structure of electricity production of different scenarios.

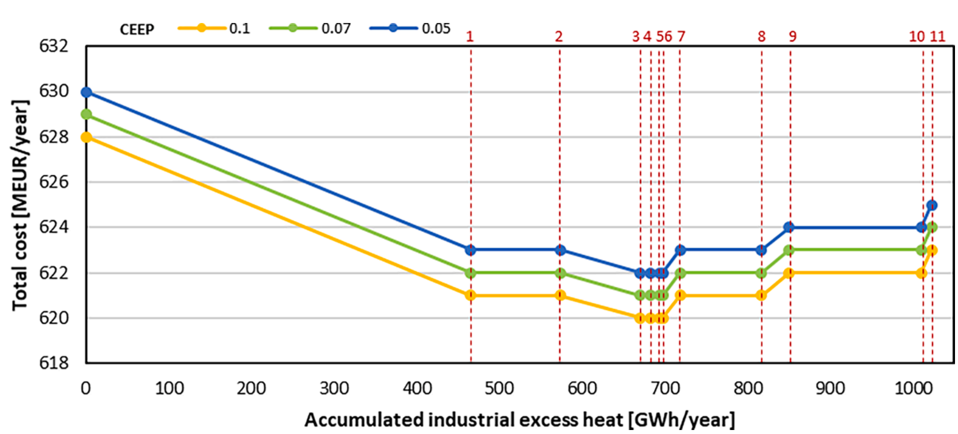

Fig. 10. The total costs of the energy system with different cumulative industrial excess heat.

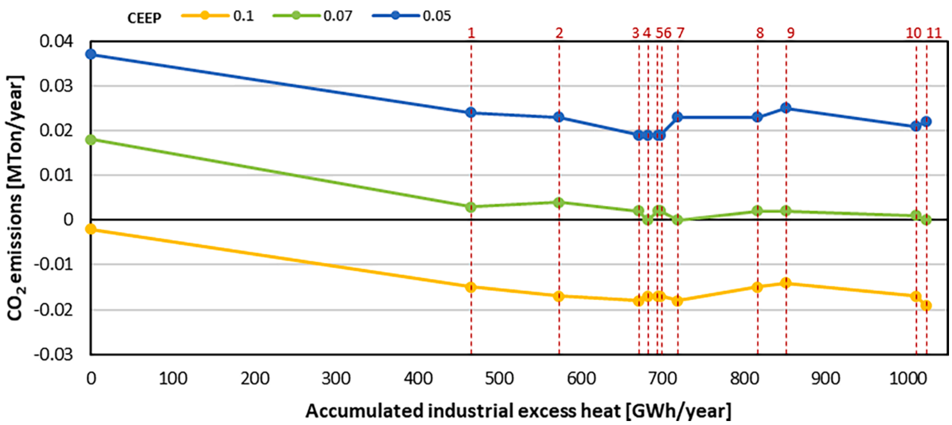

Fig. 11. The CO_2 emission of the energy system with different cumulative industrial excess heat.

Table 6
Specifics of the energy system with different industrial excess heat sources (CEEP = 0.07 TWh).

Note	Cumulative IEH [GWh]	Value of objective functions		Value of decision variables		
		Cost [MEUR]	CO_2 [Mton]	Wind [MW]	PV [MW]	HP [MW]
0	0	629	0.018	427	269	59
1	466	622	0.003	417	274	38
2	573	622	0.004	403	302	32
3	671	621	0.002	404	295	29
4	683	621	0	385	349	30
5	694	621	0.002	408	296	24
6	698	621	0.002	405	292	27
7	719	622	0	393	321	34
8	817	622	0.002	390	339	25
9	851	623	0.002	394	317	28
10	1010	623	0.001	397	313	18
11	1023	624	0	382		24

In addition, the results of single-objective optimal cases are presented in Table 5. It is found that the planning results may be unrealistic when only perusing one objective in the process of energy system planning. The minimum annual cost, CO_2 emission, and CEEP to obtain is 620 MEUR, −0.124 Mton, and 0.01 TWh, respectively. When comparing the results of the single-objective and the three-objective system, the three-objective optimization is more acceptable for reaching a compromise among all objectives, which owns the features of more comprehensive consideration in the techno-economic aspects.

