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Techno-economic modelling and optimisation of excess heat and cold recovery for industries: A review

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ABSTRACT

Recovery and use of industrial excess heat and cold are expected to play a huge role in the decarbonisation of heating and cooling systems in Europe. From the perspective of the industry, it could also promote a coupling between the sectors and help offset emissions, leading to a sustainable industry. However, there exists a gap in knowledge regarding the planning of infrastructure for utilization of excess heat, specifically for industries. This study aims at reviewing energy system optimisation tools that can be used by industrial stakeholders to plan energy investments for recovery and utilization of excess heat and cold. Through a study of existing energy systems models, seven tools are found suitable for analysing industrial excess heat and cold recovery. A detailed review of these tools is conducted and they are compared. The capability of the models to represent and analyse industrial excess heat and cold recovery options are critically discussed. The main requirements of such an analysis are used to establish criteria for comparison. The results of the comparison are used as a knowledge base to form a simple decision support tool to help industrial stakeholders choose the most suitable energy system model. The results from the review, comparison and decision support tool indicate that none of the models is capable of fulfilling all needs in every case. They also highlight that the choice of the tool depends especially on the required temporal and spatial resolution and its interoperability.

1. Introduction

With a growing need for sustainable resource use, energy policy and long-term strategic energy planning have gained prominence as distinct fields. Energy policy analysis and long term energy system planning have long been carried out using energy system models. Mathematical models have previously been used to represent the complex flows in an energy system. In the 20th century, significant emphasis was placed on modelling aspects of the energy supply, energy security, availability of resources, and increase in demand [1]. In the last two decades, energy system modelling has been driven mostly by environmental concerns and the development of climate policy. Most recent models have focused on reducing greenhouse gas emissions, reaching climate targets and assisting policy development, while considering energy economics. These models have focused on a detailed representation of various sectors in the larger energy system.

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the industrial sector is responsible for 30% of the global greenhouse gas emissions, surpassing the emissions of the buildings and the transportation sectors as shown in Fig. 1 [2].

The industry is thus seen as one of the keys to decarbonisation. However, it is also one of the most difficult sectors to decarbonise [2]. Replacing fossil fuels in the industrial processes where they are used as reducing agents, for example, the steel industry, is a complex process [3]. An absolute reduction in emissions from the industry will require a broad set of mitigation options and energy efficiency measures, as defined by Rissman et al. [4]. Among these measures, mitigation options such as re-use and recycling of products and energy flows are essential. These can offset the emissions by reducing emissions in the other sectors leading to an overall reduction of emissions in the system [2].

Many industries such as steel, cement, paper and pulp etc. have extremely high and low temperatures processes. These industries often generate excess heat and cold (EHC) at temperatures (hence exergy levels) that allow for their effective reuse. According to Lund et al. eliminating barriers for integration of EHC sources in District Heating Systems (DHS) is a key aspect of moving towards 4th and 5th generation DHS [5]. Forman et al. estimated global industrial EHC potential as 32 PJ in 2012 [6] and Albert et al. estimated the industrial EHC in the UK to be 46,000 GWh in 2018 [7]. Geographic mapping of the industrial EHC sources indicated an overlap with space heating demand sites. Miró et al. estimated the industrial EHC potential in Europe to be 1106–2708 PJ per

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Nomenclature

4GDH	4th Generation District Heating
AC	Alternating Current
ANN	Artificial Neural Networks
CHP	Combined Heat and Power
COP	Coefficient of Performance
DCS	District Cooling Systems
DES	Distributed Energy System
DH	District Heating
DHCS	District Heating and Cooling System
DHN	District Heating Network
DHS	District Heating System
DST	Decision Support Tool
EH	Excess Heat
EHC	Excess Heat and Cold
EU	European Union
GHG	Green house gas
GIS	Geographic Information System
GWh	Giga Watt Hours
HESYSOPT	Heating System Optimisation Tool
HP	Heat Pump
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
LCOH	Levelised Cost of Heat
MCS	Multi Criteria Analysis
MILP	Mixed-Integer Linear Program
NPV	Net Present Value
PJ	Peta-Joule
SPORES	Spatially Explicit Practically Optimal Results
TEOM	Techno-Economic Optimisation Model
TWh	Tera Watt-Hours
UC	Unit Commitment
UEH	Urban Excess Heat

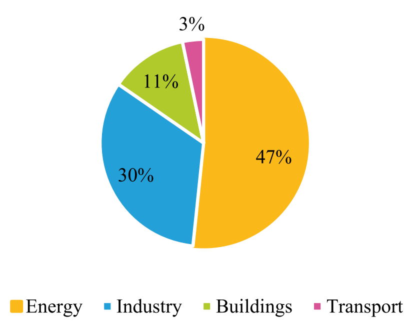

Fig. 1. Contribution to Global Greenhouse Gas (GHG) emissions.

year in 2018 [8]. Pili et al. estimated the EHC potential in the German industrial sector to be 200 TWh per year. A process module was used to conduct a detailed exergy analysis to determine the actual technical potentials from different industries [9]. Fleiter et al. carried out a Geographical Information System (GIS)-based analysis of 1608 industrial sites in Europe with a process-specific assessment of their excess heat (EH) potentials and matching them with nearby district heating (DH) demands [10]. The study indicated that 151 PJ of EH could be used in DHSs in 2020, which is about 8% of DH in the European Union (EU), in energy terms. Lund et al. estimated future EH potentials and concluded that the potentials could increase due to the expansion of DHSs and utilization of low-temperature EH sources [11]. There is a huge potential to make use of EHC to meet heating and cooling demands.

Further, another study conducted by Fleiter et al. indicated that in 2012, 75% of the primary energy used for heating and cooling in EU came from fossil fuels [12]. Therefore, it is important to determine pathways of EHC recovery and use in district heating and cooling systems (DHCS). Various types of modelling tools can be used to quantitatively assess the potential for EHC recovery. These tools can quantify EHC potential and evaluate pathways for use of the recovered EHC. Energy system optimisation models can be used to optimise the exploitation of the techno-economic potential of EHC recovery within the energy supply system. The importance of optimisation in this context lies in the need to base investment decisions on costs, among other factors, whether for budget or business reasons.

This paper analyses a selection of energy system optimisation tools, to understand their capability of assessing the pathways for EHC recovery. The paper is structured as follows. Section 1.1 provides the background and the scope of the study. Section 2 describes the methods used, while Section 3 provides an analysis of the reviewed tools. Section 4 presents the discussions and Section 5 presents the main conclusions.

1.1. Background

Energy system models have been used in several studies to analyse both the design and operation of DHCS and the use of recovered EH in DHCS. Zuberi et al. analysed the techno-economic feasibility of implementing EHC recovery in the Swiss industrial sectors. The study introduced a novel method for including spatial mapping and exergy analysis to estimate the actual techno-economic potential of EHC recovery [13]. Chambers et al. conducted a spatiotemporal analysis to determine the possibility of including industrial EH in the DHS in Switzerland. Spatial mapping of heating demand and EH sources was used to determine the technical feasibility. Further, a temporal energy balance was simulated at a monthly resolution to determine the theoretical potential of using seasonal storage [14]. Fitó et al. used a Mixed-Integer Linear Program (MILP) based optimisation model OMEGAlpes to develop an exergy optimal design of DHS [15]. Cunha et al. used a source and sink characterisation based physical model to compare two options for integrating industrial EHC into a DHS [16]. This study compares the cost of extending the DH network to using a continuous supply of portable thermal storage modules. A market perspective on the utilisation of EH in DHS was analysed by Doračić et al. [17]. A day ahead market model is used to model third party access to the DHS for industrial EHC sources. The study concluded that the day ahead market would facilitate the inclusion of EHC into the DHS and also reduce the costs on the consumer's side. Bürger et al. further analysed the introduction of third party access in DHS, by studying the institutional frameworks and set-up of the heating market in the EU and exploring various regulatory challenges [18]. The study concluded that granting third-party access alone is not sufficient to integrate industrial EHC into DHS and further policies to incentivise industries are also needed. Moser et al. proposed a heat merit order based method to determine the profitability of introducing industrial EHC into DHS [19]. Zühlsdorf et al. used a numerical model of system components with mass and energy balance equations to analyse the introduction of EH from a supermarket into a DHS. The model compares two system alternatives to choose the cost-optimal solution [20]. Halmschlager et al. developed an MILP based optimisation algorithm to determine the optimal scheduling of processes in a chipboard production plant to maximize the supply of EH to the DHS [21].

This study focuses specifically on techno-economic optimisation models (TEOMs) and their application to the case of industrial EHC recovery. A TEOM can be used to determine the optimal energy investments and dispatch for EHC recovery. They can be used for both long-term capacity expansion problems and short-term operational problems. The results of the TEOM such as costs and energy dispatch are crucial for determining the best business cases.

The integration of industrial EHC into DHCS has been modelled in several studies. Pulat et al. used an exergy analysis to determine the EHC recovery potential in Turkish textile industries. The thermo-economic analysis concluded that the payback time of investments could be less than 6 months and several EHC parameters could further boost the efficiency of the system [22]. A TEOM was developed by Söderman et al. to optimise both the structure of the DHCS and its operation [23,24]. These models have also been used to model the integration of industrial EH in the DHS [25]. Holmgren et al. modelled the optimal inclusion of industrial EH into the DHS in Gothenburg using the linear optimisation model MODEST[1] [26]. Karlsson et al. analysed the potential for a heat market in a region with a high density of energy-intensive processes with three industrial plants, four energy companies and three local DHS, in MODEST [27]. The study determines the economic potential of connecting these supply and demand points to form a joint heating grid based on industrial EH. A similar study was conducted using MODEST by Gebremedhin et al. to determine the techno-economic potential of connecting a DHS with three industries in the municipalities of Gävle and Sandviken in Sweden [28]. Sandvall et al. investigated long-term system profitability for a large heat network between a cluster of chemical industries and two DHSs using MARKAL [29].