5.2. Techno–economic analysis of different scenarios

5.2.1. Impacts on total annual cost

Fig. 7 provides a detailed cost division of the proposed scenarios. The Optimal scenario has a minimum total annual cost of 622 MEUR, which is 7.58% and 0.8% less than the BAU and Energy Vision scenarios, respectively. The transportation takes up the largest part, which represents the annualized costs for vehicles, charging stations and other infrastructures for road & rail. This is followed by the variable RES, liquid and gas fuel generation (biogas and gasification plants, electrolyser and hydrogen storage, and electrofuel generation), and energy savings (heat, electricity, and fuel savings in individual heating and DH system, households, and industry). When excluding the transportation sector, the cost decrease of the Optimal scenario will be 38.72% and 1.85% compared to the BAU and Energy Vision scenarios, respectively.

For scenarios other than the BAU, the change of costs only occur on the annualized costs (annual investment and fixed O&M) of PV, wind, HP and IEH, and the variable costs including coal, oil, gas, CO_2 emissions and variable O&M. The other costs of the Optimal, IEH@0, and IEH@-Max scenarios are the same as the Energy Vision scenario. Note that the cost of electricity exchange is not included to stay consistent with the

Table 7
Optimization results of balanced gas test.

Cases	Note	Value of objective functions			Value of decision variables			
		Cost [MEUR]	CO_2 [Mton]	CEEP [TWh]	Wind [MW]	PV [MW]	HP [MW]	IEH [GWh]
Balanced gas	Net gas ≤ ±0.01	623	0.04	0.04	349	308	22	648

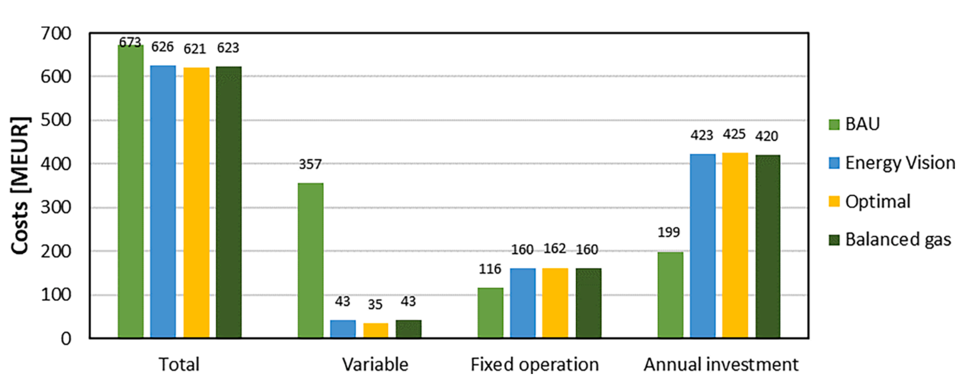

Fig. 12. Detailed cost comparison between different scenarios.

Table 8
Results of three objectives under different gas prices.

Gas price	Notes	Costs [MEUR] Variable	Fixed operation	Investment	Total	CO_2 [Mton]	CEEP [TWh]
0	Extreme	41	162	425	628	0	0.07
↓50%	Low price	38	162	425	624	0.002	0.07
Unchanged	Normal	35	162	425	621	0.001	0.07
↑50%	High price	32	162	425	618	0.001	0.07

Table 9
Specifics of the Aalborg energy system under different gas prices.

Gas price	Notes	Wind [MW]	PV [MW]	HP [MW]	IEH [GWh]	Net gas export [TWh]	RES power generation [TWh]	RES share of electricity production [%]
0	Extreme	393	310	34	716	0.2	2.98	93.6
↓50%	Low price	393	313	32	684	0.2	2.99	93.8
Unchanged	Normal	375	374	32	665	0.21	3	93.8
↑50%	High price	382	357	32	644	0.21	3	94

Table 10
The sensitivity analyses results on different setting of the subjective weights.

Cases	Subjective weights	Note	Value of objective functions Cost [MEUR]	CO_2 [Mton]	CEEP [TWh]	Value of decision variables Wind [MW]	PV [MW]	HP [MW]	IEH [GWh]
Balanced	[111]	Equal subjective weights for three objectives	621	0.001	0.07	375	374	32	665
	[122]	Lower subjective weight for cost	622	0.009	0.06	407	245	33	672
	[212]	Lower subjective weight for CO_2 emissions	622	0.023	0.05	404	210	29	621
	[221]	Lower subjective weight for CEEP	621	0.001	0.07	375	374	32	665
Unbalanced	[111]	Equal subjective weights for three objectives	620	−0.077	0.25	495	470	35	712
	[122]	Lower subjective weight for cost	620	−0.077	0.25	495	470	35	712
	[212]	Lower subjective weight for CO_2 emissions	620	−0.048	0.16	432	470	34	719
	[221]	Lower subjective weight for CEEP	621	−0.103	0.36	529	595	27	787

Smart Energy Aalborg models.