While models have been used to determine optimal pathways for the inclusion of industrial EHC into the DHS, several factors have hindered the implementation of these pathways. Jodeiri et al. reviewed the challenges to integrating industrial EHC into DHS and highlighted the '*distance of heat sources from DHS, incompatibility of source temperature with grid temperature and temporal mismatch of heat availability and demand*' as major challenges. This indicates the need for a detailed techno-economic modelling of industrial EHC considering high spatial and temporal resolution, and storage options [30]. Albert et al. indicated a poor response rate from industries to a survey on EH potentials and highlighted that large financial incentives would be needed to promote industrial EHC recovery [7]. Viklund et al. conducted a survey-based study to determine the impact of the policy incentives on promoting energy investments for EHC recovery in industries. Most industrial stakeholders were well aware of the broad spectrum of options available for EHC recovery but seemed to lack the know-how for the implementation [31]. They are dependent on the DHS operator for planning. Wahlroos et al. studied the possibilities for EHC recovery from data centres in Nordic countries. The study indicates the main barrier for EHC recovery from data centres is that the data centre operators lack the knowledge of how to implement EHC solutions. Further, there needs to be a transparent contract between the DH operator and the data centre [32]. Brueckner et al. reviewed various methods for estimation of industrial EHC potential and concluded that lack of data availability and lack of know-how in industry are the main obstacles to EHC recovery and use [33].

Studies considering scenario analysis of energy investments for heat recovery in industries indicated positive Net Present Value (NPV) for investment in EHC recovery and delivery to DH grids [34]. However, despite several favourable techno-economic factors, the implementation of EHC recovery depends on the willingness and cooperation between the stakeholders [35]. Thollander et al. analysed and classified parameters as obstacles or facilitators of the cooperation. Structure and length of contract were identified to be enablers [36]. On the other hand, unwillingness to take risks due to imperfect and asymmetric information, credibility and trust, and opposition to change were obstacles. Several policy instruments such as investment support, green certification, and third party access to heating systems increase the willingness of industries to implement EHC recovery. However, the large dependency of the industrial stakeholders on the DHCS operators coupled with parameters hindering the collaboration is a major roadblock for implementing EHC recovery [31]. Modelling studies using energy system optimisation models are shown to ease the problem of imperfect information, further boost cooperation and reduce dependency on the DHCS operators. Gustafsson et al. analysed the role of spatial analysis and planning as enablers of industrial EHC use in DHS. The study concluded that the strategic spatial planning with involvement of industrial stakeholders could further facilitate the inclusion of industrial EH in DHS. This indicated the importance of capturing the spatial aspects while analysing the inclusion of industrial EHC in DHS [37].

Thus, the choice of the model is very crucial for long term energy planning in industries. While several studies in the past have conducted a detailed review of Energy System Optimizatio Models (ESOMs), there is sparse literature that presents the review from the perspective of an industrial actor and analyses the capabilities of the ESOMs to satisfy the requirements to model industries as a part of the energy system. Hence, in this paper, the capabilities of the tools needed to satisfy the requirements of an industrial EHC recovery and use from an industrial perspective are first mapped and then used as criteria to compare several modelling tools. This study aims to review various energy system modelling tools that can be used for techno-economic optimisation and determining cost-optimal pathways for EHC recovery. The scope of the tools is limited to energy system optimisation. The reviewed tools are critically analysed and compared based on their ability to conduct a comprehensive analysis. A decision support tool (DST) is designed based on a review of various energy system modelling tools. The DST enables industrial stakeholders to obtain a quick overview of the most-suited TEOM according to a set of preferences.

2. Methodology

A literature review of TEOMs is conducted to determine their capability of modelling industrial EHC recovery. The selection of the TEOMs, the criteria for comparison, the review and critical analysis, and the comparison of the TEOMs are further explained in sections 2.1, 2.2, 2.3 and 2.4 respectively.

2.1. Selection of optimisation tools

The optimisation models provide a framework for determining cost-optimal investment and energy dispatch, conducting scenario analysis, and performing sensitivity analysis. An exhaustive list of relevant optimisation tools is shown in Table 1. These tools were chosen based on a preliminary study of tools used for modelling energy systems. A search was conducted in citation database SCOPUS using keywords such as 'Optimisation model', 'Energy system modelling', 'Energy systems analysis', and 'Energy system model'. A specific time frame, after 2010, has been used to identify relevant research articles describing the models. Conolly et al. reviewed 37 computer models of energy system analysis and classified them into simulation and optimisation models [38]. Based on their relevance to this study, the models classified as optimisation models in ref. [39] are considered. Articles describing reviews of energy models [38–40] and Open mod webpage [41] were used to further support the selection.

While many models listed in Table 1 are suitable to model EHC recovery, a finer selection of tools is used to fit within the scope of this study. Connolly et al., Groissböck et al. and Ringkjøb et al. were used as references for the characteristics and features of the tools [38,39,58]. In these articles, the authors review the functionalities of a large set of energy system tools. Using data available from these reviews, the modelling tools were further filtered based on the following two criteria.

[1] Model for optimisation of dynamic energy systems with time-dependent components and boundary conditions.

Table 1
List of optimisation models.

Tools	Developer/Author	Year	Reference
Balmorel	Hans F. Ravn	2001	[42]
Backbone	VTT Technical Research Centre of Finland; University College Dublin	2019	[43]
Calliope	ETH; Swiss Federal Institute of Technology in Zürich	2015	[44]
ELMOD	Technical University, Berlin	2012	[45]
Energyscope	Swiss Federal Institute of Technology Lausanne, Catholic University of Louvain	2019	[46]
EnergyPlan	Aalborg university	1999	[47]
EnergyPRO	Energi-Og Miljødata (EMD) International	1990	[48]
LEAP	Stockholm Environment Institute	1980	[49]
MESSAGE	International Institute for Applied Systems Analysis (IIASA)	1980	[50]
NEMS	Energy Information Administration	1993	[51]
OEMOF	Reiner Lemoine Institut/Centre for Sustainable Energy Systems - Hochschule Flensburg	2017	[52]
OSeMOSYS	KTH Royal institute of technology	2008	[53]
FICUS	Institute for Energy Economy and Application Technology	2015	[54]
URBS	Technical university Munich	2014	[55]
Temoa	North Carolina State University	2013	[56]
TIMES (derivative of MARKAL and EFOM)	International Energy Agency-Energy Technology Systems Analysis Program (ETSAP)	2004	[57]

1. Modelling the heating/cooling sector: The tool is considered if it can completely or partially model the heating sector.
2. Availability of information on all the criteria in Section 2.2: Tools with extensive available literature were considered as they can be validated easily while modifying and applying to new cases.

Based on the filtering, the following 7 models were chosen for further detailed review:

- OSeMOSYS
- EnergyPlan
- TIMES
- EnergyPRO
- BALMOREL
- OEMOF
- Calliope

Research articles, reports, and factsheets of studies conducted using these tools were reviewed. The literature search was conducted on the abstract and citation database SCOPUS using keywords such as tool names, 'district heating', 'Optimisation modelling', and 'Techno-economic optimisation'. Further, the websites of the tools were also used to conduct a literature search. Finally, grey literature such as reports documenting the development of the tools was included in the review. These were obtained from the websites of the tools and the corresponding online repositories.

2.2. Criteria for comparing the tools

The criteria for the comparison are developed by considering the requirements of a TEOM to support various levels of decision making around the expansion or installation of a DHCS for recovery and use of industrial EHC. There are different levels of decision-making and thereby assessments needed to support the decisions, as shown in Fig. 2. These levels are based on the perspectives of different involved actors. For example, decisions may be taken by an industrial stakeholder or a network operator. The objectives of these two actors are different, i.e. the objective of the industry would be to maximize the use of EH from the industry thereby maximizing the profits, while the network operator aims to minimize the overall investment and operating costs of the heating network. At different levels, different decision-making criteria will dominate. These are detailed in Table 2.

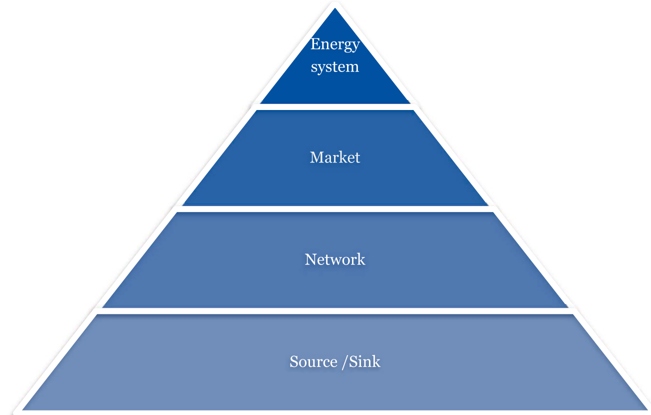

Fig. 2. Levels of decision making for a DHCS based on industrial EH.

Modelling tools exist that support decision at each level separately. However, it is argued that the levels of decision making and related decision criteria need to be considered as far as possible together, to achieve a comprehensive plan for the reuse of EHC.

The decision criteria listed above are used to establish the criteria for comparing the tools. The criteria are also based on previous reviews [1, 38] and the requirements of a tool to enable industry stakeholders to conduct energy analysis [30–37]. Lopion et al. indicated that several previous reviews [38,39,58] have used the following as major criteria used to compare the tools: access, spatial and temporal resolution, representation of techno-economic parameters, technological richness, modularity, methodology, type of objective function and usability [1]. In addition to these features, at each level of analysis, the TEOM might not be able to capture all aspects of the system. Hence, the tool must either be modified or be linked to other tools to capture all aspects. Thus, the ability of the tools to interoperate with other tools, flexibility and ease of modification are also included as criteria for comparison. Furthermore, the representation of technologies and fuels for modelling industrial EHC is also added as a sub-criteria for the comparison. The chosen criteria are further explained in Table 3. The column 'Possible Inputs' will be explained later in Section 2.4.

2.3. Analysis of the selected tools

This section will provide a review of the chosen optimisation tools, which will be compared in section 2.4 based on the above criteria.

Table 2
Different perspectives in an EHC analysis.

Decision-making level	Explanation
Source/sink level	• The techno-economic constraints of each actor need to be represented in detail
Network	• Decisions made by the distributor utility or the actor who owns the network • Need for spatial analysis
Market	• Optimisation of a market-based system • The bids of each energy-producing actor are considered
Regional/National energy systems	Analysis for the entire energy system while considering • Integration with existing infrastructure • The policy targets for the heating and cooling system, and overarching view considering wider system and sector coupling, decentralised options and regulatory framework

Table 3
Criteria for the DST.