In the Energy Vision scenario, the gas grid is balanced with zero net import of gas, while for the Optimal, IEH@0, and IEH@Max scenarios, additional income comes from net gas export, which is obtained from the local gaseous electrofuel production after compensating the gas demand for CHP plants, boilers, and industry. The gaseous electrofuel is produced from biomass together with hydrogen generated from electrolysers by utilizing the excess electricity generated from wind turbines and solar power. This reflects the effect of cross-sector interaction between heat, electricity and gas grid in an integrated smart energy system.

5.2.2. Changes in district heat system

Fig. 8 presents the structure of the DH network in five scenarios that differ largely. The BAU heating system largely relies on CHP plants, while the others depend on IEH and HPs. The share of IEH in the total heat production of the five scenarios is 14%, 49%, 40%, 0, and 56%, respectively. It is found that the amount of IEH and HPs will have an impact on the operation of the existing CHP plants. The CHP units will experience decreasing hours of operation in an energy system with high a share of IEH, leading to redundant capacity.

The larger-scale integration of HP will bring a more balanced DH system. The Optimal scenario reduces 4% unbalanced heat compared to the Energy Vision scenario, while in the IEH@0 scenario the unbalanced heat decreased to zero. The share of HPs in the DH system of Aalborg will be between 11% and 52%, which is the result of an energy system using the full potential of IEH and zero-IEH, respectively. For the Optimal scenario, a 20% share of HP and a 40% share of IEH is recommended.

5.2.3. Changes in the structure of electricity generation

Fig. 9 presents the electricity generation structure of different scenarios. The power generation from offshore wind turbines, waste incineration plants, and industrial CHP plants are the same for the four scenarios aside from the BAU. It can be seen that the IEH@0 scenario reaches the highest net electricity production at 3.49TWh, followed by the Optimal and IEH@Max scenarios at both 3.32 TWh, while the BAU and the Energy Vision scenarios are lower at 2.48 TWh and 3.13 TWh, respectively. The dotted line shows the amount of electricity generation from the variable RES. Compared to the Energy Vision scenario, the Optimal scenario increases about 8% RES electricity production, which clearly shows that replacing part of the IEH by increasing the share of HPs in the DH network will help to the further penetration of RES in the electricity production.

From the perspective of the net electricity export (export minus import), it can be seen that the BAU scenario reaches the maximum at 0.47 TWh while the Energy Vision scenario reaches the minimum at 0.01 TWh. The value of the Optimal scenarios is in between at 0.03TWh which has very slight differences from the Energy Vision scenario. A higher HP installation also helps to reduce the excess electricity production and increase the operation of CHP to decrease redundant capacity.

5.3. Technology choice between IEH and HP and its impact on RES

This section identifies the impacts of each IEH source in terms of cost and CO_2 emission by including the 11 IEH sources (see Table 3) one by one into the Aalborg energy system. The corresponding capacities of HP and RES are calculated by employing the proposed methodology. Figs. 10 and 11 present the change of the annual cost and CO_2 emission, respectively, with an increase in the accumulated quantity of IEH under three different levels of CEEP. It can be found that a near carbon–neutral system with an acceptable annual cost can be realized when CEEP is around 0.07TWh, so which is recommended for the Aalborg case.

Table 6 provides the optimal results of the Aalborg energy system with different IEH sources at a CEEP of 0.07 TWh. The change of the capacities of PV and wind shows different directions with the increase of IEH, which reveals that technology choice among different RES is case depending. The policymaker should evaluate each energy generation technology carefully according to the situation of the system. Moreover, it is found that increasing the utilization of IEH is not necessarily lower the total annual cost of the energy system. It also depends on the selection of the IEH sources. The effect of various IEH sources on the total cost is different, which decreases first (options 1–3) and then increases (options 7–11). The lowest system cost occurs between options 3 and 6, i.e., 671 ~ 698 GWh, which is in line with the result of the Optimal scenario (665 GWh). The corresponding HP installation capacity is between 24 ~ 30 MW.