Criteria	Description	Alternatives considered
Access	A free to access tool could enable: • Energy and investment planning free of cost • Collaboration between industry and not-for-profit institutions (e.g. academia, for research and innovation purposes). • Transparency, collaborative development, quality assurance through a large user base	Open access/Commercial/No preference
Modelling language	The compatibility between the modelling languages of different tools may facilitate their linking	Single language/Multiple languages/No preference
Spatial resolution	There may be a need to: • Represent both the technologies for EHC recovery and the network of pipes used for transporting the energy between the sources and the sinks. • Optimise the capacities of the network based on the investment costs. • Capture the spatial aspects of the district heating network such as pipe layouts and locations of heat generation and demand sites	Low/High/No preference
Temporal resolution	• The demand and supply for energy tend to vary with time. • The variation of the demand determines the capacities of the various technologies. • In most ESOMs, the high temporal resolution also leads to large scale models which might cause the failure of the algorithm or long computational time. This is also considered while evaluating the temporal resolution of the models.	Low to medium/Medium/Medium to high/High/No preference
Technical and economic parameters	For an analysis to be relevant at all the decision levels shown above, the tool should include a representation of: • Technological richness - The ability of the tool to model or represent in detail several different types of technologies. • Thermal storage • Market • Policy measures • Representation of Industrial EHC sources - These are usually represented in TEOMs through a set of techno-economic characteristics, upon which the optimisation is made. The ability of the tool to model DHCS is regarded as representative of the tool's capability to model industrial EHC as well. Furthermore, for each tool, the exact methodology for modelling industrial EHC is also considered. However, the ease of modelling industrial EHC between the tools is not considered since this can be a subjective evaluation.	Yes/No/No preference
Accuracy and error	The ability of the tool to model different components and equipment for EHC recovery and the level of detail in which the equipment and processes can be modelled are considered representative of the accuracy of the tool.	Low/Low to medium/Medium/Medium to high/High/No preference
Representation of regulatory framework//Emissions accounting	The broader energy system that the DHCS is part of often has a regulatory framework in place, e.g. comprising of: • Emissions caps • Carbon taxes • Feed-in tariffs The regulatory framework may influence the competitiveness of different technical solutions.	Yes/No/No preference
Type of objective function	The objective function is the main goal that is to be achieved by the optimisation model. For industrial EHC recovery, there may be a need to meet one or multiple objectives simultaneously (e.g., reduce emissions and the total cost at the same time).	Single objective/Multi objective/No preference
Modelling method	The formulation of the optimisation problem can be a linear program, non-linear program, or mixed-integer program. Depending on the formulation, different techno-economic constraints may be represented.	Linear/Mixed-Integer/Non-linear/No preference
Flexibility, modularity and interoperability	• Connecting different modelling tools may enable insights for the different levels of decision making involved (i.e. as per Fig. 2) • The possibility of adding new features and functionalities to the modelling tools may enable analyses that are more relevant to specific actors and cases.	Low/Low to medium/Medium/Medium to high/High/No preference

2.3.1. *OSeMOSYS*

OSeMOSYS is an open-source energy system model generator that can be used for the optimisation of long-term energy system investments and operation. It was developed as an open-source tool that can be used by researchers and policymakers to enable energy planning. OSeMOSYS is formulated as a linear optimisation problem that computes the least-cost dispatch options for each year within a defined time domain, to meet exogenously defined demands [60]. The tool conducts a socio-economic optimisation and minimises the overall system costs. It does not deal with business-economic optimisation. In the OSeMOSYS framework, solver, code and solving environment are all open-source [60]. The source code of OSeMOSYS is available in several different languages, GNU mathprog, GAMS, and Pyomo and PULP packages in python [53].

OSeMOSYS has been used to model DHCSs in following discussed studies. Smeureanu et al. [61] used OSeMOSYS to model the residential space heating demand in Romania considering various financing modes. The investments in heating technology are weighted against investment in thermal insulation to determine the cost-optimal mix for meeting the domestic heating demand. Burandt et al. modelled pathways for decarbonizing the Chinese energy system by 2050 using a OSeMOSYS based model called GENeSYS-MOD (Global Energy System Model) [62]. The study analysed in detail the decarbonisation of the heating sector including the supply of heat for space heating and industrial processes. The study highlights the variety of technological options that can be used within the OSeMOSYS framework to represent heat demands and generation units at different temperature levels. The study uses different technological representations within OSeMOSYS to represent heat demand for industry at three temperature ranges and space heating demand at a temperature range of 0–100 °C. Furthermore, the model also included heat pumps (HPs), Combined heat and power (CHP) plants and heat storages on the heat supply side. The studies highlight the capability of the tool to model heating systems. Based on experiences such as the above, the tool has been used to build the techno-economic optimisation module within the EU horizon 2020 project EMB3RS [63]. Here, it is used as the main techno-economic energy system optimisation module in a platform to analyse the recovery and use of EHC for industries. The development made to the tool within the EMB3RS project is documented on GitHub repository [64].

Rocco et al. analysed the electrification scenarios for Tanzania coupling OSeMOSYS and Leontief Input-Output model using a soft link [65]. The study analysed among others the electrification of industries via the potential of increasing energy efficiency and decarbonisation of industries.

Palombelli et al. indicated the level of flexibility that OSeMOSYS provides by including new storage representations of water dams and batteries including storage losses in OSeMOSYS [66]. The results highlighted that a better storage representation can be achieved using the new storage equations with a lower computational effort than before. However, the study also indicates that there are certain non-linear characteristics of battery storage such as cycle life losses that could not be linearized. The ease of linking OSeMOSYS to other special-purpose tools was also highlighted by Riva et al. [67]. OSeMOSYS was linked to two other tools, a bottom-up model built from scratch to project household demand and the software LoadProGen, a stochastic load profile generator. Dreier et al. developed OSeMOSYS-PULP, a stochastic modelling framework for long-term energy systems modelling by adding the feature of Monte Carlo simulations to OSeMOSYS [68]. The enhancements and the improvements made to OSeMOSYS indicate the modularity of the modelling tool.

It is possible to build models with very high (up to hourly) temporal resolution in OSeMOSYS since the user can freely choose the number of time steps. However, the required computational effort increases significantly leading to very long simulation times, making it almost infeasible. This disadvantage was partially addressed by Welsch et al. wherein a model of the Irish electricity system with high penetration of variable renewable energy sources was developed in OSeMOSYS and TIMES-PLEXOS [69]. An enhanced OSeMOSYS code with additions for consideration of operating reserve requirements was used at a resolution of 12 intra-annual time steps. In contrast, a large time resolution of 8784-time steps was used in TIMES-PLEXOS. Results for energy dispatch from the power plants indicated that the new enhancements in OSeMOSYS enabled it to produce results that were very similar to that from TIMES-PLEXOS. The difference in these results between PLEXOS and OSeMOSYS was brought down from 21% to 4% using the new enhancements. Further, various pre-processing scripts have been developed to make the Linear Program's matrix generation more efficient and reduce the computational effort and increase the calculation speeds [70]. These further indicate the ease of modification.

The ability of OSeMOSYS to capture the market aspects has been indicated by Fragnière et al. by coupling OSeMOSYS with a 'share of choice model' to take into account the consumers' real behaviour [71]. Niet et al. implemented a stochastic risk structure in OSeMOSYS to incorporate uncertainty related to the emissions of electricity generation technologies [72]. Lavigne et al. introduced demand elasticity in OSeMOSYS and used it to assess reductions in end-use demands and related GHG emissions [73].

It is possible to represent trade and energy flow between different regions in OSeMOSYS. However, the spatial energy flow cannot be mapped. Nevertheless, the tool has been linked to various GIS-based spatial models to account for the lack of spatial resolution. Moksnes et al. investigated pathways for Kenya to reach its electrification target for the year 2030 using a soft link between OSeMOSYS and a spatial analysis tool called OnSSET[2] [74].

There are no pre-defined representations of any technologies in OSeMOSYS. The tool provides user the freedom to model different types of technologies along with several techno-economic parameters for each technology namely, availability factor, capacity factor, capital, fixed and variable costs, efficiencies, emission factors, capacity and energy generation constraints, and residual capacity. However, the lack of predefined representation implies that the model does not consider technology-specific characteristics such as variation of Coefficient of performance (COP) of a HP, variation of back pressure of turbine in a CHP etc. Thus, the model is only able to obtain a medium accuracy in its representation of technologies.

Similar to other technologies a predefined direct representation of EHC doesn't exist in OSeMOSYS. This is how usually energy supply of any type is modelled in the tool. Different types of technology-fuel combinations can be used to represent several types of energy and non-energy flows. This is illustrated by Grosso et al. in a study where OSeMOSYS was used to model the flow of passengers within a transport system [75]. Both the demand and the supply side can be disaggregated and detailed further. Thus, EHC can be modelled as a technology with 100% efficiency. There is no need to have an input fuel for this technology, but an output fuel must be defined. The capital, fixed and variable costs, emission factors and operation limits can be defined for the technology. The variability of EHC availability in each time step can be defined using a parameter called the capacity factor. Thus, the tool provides several options to the user to model EH despite the lack of direct implementation.

The main features and functionalities of the tool are shown in Fig. 3. In summary, OSeMOSYS is proven to meet openness, flexibility and interoperability requirements. It is capable of modelling energy storage, though only using a linear representation. The modelling tool has, in most applications a low spatial and temporal resolution, due to computational constraints. It is able to represent EHC sources using a technology based representation. However, improvements have been made in this direction using enhancements to the code or links to other special-purpose tools.

2.3.2. EnergyPlan

EnergyPlan is a deterministic tool that optimises an energy system based on a set of inputs given by the user. The tool has been used to model national or regional energy systems including electricity, heating, transportation, industrial sectors, and various policy and regulating measures [76]. It is a unit commitment (UC) model that optimises the operation of a system over a year at an hourly time resolution based on linear programming. The source code of EnergyPlan was programmed in Delphi Pascal [77]. EnergyPlan is classified as freeware i.e. the user interface of the tool can be downloaded from the website for free. EnergyPlan can also be executed from other user platforms such as Excel or MATLAB [76]. The tool allows the user to contribute in a semi-open source way by creating 'Add-ons and help tools' [76]. In summary, it is open to use and is semi-open for contributors.

The model can be used for three different types of analysis:

- Techno-economic analysis: This analysis consists of the optimisation of an energy system and provides an optimal dispatch of the different technologies.
- Market exchange analysis: The market economic simulation is based on a short-term marginal price based market model that analyses bids to the market while optimizing business-economic profits and reducing short term district heating costs. Price elasticity can also be modelled in such an analysis.
- Feasibility studies: The model calculates the feasibility of the different investments in the system by optimizing the total annual cost of the system. It also determines the socio-economic consequences of the system in this case.

A review of EnergyPlan's applications by Østergaard et al. in 2015 showed that the tool has been used to model DHSs in at least 6 studies [78]. This is further complemented by Lund et al. in a review of the tool's functionalities. There at least 3 more studies are found where EnergyPlan has been used to model DHS as a part of the energy system

[2] OnSSET uses a GIS-based approach to estimate, analyse and visualise the most cost-effective electrification option for the residential demand.

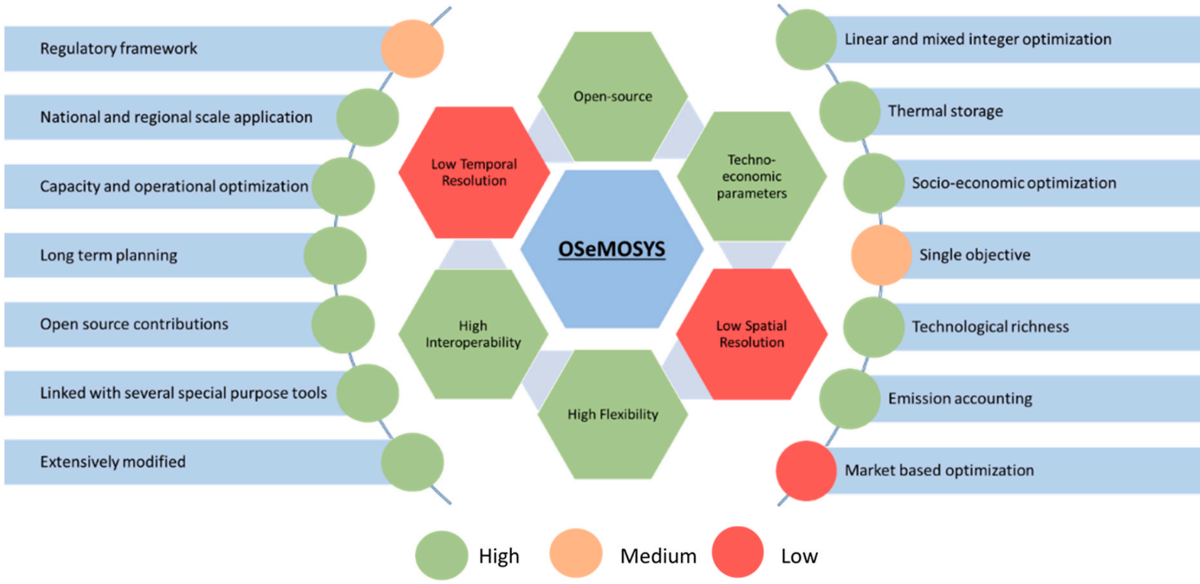

Fig. 3. Features and functionalities of OSeMOSYS.

[76]. A DHS model in EnergyPlan includes boiler systems, centralised and de-centralised CHPs, HPs and industrial EH. The modelling tool can also be used to compare cases between DHS and decentralised heat production. This confirms the tool's versatility in the representation of technological options for heat supply. EnergyPlan has been continuously developed by a team of developers and released in one official package up to the current version 15.1. This indicates the flexibility and the modularity of the tool.

Zhang et al. used EnergyPlan to analyse pathways for decarbonizing the DHS in Beijing [79]. The electricity system was modelled with DHS indicating the tool's ability to analyse sectoral coupling. Lund et al. investigated the socio-economic potential of large-scale HPs in the Danish DHS using EnergyPlan [80]. The results from EnergyPlan are compared to the results of similar analysis from another modelling tool. One of the main discussion points from the study was the large variation in the time resolution of the two models. EnergyPlan has an hourly resolution for an analysis period of one year, while the model developed in the other tool had 96 time divisions for the same analysis period. The study provided a conclusion that an hourly model may not be necessary even at large-scale integration of variable renewables in the system. Liu et al. analysed sustainable pathways for the development of a DHS by modelling it with the electricity system [81]. The scenarios analysed the optimal mix of investments in the DHS and individual heating in the houses. Askeland et al. used EnergyPlan to analyse the utilization of industrial EH in a 4th generation district heating (4GDH) [82]. The study concluded that the introduction of a 4GDH allows for a larger share of low-temperature EH potential to increase system efficiency. Xiong et al. analysed the development of new heating strategies in China using EnergyPlan [83]. The DHS comprising of surplus heat from industries and CHP was modelled and compared with individual heating solutions. Nielsen et al. used EnergyPlan to analyse the feasibility of integrating unconventional heat sources in the DHS. Four heat sources were considered and the analysis was conducted at an hourly resolution for two separate years, 2015 and 2050. The results indicated a large potential for use in the heat sources in all analysed cases [84]. In these studies, EnergyPlan has been used to model DHS at the regional/national energy systems level [78–83].

Möller et al. conducted a geographical study of heat supply consequences of replacing individual natural gas-based heating solutions with district heating [85]. A heat atlas was designed as a database using geographical information systems (GIS) and was used to quantify and locate the heat demand. This tool calculated the costs of connecting buildings to new or existing DHSs. It was soft-linked to EnergyPlan to optimise the investments and the operation of the DHS. Connolly et al. further expanded this methodology and analysed the expansion of district heating combined with heating savings as a measure to decarbonise the EU energy system [86]. GIS-based mapping of local conditions was used to examine the potential expansion of DHS. The heat mapping results from the analysis were used as an input in EnergyPlan to determine the optimal design of the energy system. These studies indicate a successful link between EnergyPlan and a special purpose tool for spatial analysis.

Yuan et al. soft linked EnergyPlan with a Multi-Objective Particle Swarm Optimisation algorithm (MOPSO) in an iterative link to conduct a multi-objective optimisation, with multiple-criteria decision making [87]. The framework is used to determine the trade-offs between the HPs and industrial EHC sources in a 100% renewable energy system for 2050 for Aalborg Municipality in Denmark. The study determines the optimal share of HPs and industrial EHC sources in the DHS while considering cross-sectoral effects of the electricity and natural gas systems.

EnergyPlan contains pre-defined blocks of several heat generation technologies, such as CHP, HPs, boilers, and industrial EH. The model considers the efficiencies, capital, fixed and variable costs, maximum and minimum capacities, and the fuel costs for each technology [76]. Thus, like OSeMOSYS, the tool does not consider the individual technical characteristics of each equipment and thus the accuracy is medium for EnergyPlan.

There is a predefined block for Industrial EH in the EnergyPlan tool. The annual availability of EHC in energy units and the hourly availability profile of the EHC for each hour in the year are the main inputs to the module. The ease of using the tool to model industrial EHC is increased due to the predefined modules, however, this restricts the flexibility of other parameters associated with EHC recovery such as costs and emissions.

In synthesis, EnergyPlan is mostly used for operation optimisation in short-time domains (one year). While the tool has not been modified extensively to fit the requirements of every study, the flexibility of the tool has been demonstrated by modifications made to the tool to improve its functionalities. The model is capable of analysing heat storage connected with different technologies, only using a linear programming method. Industrial EHC sources can be modelled using predefined settings in the tool. As shown in Fig. 4, the temporal resolution of EnergyPlan is very high, while the spatial resolution is low. It has been linked with several tools in previous studies indicating high interoperability.

2.3.3. TIMES

TIMES (The integrated MARKAL-EFOM System) is a bottom-up (technology-rich) modelling tool developed based on linear programming to determine the least-cost energy system. The model represents the entire chain of material and energy flows in an energy system, starting from fuel mining on the supply side to the energy delivery on the demand side, with primary and secondary energy generation, transport, import and export between the two sides. The source code for TIMES has been written in GAMS [57].

Sandvall et al. used TIMES to develop a model to analyse the use of urban excess heat (UEH) in the DHS [88]. The usage of heat from various UEH sources such as data centres, metro stations, sewage systems, and buildings' cooling systems was included in the model of a DHS using a TIMES application called 'TIMES_CityHeat'. The study examines the possibility of making DHS more competitive than individual heating by the inclusion of UEH. It was concluded that the benefits of the system are the most when UEH can replace the individual heating systems in buildings. This study also highlights the methodology for modelling industrial EHC in the 'TIMES_CityHeat' applications. Similar to OSeMOSYS, TIMES uses a 'Technology and Fuel' based representation to model EH and other technologies. The seasonal profile and the annual availability of EHC in energy units are the main inputs. Although it has not been considered in Sandvall et al. [88], there is also a possibility to attribute costs and emissions to industrial EHC sources. Similar to EH, the tool uses technical and economic constraints, such as capacity factor, availability factor, capital, fixed and variable costs, efficiency, start-up and shutdown times, capacity and energy generation limits for all technologies. TIMES also does not have a detailed equipment-based representation of technologies and thus the accuracy is set to be medium [89]. Sandvall et al. furthered the previous study by analysing the system profitability of EH utilization using TIMES [90]. The results indicated that EH could be used to phase out natural gas from the DHS and the profitability increases with the introduction of a carbon tax. Karlsson et al. used TIMES to examine the replacement of the existing DHS [91]. A techno-economic energy system analysis of the DHS was performed using the TIMES-DK model. These studies indicate the capability of the tool to analyse DHS as part of the regional energy system.

Traditionally, the TIMES model is solved for a limited number of annual time steps, usually between 4 and 16. However, by improving the computing capabilities of the tool, a higher time resolution has been achieved in some studies. Krakowski et al. developed a TIMES model with 84 intra-annual time steps to analyse the feasibility of a 100% share of renewables in the electricity system in France [92]. Kannan et al. developed the Swiss TIMES electrical system model (STEM-E) to analyse electricity generation at the hourly level [93].