In some cases, with the growth of the installed capacity of renewable power, the annual cost of the 100% renewable Aalborg energy system not increases as expected in the fossil-fuel dominant energy system but decreases. It is because of the increasing production of the gaseous electrofuels (generated from local electrolysers and biomass) which brings export revenue.

5.4. Sector synergies between heating, electricity and gas grid

5.4.1. Impacts of the gas balance

An additional analysis of gas balance is made in this section, which is carried out by adding a gas balance constraint in MOPSO to limit the net gas to be within ± 0.01 TWh to avoid unnecessary gas export. Table 7 provides the optimization results of the balanced gas test. Due to the gas balance constraint limiting the additional income from gas export and the corresponding electricity demand for local gas production, fewer wind turbines and solar power panels will be installed in the balanced gas case compared to the Optimal scenario, which further limits the installation of HPs. Even though the balanced gas case has a slightly higher cost and more CO_2 emission than the Optimal scenario, the values of the three objectives are still better than the Energy Vision scenario. There is 0.33 TWh net gas import in the BAU scenario, while the gas exchange for the Optimal scenario and the balanced gas case will result in a net export at 0.21 TWh and 0.01 TWh, respectively.

A detailed cost comparison between different scenarios is given in Fig. 12. Compared to the Optimal scenario, the costs of fixed operation and annual investment in the balanced gas case will decrease, caused by less capacity of variable RES and HPs, while the variable cost will increase.

5.4.2. Sensitivity analysis of the gas prices

Tables 8 and 9 provide the results of the three objectives and the specifics of the energy system under four different levels of gas prices. The gas price zero presents an extreme case and only affects the income from the gas sales. The unchanged case denotes the normal price in the Optimal scenario. With the increase of gas price, the variable cost decreases due to the increase of additional income from gas export while the investment cost and fixed operation cost remain unchanged, which leads to a decline in total annual cost. More wind turbines and PV will be installed caused by increased electricity consumption from gaseous electrofuel generation resulting in increased RES power generation and RES share. The change of gas prices within a range of ± 50% has no impact on the HP capacity, however, a ± 3% change in the quantity of IEH will happen. Less IEH will be the result in the higher gas price case.

5.5. Impacts of preference of policymakers

This section analyses the impact of the preference of the policymakers on the design of the energy system, which is made by implementing a sensitivity analysis on the subjective weights in the TOPSIS approach as illustrated in Section 3.2. The results of both the balanced and the unbalanced systems are given in Table 10.

As shown, the sensitivity of cost is low, the relative change is less than 1% compared to the optimal results obtained under equal subjective weight, while that for CO_2 emission and CEEP is much higher. In the balanced case, the impact of subjective weights on PV is greater than wind power, with a variation range of 375 ~ 407 MW and 210 ~ 374 MW, respectively. The variations of HP capacity and IEH quantity is not significant, with a range of 29 ~ 33 MW, and 621 ~ 672 GWh, respectively. The unbalanced case features higher capacity in all types of investigated intermittent RES and heat generation options.

6. Conclusions

This paper proposes a general methodology framework for the optimal heating strategy selection in a 100% renewable smart energy system by coupling the smart energy system simulation tool EnergyPLAN, the multi-objective optimization algorithm MOPSO, and the multi-criteria decision-making approach TOPSIS. The framework aims to compare the impacts of different heating technologies on the entire energy system. The detailed decision-making entails determining the best heating generation mix with a special focus on the trade-off between heat pumps and industrial excess heat, and the optimal configuration of associated fluctuating wind and solar power.

The proposed framework is carried out using the case of 100% renewable smart energy in Aalborg Municipality, Denmark in the year 2050. The maximum potential of HP and IEH has a share of 56% and 52% in the total DH supply, respectively. Results indicate that a proper mix of both HP and IEH technologies in the DH supply will bring larger benefits. In the Aalborg case, they have a share of 20% and 40%, respectively, while the rest is supplied by CHP, boilers, waste incineration, and excess heat from electrofuel conversion.

The cross-sector effects among the power grid, district heating network, and gas grid are illustrated in the smart energy system context. Higher gas prices will stimulate gaseous electrofuel export production which consumes higher levels of RES electricity promoting RES integration in turn. As a result, the DH demand met by IEH will be reduced to increase the share of power-to-heat HP. Even though an additional gas balance constraint is included to limit the net gas exchange, the obtained result is still superior to the previous research in terms of cost, CO_2 emissions, and CEEP.