TIMES has been soft-linked to other models and analytical tools in several studies. Petrovic et al. proposed a method to couple TIMES with a GIS-based spatial analysis tool 'Danish heat atlas', which is used for mapping potential heat savings and to calculate costs for expansion of DHS [94]. The marginal costs for expansion of DHS and heat savings measures are input to the TIMES model. Vaillancourt et al. used a multiregional TIMES model to explore the decarbonisation pathways for Canada using a soft-link with a simulation model calibrated with historical data in one-year steps [95]. Tigas et al. used a TIMES model to study the decarbonisation of the Greek electricity and transport systems [96]. A probabilistic production simulation model ProPsim was soft-linked to TIMES to incorporate the stochastic aspects related to renewable energy. Welsch et al. soft-linked a TIMES model with a UC model called PLEXOS which allows for simulating an electricity market with more detailed temporal resolution [69]. McDowall et al. examined the possibilities of linking TIMES to an LCA-based tool to facilitate the inclusion of indirect emissions in an analysis of decarbonising the European energy system [97]. Thellufsen et al. analysed the inclusion of DHSs into the future energy system where individual heating is expected to provide a large share of the heat [98]. A link between TIMES and EnergyPlan was used for the analysis. TIMES was used to model the initial framework for the future energy system, while EnergyPlan was used to optimise the operation of the DHS under different scenarios at an hourly resolution over one year. The pan-EU TIMES model created by Korkmaz et al. was soft linked with an impact assessment model, Eco-Sense, and with a general equilibrium model, NEWAGE to capture macro-economic impacts of the energy transition [99].

In summary, TIMES is primarily used to conduct long-term energy scenario analysis. As shown in Fig. 5, TIMES partially meets openness requirements, since the code is open source, but the modelling language and interface are not. The tool can model thermal storage, again only with a linear formulation. Its interoperability has been proven by the links to several special-purpose tools, and the code has been modified in several applications as well. The flexibility of TIMES is evident from the various applications and developments of the model. The national model application of TIMES focuses on energy planning and policy issues, while TIMES is also applied at a local level in various projects for city and community planning. The time resolution can be high, while the spatial resolution is low.

2.3.4. EnergyPRO

EnergyPRO is an optimisation modelling software that has been used for detailed technical and financial analysis of energy systems. The tool, developed by EMD International, is a commercial software and can conduct operational optimisation, accounting for technical properties of units, maintenance costs, fuel prices, taxes and subsidies. EnergyPRO has six different modules: design, finance, accounts, operation, region and markets. The design module optimises the dispatch of a set of power plants at an hourly simulation over a year. The finance module considers the investment costs and calculates cash flows and key investment figures. The accounts module uses the results from the finance and design module to produce a complete business plan. The operation module determines the optimal production plan for a single power plant. The region module facilitates the definition of a set of demand and generation units that are in different regions. While the module does not consider the spatial aspects of the energy system, it can model the trade and transmission between the different regions. The market module can optimise the participation of different generation units in an energy market. The tool can be used to model the system in great detail, i.e., it is possible to model individual units within an energy generation plant [48]. Thus, the tool can be used to analyse DHS at various levels of analysis, i.e. regional, market and source/sink levels.

EnergyPRO has been widely used in both industry and academia to analyse DHCS. Trømborg et al. used EnergyPRO to analyse the effect of future electricity prices on heat-only DHS in Norway [100]. Sneum et al. analysed the economic incentives for four different types of district heating plants under the Danish, Finnish, Norwegian and Swedish framework to conduct a Levelized cost of heat (LCOH) based investment analysis [101]. Fragaki et al. used EnergyPRO to optimise the capacity of CHP plants and thermal energy storage for a case in the UK [102]. In this study, EnergyPRO was coupled with an excel-spreadsheet based tool that calculates the net present values of different investments. Rudra et al. modelled the operation of a DH plant in Denmark using EnergyPRO [103]. Kiss et al. analysed the development of a sustainable city using EnergyPRO for the city of Pécs in Hungary [104]. A model of the energy system of the city consisting of heating, electricity and transport sectors was developed. This indicates the cross-sectoral modelling capabilities in the tool. Hast et al. modelled the future DHS of Tuusula in Finland to determine the optimal design capacities of thermal storages, HPs and solar collectors [105]. Østergaard et al. used a operationla optimisation model in EnergyPRO to conduct a comparative study between the deployment of booster HPs and centralised HPs in a low-temperature DHS [106]. Hast et al. examined various DH scenarios towards the development of a carbon-neutral DH generation in 2050 [107]. The

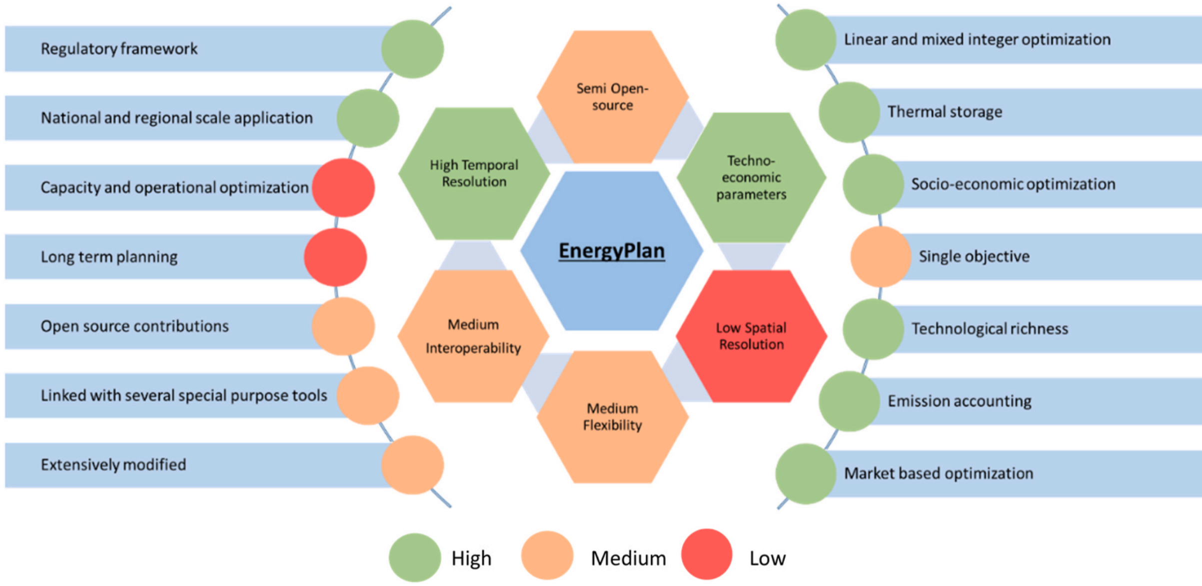

Fig. 4. Features and functionalities of EnergyPlan.

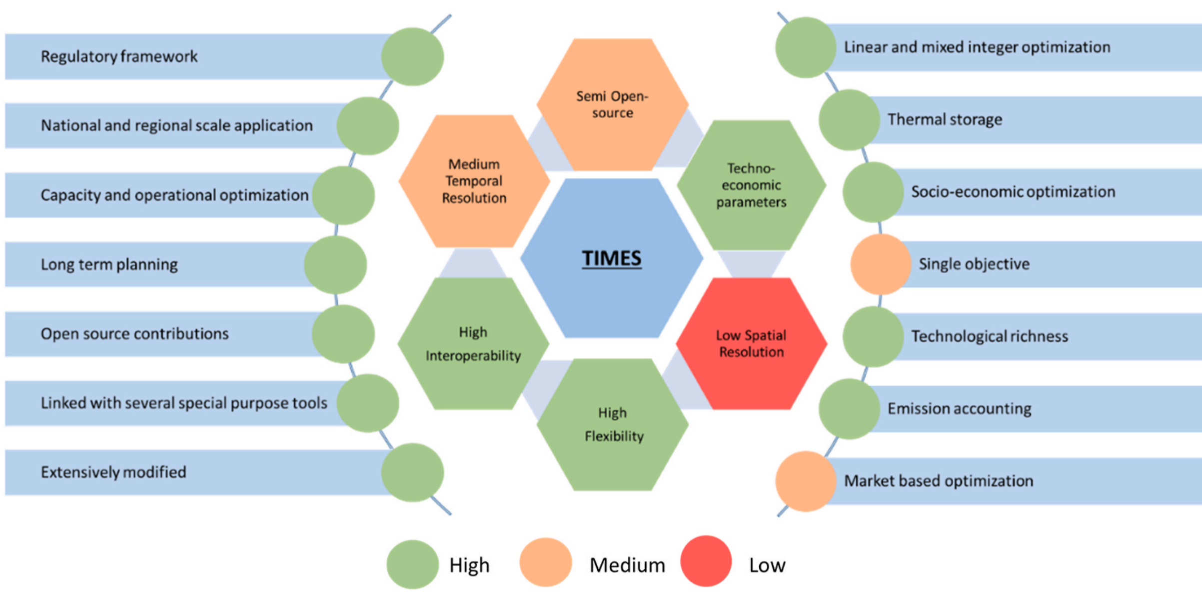

Fig. 5. Features and functionalities of TIMES.

results showed that a large share of energy supply from geothermal sources and industrial EH is needed to achieve a carbon-neutral DHS by 2050. Su et al. conducted a similar study to determine decarbonisation pathways for the DHS in Helsinki, Finland using EnergyPRO. The study found that the inclusion of EH from industries and data centres could significantly reduce the emissions in the DHS [108].

The tool has also been used to model interactions between the DHS and the electricity market by Østergaard et al. [109] where the business economic design of integrating HPs along with thermal storage was optimised. Andersen et al. used EnergyPRO to compare different policies for providing support schemes to increase flexibility in DHCS [110]. Doračić et al. modelled the utilization of EH combined with the implementation of thermal energy storage in a DHS [111]. The availability of EH was modelled at an hourly resolution to account for its variability. The DHS also consisted of CHP units and solar thermal plants. The results indicated that the EH tends to increase efficiency in the system, but the implementation of storage is crucial due to the variable nature of the EH availability. Hiltunen et al. determined the optimal capacity of EHC required to design a DHS based on EHC, HPs and renewable fuels using scenario analysis in EnergyPRO [112]. The results showed that prioritization of EHC allowed reaching the goal of 95% renewable heat generation.

In EnergyPRO, there are predefined settings for defining several types of technologies – fuel generation, energy conversion, solar and wind, batteries and electric vehicles and electric HPs. The tool only considers the technical and economic parameters for fuel generation and energy conversion units similar to the other tools. However there exist detailed technical and process models for solar collectors, wind farms, and HPs. The tool considers solar isolation and angle of the collectors for solar PV technologies, wind speeds, hub heights and other technical parameters for wind turbines and wind farms, temperature difference, and Coefficient of Performance (COP) variation for HPs. For other technologies, the level of detail is unclear due to the lack of information in user guides and the model not being open source. Thus, the accuracy of the model is set to medium to high [113,114]. Despite the tool having several predefined technologies, there is no predefined setting for industrial EHC sources. Furthermore, the tool does not provide the user with the flexibility to create new technologies like in the case of TIMES and OSeMOSYS. Thus, to model an industrial EHC source in EnergyPRO, a predefined set of technologies should be used and the techno-economic parameters must be added in a manner that can represent an EHC source. For example, a boiler can be used to represent the EHC source by assigning a 100% efficiency and no capital costs. In this manner, other parameters, such as emission factors, variable costs and variability of the heat availability can also be added as techno-economic parameters for the boiler. Therefore, the user has to use a customised approach using the predefined model objects in order to model EHC sources in EnergyPRO.

Thus, EnergyPRO is a commercial tool that is sold as an interface. The main functionalities are highlighted in Fig. 6. The model uses a MILP formulation and has been extensively used to model DHS in various previous studies. The tool is capable of optimizing the dispatch of energy generation units at a high time resolution and representing market-based scenarios. It also accounts for emission and model policy measures and is used to model thermal storage. It can also provide a business plan based on detailed economic accounting. There is a lack of available literature on the flexibility and modifiability of the tool. Further, the tool has only been linked to excel based optimisation tools in previous studies and does not capture any spatial aspects.

2.3.5. BALMOREL

Balmorel is a partial-equilibrium model used for the analysis of energy systems [115]. It is formulated as a linear programming optimisation problem and can be used for both long-term planning and short-term operational optimisation. Balmorel is an open-source energy system model and detailed documentation of the functionalities is provided along with the source code, which is written in GAMS. The code can be modified by the user to fit the specific requirements of the application [116].

Balmorel has been widely used to model heating and electricity systems in various studies. Münster et al. analysed the role of a DHS in the future Danish energy system using Balmorel [117]. The functionality of the model has been enhanced to optimise investments in decentralised heating or expansion of the district heating networks. The optimisation is based on investment costs, the energy density of the potential areas and their distance to existing DHN. Balmorel was linked to another optimisation model called OptiFlow to analyse the socio-economic value of combustible waste import in Denmark by Pizarro-Alonso et al. [118]. The socio-economic value considers both the value from providing energy and benefits from avoiding an alternative waste disposal process. OptiFlow was used to optimise the Danish waste management and transport systems, while Balmorel is used to optimise the northern European energy system. Hedegaard et al. investigated the potential of using individual HPs along with heat storage to enhance flexibility in an energy system with large penetration of wind power [119]. A similar study was conducted by Kiviluoma et al. where the flexibility provided by plug-in electric vehicles was also analysed in addition to the HPs and storage [120]. Bach et al. analysed a large-scale integration of HPs in the DHS in Copenhagen [121]. The system was modelled in a way that differentiated between the HPs connected to the transmission network and those connected to the distribution network. Furthermore, functionalities were added to the Balmorel model to capture the hourly and seasonal variations of the technical characteristics of HPs. Kirkerud et al. modelled different scenarios for the heat sector development using Balmorel while considering the impact of the electricity markets [122]. Jensen et al. used Balmorel to investigate the integration of a gas grid based on renewable gas to the electricity and heating systems in 4 countries [123]. A similar study was conducted by Ikäheimo et al. to determine the techno-economic potential of power to ammonia in the future heat and electricity systems [124]. Kirkerud et al. modelled the integration of power and heat markets to make use of the power to heat as flexibility measures in an energy system with high variable renewable shares [125]. Balmorel has thus been used to model DHS at both the source/sink level and the regional energy system level. Balmorel has been continuously developed by the community with a great emphasis on open-source development. The additions and updates made to the tool have been documented [126].

Similar to OSeMOSYS and TIMES, Balmorel does not have any predefined technologies for modelling industrial EHC sources. However, there are several other predefined heat generation technologies in the model such as CHP, HPs and boilers for reference purposes. Furthermore, the model also provides the user with the flexibility to add new heat generation technologies. Thus, in Balmorel, both the predefined technologies and new technologies can be used to represent industrial EHC sources. In addition, the costs, emission factors and variability of EHC can be represented using the techno-economic parameters in the model. The tool represents technologies using parameters such as efficiencies, emission factors, capital, and operating and fixed costs.

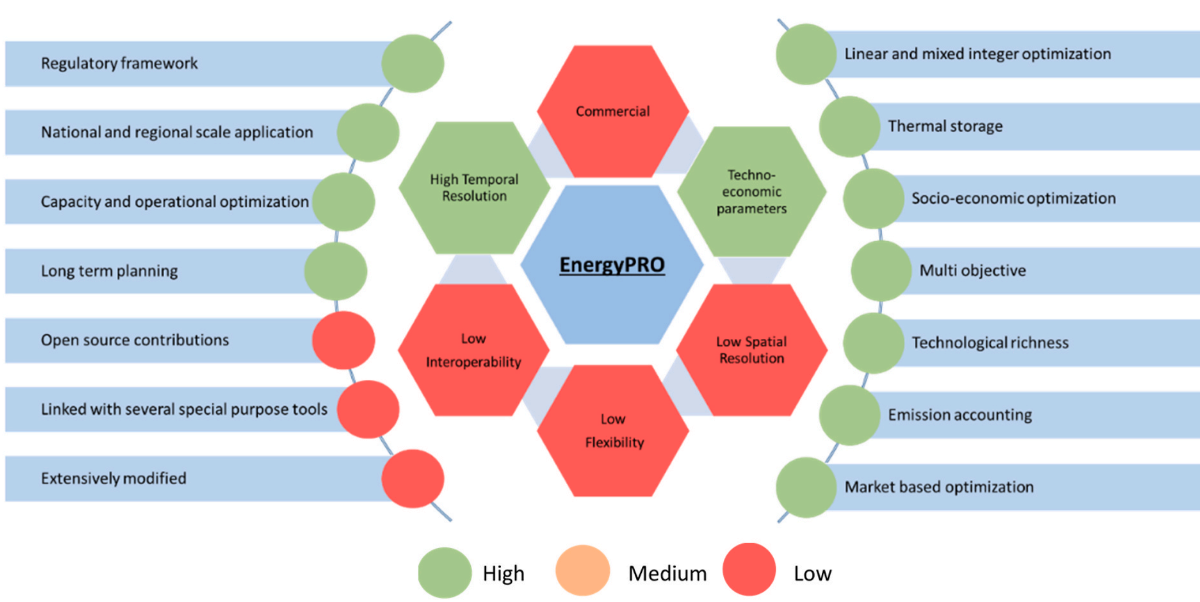

Fig. 6. Features and functionalities of EnergyPRO.

Therefore, there is no detailed process or equipment-based representation of technologies in Balmorel, and the accuracy is deemed to be Medium.

Balmorel is an open-source linear program based on TEOM. It has been used extensively to conduct detailed techno-economic and socio-economic analyses of heat and electricity systems covering various aspects such as storage, cross-sectoral integration, and market aspects. The model has been used to run simulations at hourly time resolutions and has been linked with various models in different studies. However, the tool has a low spatial resolution as shown in Fig. 7. The flexibility and modularity of the tool have also been proven in various previous studies, where additions and enhancements have been made. Despite the open-source development of the tool, the code is formulated in GAMS which is a commercial modelling platform.

2.3.6. OEMOF

The Open energy modelling framework (Oemof) is an open-source toolbox for the representation, analysis and modelling of energy systems. The tool is based on a generic graph-based description of energy systems and can model complex cross-sectoral energy systems. The energy system is represented as a set of nodes and edges that connect the nodes. The nodes represent the sources, sinks and other processes in the energy system. Edges are used to represent the inputs and outputs of a component. Oemof is formulated as a MILP optimisation problem based on a pre-defined set of components. The framework is implemented using the high-level programming language Python and the main component of the framework is formulated as a python package named 'Oemof package' [127].

Oemof has been used in several research studies. Möller et al. evaluated the potential of energy storage in the northern German region of Onsabrück-Steinfurt using Oemof [128]. The targets for the expansion of renewable capacity and the projected increase in demand were included in the model. The model was formulated at an hourly time resolution and considers the profitability of using centralised and de-centralised storage. Röder et al. analysed the possibility of using curtailed electricity from wind in the DHSs for setting up system-beneficial[3] power-to-heat-based district energy systems [129].

Wingenbach et al. developed the openMod.sh (Open Energy Model Schleswig-Holstein) model within the Oemof modelling framework [130]. The model was used to optimise the electricity and heat generation. The model includes the sources, sinks, and transmission and distribution networks of the heating and electricity systems. It can be used to analyse, visualise and optimise the energy system at an hourly time resolution. Oemof has been developed further to create the 'Oemof_heat' for modelling heating systems. This model has been developed by including the individual components for heat generation into the Oemof framework. It analyses the development of heating systems under different scenarios and the interaction with electricity systems. The focus of this model lies in an effective representation of heat supply networks, thermal energy storage, heat sources and sinks. Hilpert et al. developed the Heating System Optimisation Tool (HESYSOPT) to analyse the flexibility of DHSs [131]. The models are formulated as a MILP problem using the Oemof framework and facilitate detailed modelling of DHSs. DHNx, a package for optimisation and simulation of DHN was developed within the Oemof framework by Röder et al. [132]. The main objective of DHNx is to develop a library for optimizing the investment and planning of DHS. The package can be used to optimise the capacities and locations of new heat generation units and pipes in the network. However, it cannot optimise the dispatch of the heat simultaneously. The dispatch of the heat generation units can be optimised when an existing network is uploaded into the model and extension of the network is not considered. Thus, the tool has been developed to include spatial aspects of an energy system, however, the other basic functionalities of the tool such as optimisation of dispatch are not operational when these additions are made. To the best knowledge of the authors, there is no literature available for coupling DHNx with other packages in Oemof. However, the package is still being developed and it is expected that it will be linked with other packages in the future [133].