This work has provided a reference and a methodology for policymakers and system operators in the design of district heating systems under multiple feasible technical options. Despite the case studied in this paper is city-level planning, it can be employed in other geographic-level systems. While industrial excess heat is a key resource for future low-temperature 4GDH and smart energy systems, it is vital to emphasize that the heat pump solution is also feasible. This is important since an over-reliance on excess heat sources from industries can also be risky as industries might relocate or change production patterns due to their own energy efficiency measures. This paper demonstrates the importance of diversifying the heat sources in a 100% renewable energy system, which is proved by comparing this work to the BAU case in Ref. [38]. By combining HP and IEH in the district heating system, a near carbon–neutral energy system can be reached which realizes a 7.7%, 85.7%, and 100% reduction respectively in total annual cost, CEEP, and CO_2 emissions compared to the BAU scenario.

CRediT authorship contribution statement

Meng Yuan: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft. **:** Visualization. **Jakob Zinck Thellufsen:** Supervision, Conceptualization, Methodology, Resources. **:** . **Peter Sorknæs:** Conceptualization, Methodology, Resources. **:** . **Henrik Lund:** Supervision, Methodology. **:** . **Yongtu Liang:** Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Detailed flowchart of methodology

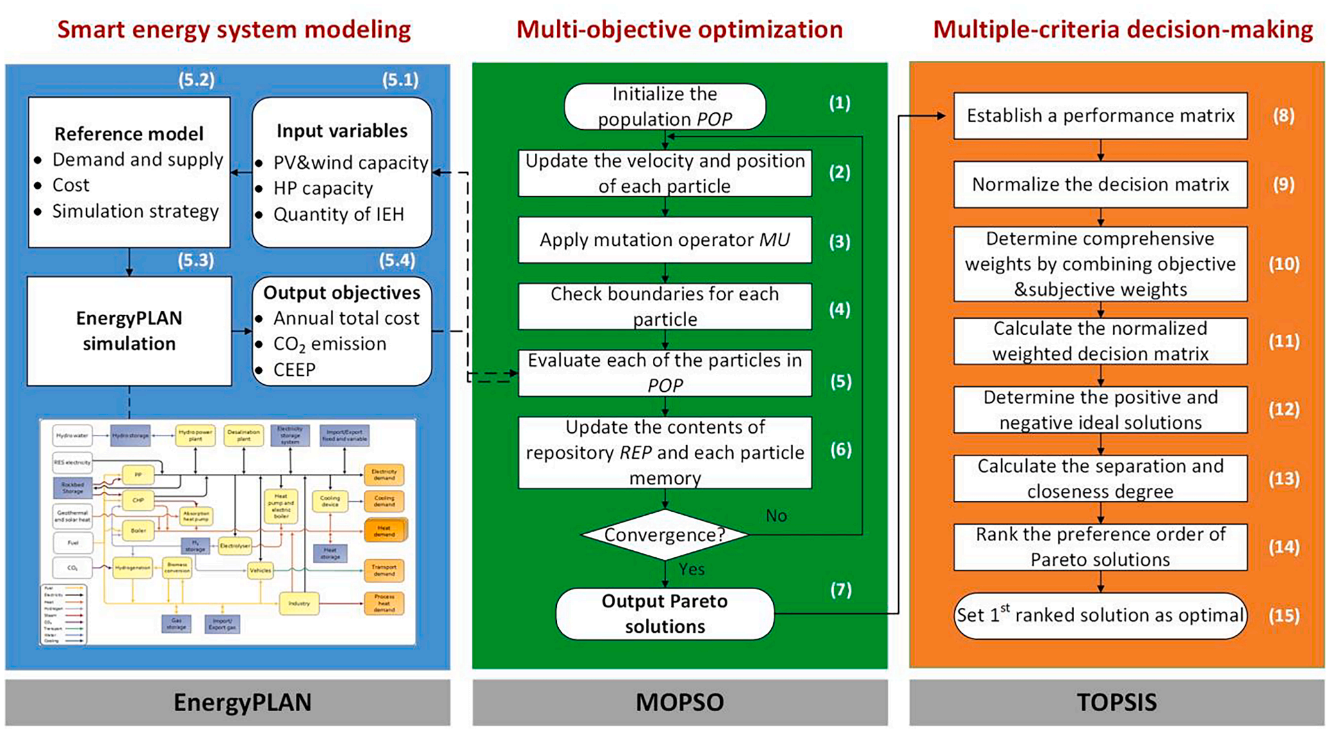

Fig. A1. Detailed flowchart of the proposed methodology for optimal DH system planning.