Schmeling et al. developed a decision-making framework for the design of a distributed energy system (DES) using Oemof [134]. The study develops a strategy for the design of DES using energy system modelling, stakeholder participation and risk assessment. Oemof was used to develop the model of the energy system and determine the optimal design capacities of the different plants under various scenarios. The results from Oemof are used to calculate Key Performance Indicators (KPI), which are fed into an optimisation algorithm to conduct multi-criteria optimisations using the tool pygmo/pagmo. Further, a risk analysis was carried out with a Monte-Carlo simulation. The risk analysis and multi-criteria analysis (MCA) are used to generate possible variable values and create several scenarios which are simulated in Oemof. This study indicates the possibility of successfully linking the Oemof tool to other tools. Interestingly, all the tools were hard-linked together within a single framework in python.

Köhler et al. investigated the possible storage options for the provision of cooling using a linear optimisation problem in Oemof. The study analyses the thermal and electrical solar cooling systems and the impact of storage on the two systems [135]. Wolf et al. studied the possibility of increasing flexibility in CHP plants by investing in different types of storage. Both thermal and electrical storage is considered in the study [136]. Fattori et al. studied the potential of DHSs as flexibility providers in a future energy system with large shares of renewable power generation [137]. An Oemof model is used to analyse the interaction of the heating and electricity systems by varying the power to heat ratio and heat storage capacities to dampen the variations in electricity production. Boysen et al. developed a UC model using Oemof to model the effect of introducing low temperatures in a DHS [138]. A novel method has been proposed within the Oemof framework to introduce the temperature in a UC model to study the effect of various temperature levels. Hilpert et al. investigated the flexibility provided by the operation of decentralised HPs and thermal energy storage for the operation of an electricity system with 100% renewable energy generation using Oemof [139]. These studies highlight the ability of the modelling tool to capture cross-sectoral interaction.

The structure of the Oemof model is similar to that of OSeMOSYS where the user is free to add new technologies and fuels. In addition, the model is loaded with several pre-defined components for technologies like CHP, boilers, and concentrated solar power. These pre-defined technologies are built based on detailed equipment and process models for each technology. The tool considers supply and return temperatures, variation of COP based on generation, inclination of solar collectors and other such technical parameters for representing the corresponding technologies [140]. Thus, the accuracy of the tool is considered High. However, there are no predefined technologies for representing industrial EHC sources. Hence, new technologies and fuels can be used to represent EHC sources. The tool is also capable of representing costs, emissions and variability associated with EHC sources using the techno-economic parameters.

Thus, Oemof is a completely open-source modelling tool that has been extensively modified to suit the requirements of the various applications. As shown in Fig. 8, the tool has also been linked to various other special-purpose models in previous studies. In some cases, it has been hard linked with others using Python modules and libraries. The tool has been developed to model spatial aspects of DHSs and has been used to run simulations at hourly resolutions in various previous studies. It provides the flexibility to the user to add technologies to represent EHC sources. Further, it is capable of physical modelling of thermal storage including energy and exergy losses using a linear formulation.

[3] A system beneficial design is developed by considering dynamic emission factors for grid generated electricity to determine the share of curtailed electricity from wind and the carbon intensity of the generated electricity.

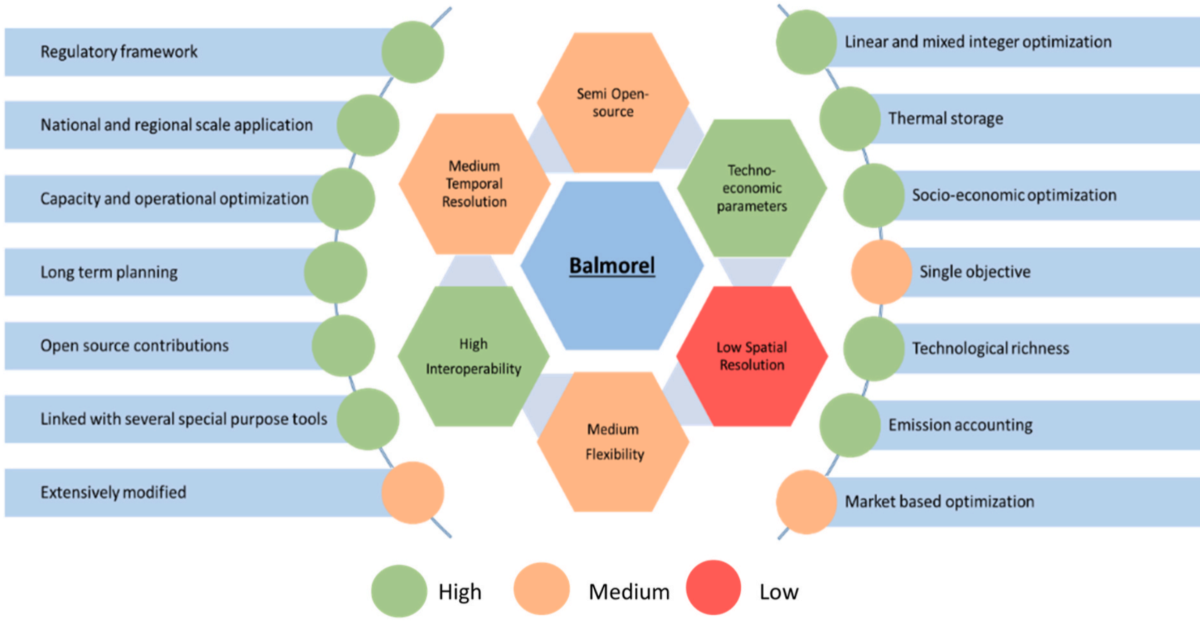

Fig. 7. Features and functionalities of Balmorel.

2.3.7. *Calliope*

Calliope is an open-source energy system model with a primary focus on planning energy systems at scales ranging from urban districts to global levels. Calliope has been developed with specific design goals in mind [33,120]:

- Analyse energy systems with high shares of renewable energy or other variable generation
- Separation of model code and data, and modular extensibility of model code
- Make models easily modifiable, achievable and auditable
- Simplify the definition and deployment of large numbers of model runs to high-performance computing clusters

One of the major features of Calliope is its high temporal and spatial resolution. Moreover, Calliope has several advanced functionality modes that allow the user to generate several alternative results within a range of optimal costs. Calliope has primarily been used for the comprehensive planning of energy systems. Lombardi et al. developed a method called SPORES (spatially explicit, practically optimal results) using Calliope [142]. The method considers the optimisation of the location of energy generation units and transmission capacities with constraints such as the density of energy generation in a region. The method provides spatially detailed power system transformation scenarios that enable decision making. This indicates the high spatial resolution of the tool.

Lombardi et al. linked Calliope with two other models in a study that proposed a multi-layer modelling method with a soft link between models [143]. A stochastic bottom-up load curves estimation model and a multi-regional input-output model were linked to Calliope. The developed multi-layer modelling method is applied to a case study of electrification of cooking. Calliope is used to determine the least-cost

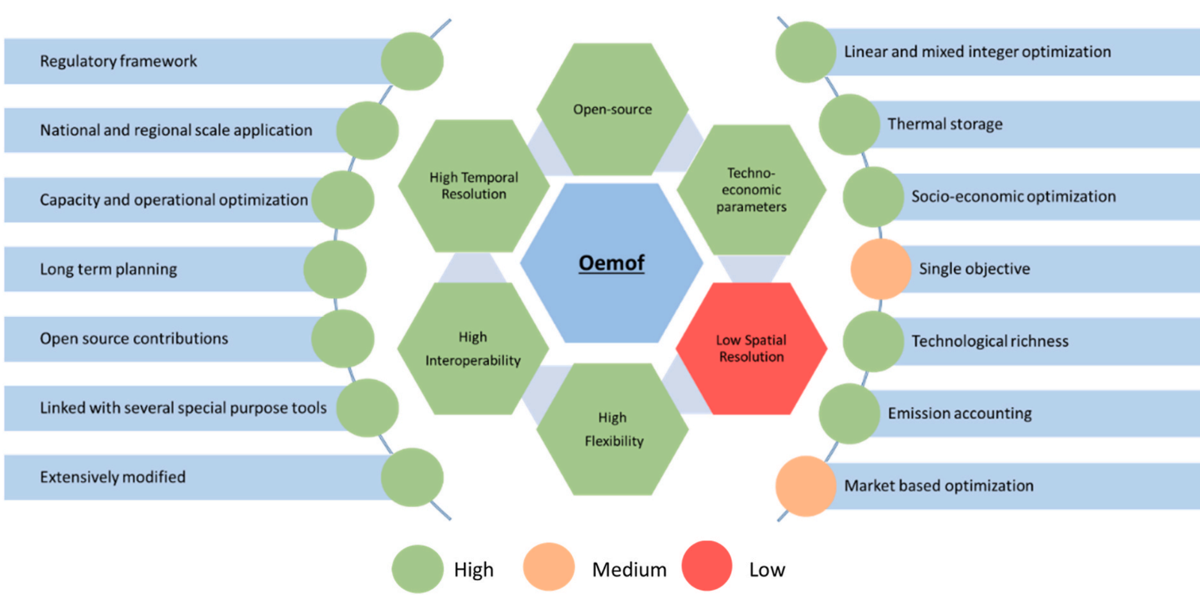

Fig. 8. Features and functionalities of Oemof.

electricity system for the increased load and the input-output model is used to assess the impact of the change in the energy system on the broader economic and environmental systems. Lombardi et al. also modelled the use of distributed power to heat technologies as a flexibility option for smart interactions between electricity and heating systems using Calliope [144]. A large number of individual HPs and thermal energy storages were modelled for various regulation scenarios to determine the flexibility potential of the different configurations.