Appendix B. Parameter setting of MOPSO

MOPSO simulates the foraging behavior in a flock of birds or a school of fish, in which each individual of the population is called a particle, whose location represents a potentially feasible solution, the location of the food represents the global optimal solution. The step-by-step process of MOPSO is provided in the green box of Fig. A1. A more detailed description can be found in [52]. The parameter setting of MOPSO employed in this paper is given in Table B1.

In each iteration, each particle moves toward the optimal position according to two pieces of information, i.e., the current optimal position found by itself called personal best and the one experienced by the whole swarm called global best. The position and velocity of each particle at $k+1$-th iteration will be updated according to Eq. (B1) and Eq. (B2), respectively. ω is the inertia weight, c_1 and c_2 are the personal and global confidence factors, respectively, r_1 and r_2 are the uniformly distributed random numbers between 0 and 1. An external repository of particles *REP* is employed to keep a historical record of the non-dominated vectors found along the search process. Furthermore, a special mutation operator *MU* is included to enrich the exploratory capabilities of the population.

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{B1}$$

$$V_i^{k+1} = \omega V_i^k + c_1 r_1 \left(x_{pbest} - X_i^k\right) + c_2 r_2 \left(x_{gbest} - X_i^k\right) \tag{B2}$$

It has been proved that a larger ω in the early stage facilitates the global search while a small ω in the late stage facilitates the local search [64]. Here, a linearly decreasing ω is applied throughout the optimization process to control the exploration dynamically, as shown in Eq. (B3).

$$\omega_k = \omega_{max} - \left(\frac{\omega_{max} - \omega_{min}}{k_{max}}\right) k \tag{B3}$$

Table B1
Parameter setting for MOPSO.

Parameters		Value
POP	Population size	100
REP	Repository size	100
k_{max}	Maximum number of generations	150
ω_{max}	Maximum inertia weight	0.9
ω_{min}	Minimum inertia weight	0.4
c_1	Personal confidence factor	2
c_2	Global confidence factor	2
MU	Mutation rate	0.15

Appendix C. The reference energy system of Aalborg

Table C1
The energy demand of different sectors in the 2050 BAU and Energy Vision scenarios [16].

Sectors	Energy demands [TWh]	2050 BAU	2050 Energy Vision
Electricity	Electricity demand	1.45	1.23
	Flexible demand (1 day)	–	0.10
	Flexible demand (1 week)	–	0.03
Heating	Oil boilers for individual heating	0.142	0
	Natural gas boilers for individual heating	0.02	0
	Biomass boilers for individual heating	0.09	0
	Electric heating for individual heating	0.06	0
	Heat pumps for individual heating	0.03	0.21
	Decentral district heating	0.07	0.04
	Central district heating	1.80	1.28
Transport	Jet fuel demand	0.46	0.33
	Diesel demand (including biodiesel)	1.20 (1.28)	0.605
	Petrol demand (including bioethanol)	0.68 (0.70)	–
	Electricity for transport (dump)	0.02	0.118
	Electricity for transport (smart)	–	0.283
Industry and other	Coal	0.82	–
	Oil	0.05	–
	Natural gas	0.15	0.322
	Biomass	0.34	0.131

Table C2
Capacities and costs of different technologies in the Energy Vison scenario [16].

Technologies		Capacities	Unit	Period [year]	Investment [MEUR/Unit]	O&M cost/year [% of inv]
Heat and electricity	Small CHP units	22	MW-e	25	0.85	1
	Large CHP units	110	MW-e	25	0.52	3.5
	Thermal storage	2	GWh	20	1.58	0.7
	Waste CHP	0.37	TWh	20	215.62	0
	Heat pumps gr.2	2	MW-e	25	3.18	0.3
	Heat pumps gr.3	26	MW-e	25	3.18	0.38
	DHP boiler gr.1	2	MW-th	21	0.51	0
	Boilers gr.2 and gr.3	630	MW-th	25	0.05	3.8
	Electric boilers gr.2 and gr.3	100	MW-e	20	0.06	0.9
	Large power plants	10	MW-e	25	0.52	3.5
	Industrial CHP electricity	0.05	TWh/year	31	60.6	2.15
	Industrial CHP heat	0.08	TWh/year	31	60.6	2.15
	Industrial excess heat	1	TWh/year	30	0	1
	Individual boilers	1000	Units	20	2.7	6.7
	Individual CHP	1000	Units	20	14	6
	Individual heat pumps	141,000	Units	15	5	3.04
	Individual electric heat	1000	Units	30	3	0.8
Renewable energy	Onshore wind	285	MW-e	30	0.93	3.4
	Offshore wind	277	MW-e	30	1.71	1.88
	Photo voltaic	458	MW-e	30	0.49	1
	Solar thermal	0.05	TWh	30	335.94	0
	Seasonal heat storage solar	41	GWh	20	0.5	0.7
Liquid and gas fuels	Biogas plant	0.14	TWh	20	209.79	1.46
	Gasification plant	101	MW	20	1.33	2.5
	Biogas upgrade	22	MW	15	0.25	2.5
	Carbon recycling	0.09	MtCO2	20	140.61	11.4
	Synthetic gas	49	MW	25	0.2	4
	Synthetic fuel	107	MW	25	0.3	4
	Jetfuel upgrade	38	MW	25	0.37	4
	Electrolyser	330	MW	30	0.4	3
	Hydrogen storage	50	GWh	20	6.4	2.03
	Methanation CO_2 cost	–	–	25	18	4
Others	District heating grid expansions	–	–	40	52.4	0.1
	Heat savings	–	–	40	243.79	0
	Electricity savings in households	–	–	10	52	0
	Electricity savings in industry	–	–	15	133	0
	Fuel savings in industry	–	–	20	380	0
	Electricity grid expansions	–	–	45	94.05	1
	Vehicles			13	1553	7.26
	Charging stations	–	–	10	82	0
	Marginal cost changes to rail and road	–	–	30	1421	0
	Other transport	–	–	1	13	0

Table C3
Technical specifics of indirectly utilized industrial excess heat through HPs.

No.	Industries	Temperature cold side [°C]		Temperature warm side [°C]		HP capacity [MW]		HP COP
		In	Out	In	Out	Thermal	Electricity	
4	Other industries-Arla Foods	35	16	25	65	2.36	0.36	6.60
6	Other industries-Industries at the commercial harbors	28	24	25	65	0.80	0.12	6.84
7	Other industries	30	18	25	65	4.59	0.75	6.12
8	Other industries-Wastewater treatment plants	15	10	25	65	18.58	4.67	3.98
9	Aalborg Portland-HP reducing return temperature to existing units	40	35	25	65	7.21	0.90	8.01
11	Aalborg Portland -Exploiting heat from filtrate water using HP	50	23	25	65	3.63	0.30	12.10

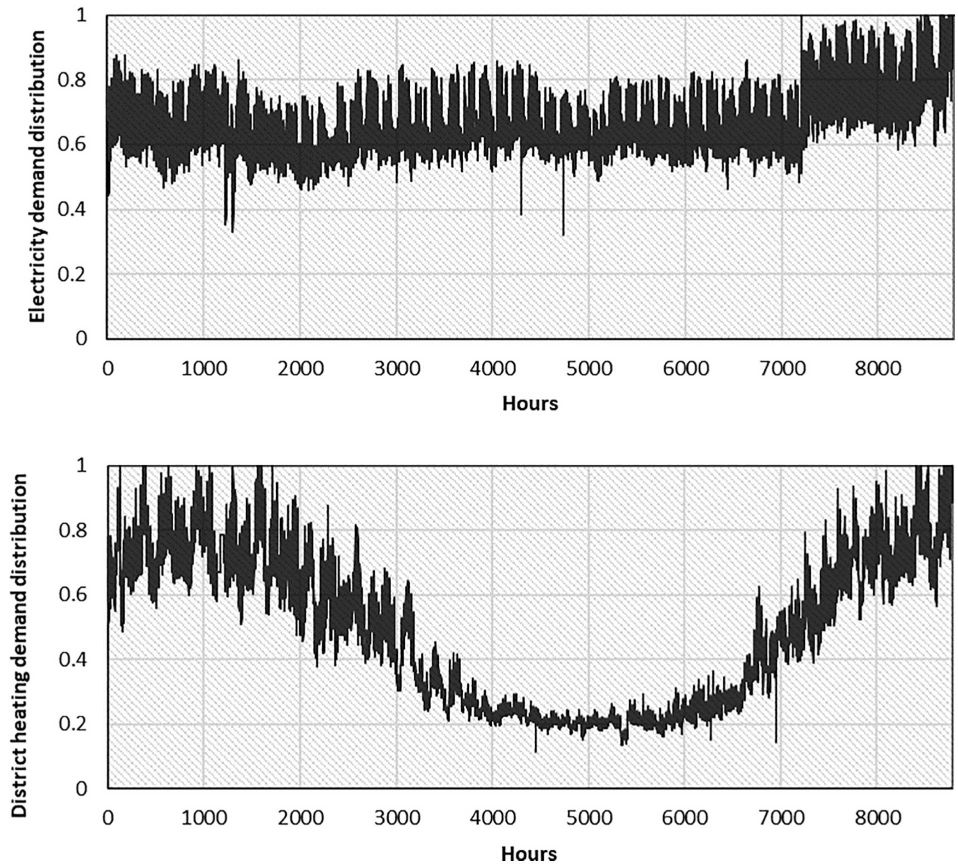

Fig. C1. Distributions of electricity and district heating demand in the Energy Vision 2050 scenario [16].

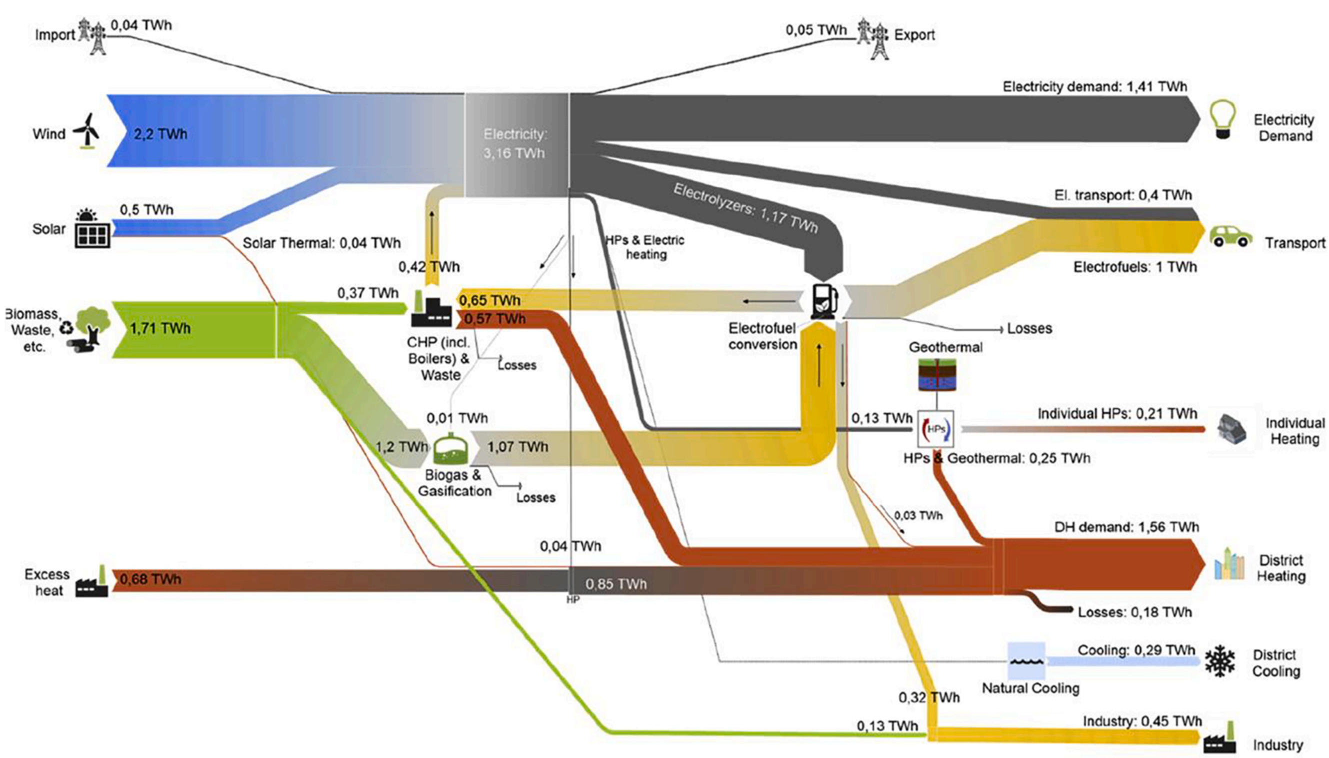

Fig. C2. Sankey diagram of Aalborg's energy system in Energy Vision 2050 scenario [38].

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