Valdes et al. created a soft link between Calliope and the power grid simulation tool PyPSA to develop a framework for regional smart energy planning considering geographical data [145]. Calliope is used to determine the least-cost investment in decentralised power generation and the optimal operation of the system, while PyPSA is used to conduct the grid calculations and simulate Alternating current (AC) power flow in the distribution grid. Pickering et al. used Calliope to demonstrate a modelling approach to integrate stochastic variability of cooling and electricity demand in energy system optimisation models using a mixed-integer optimisation problem [146].

Del Pero et al. used Calliope to design a multi-energy system for a district allowing the production of renewable electricity and heat close to main consumption points [147]. The study proposes a hard link between Calliope and an ad-hoc heat network thermodynamic model developed in python. The hard link between the models is used to calculate the COP of the HPs based on the temperature in the thermal network. The calculated COP is fed back into the energy system model to refine the optimisation based on the new temperature levels. This enables the model to account for non-linear variation in HP COP, while still maintaining the computational advantages of a linear program.

Similar to Oemof, Calliope also provides both predefined technology structures and the option to add new technologies. However, the technologies are defined using techno-economic parameters and constraints similar to OSeMOSYS, EnergyPlan and TIMES. Thus, the accuracy of Calliope is also set to medium. However, there are no predefined technologies for industrial EHC sources. The user can thus, add new technologies to represent industrial EHC and add the relevant techno-economic parameters such as costs, emission factors and hourly availability profiles.

Calliope is an open-source energy system model written in Pyomo package in python and has been extensively used to model heating and electricity systems at high spatial and time resolutions as shown in Fig. 9. The model has also been linked with other tools in several studies. There is also documentation of continuous development of the tool and improvement of its functionalities. The tool is capable of representing thermal energy storage using a linear program.

The review of tools is used to establish the base for the decision support tool (DST) further explained in the next section.

2.4. DST

A simple and illustrative DST was developed to easily and quickly choose the best-suited TEOM for industrial EHC recovery based on the needs and preferences of the user. The tool is based on an ordinal ranking of the different criteria discussed in Table 3 [148]. The DST compares the modelling tools based on their performance in the criteria. These criteria are arranged into a decision-making flowchart that is used to structure the DST as shown in Fig. 10. An excel-based DST is designed to input data for the different criteria.

2.4.1. Functioning of the DST

The structure of the DST is shown in Fig. 10. The criteria specified in Section 2.2 are used to specify the requirements of the analysis that the user wants to carry out. For example, the criterion time resolution can be set to high, when the analysis must have a high time resolution, e.g. hourly. As seen in Table 3, the DST is structured such that some criteria like access, type of objective function etc. present a binary question. Other criteria such as temporal resolution, spatial resolution, flexibility and interoperability present several choices to the user such as high, medium and low. The ranges of the features are detailed in Table 4.

The TEOMs that meet all criteria are displayed as possible options. For criteria with multiple options, all TEOMs that meet the requirement will be chosen. For example, if a medium time resolution is chosen for the analysis, all TEOMs that have a medium or high will meet the criteria. If the choice is ‘No preference’ all tools will meet the criteria.

The second step of the DST is the ordinal ranking of criteria to determine the modelling tool that is most suited to the analysis. Four criteria are used for the ordinal ranking, ‘Temporal resolution, spatial resolution, Flexibility and Interoperability’. These four criteria are used since they present multiple options to the user and can be used to specify the most important objective of the analysis. In addition, the modelling tools are also ranked based on their performance in these criteria. The criteria must be ranked from 4 to 1 with 4 being the most important and 1 being the least important. For example, if a high time resolution is the most important requirement, then Time resolution can be given a score of 4. Based on the scores assigned to the modelling tools and the ranking

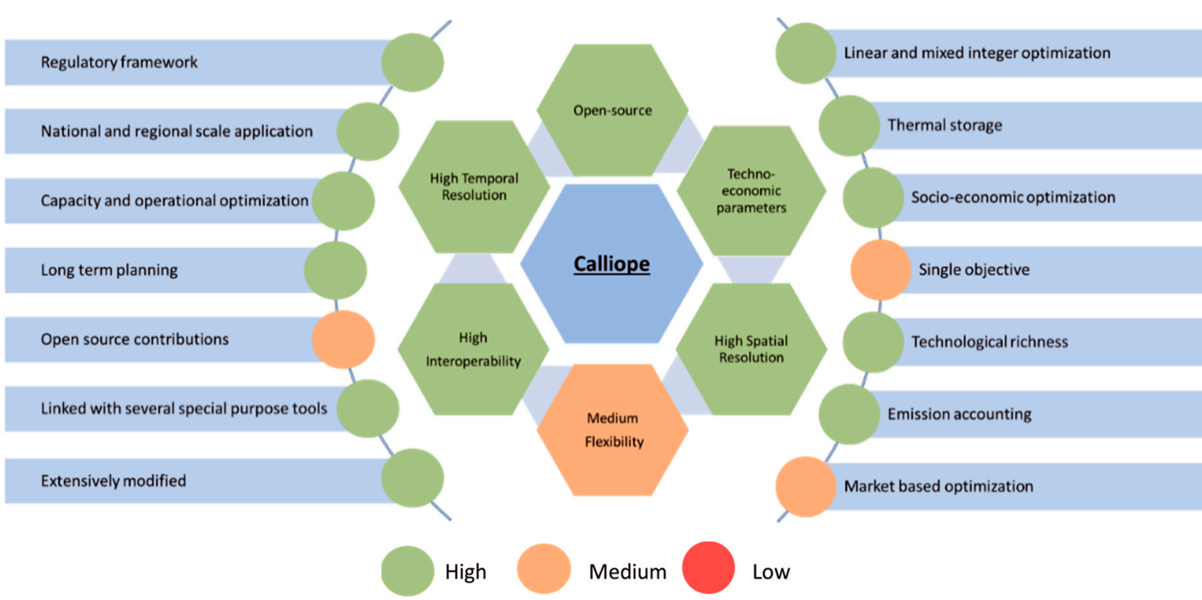

Fig. 9. Features and functionalities of Calliope.

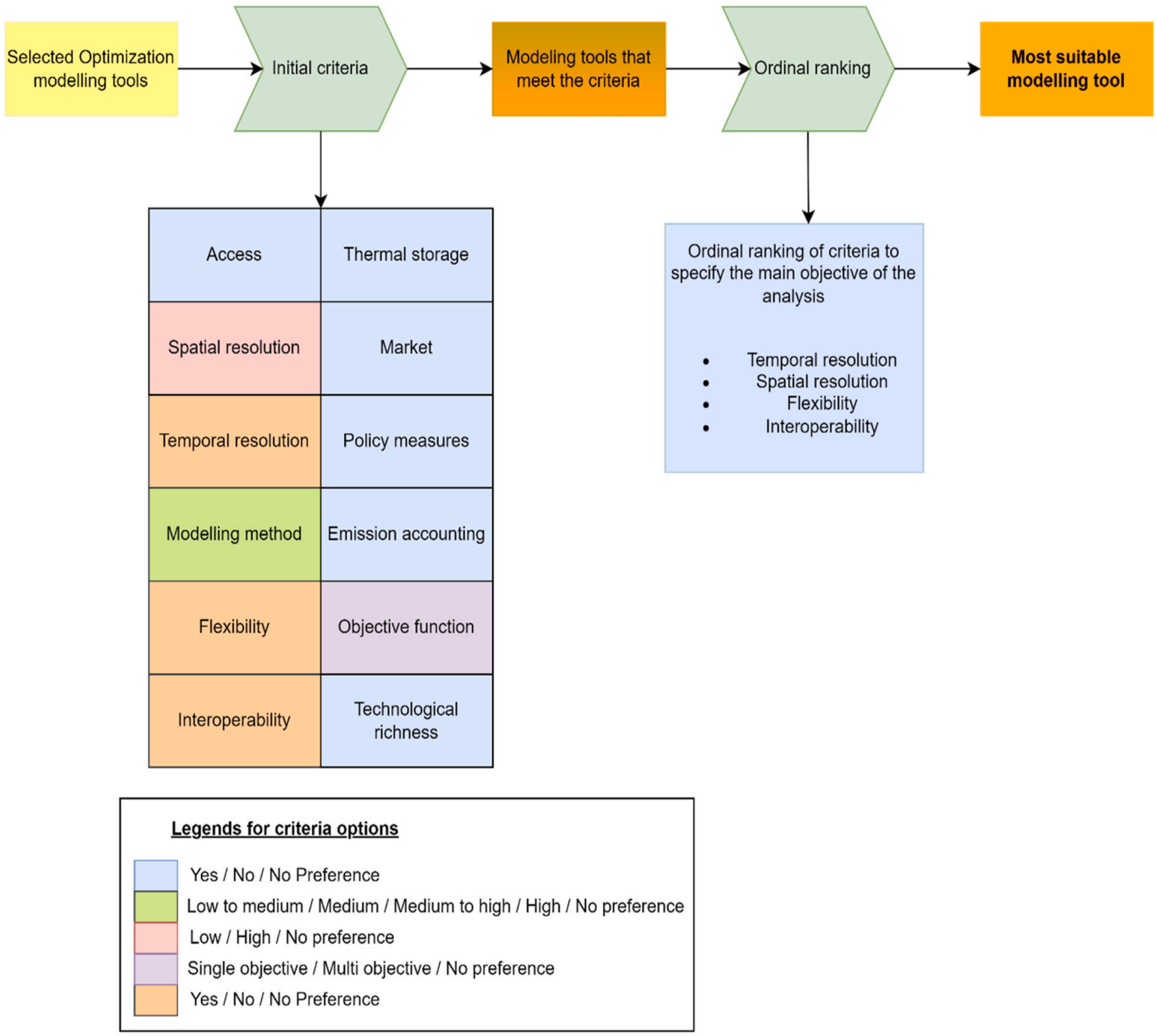

Fig. 10. Structure of the DST.

of the criteria, the most suitable modelling tool, is chosen. An example application of the DST is shown in section 4.

3. Discussion

In this section, the capabilities of the different tools and the performance in the different criteria are discussed and compared. Table 5 shows the access and availability of the tools. OSeMOSYS [60], Oemof [52], Calliope [44] and EnergyPlan [77] are available as open-source models, while EnergyPRO is a commercial software, and TIMES [57] and Balmorel [116] have been written in GAMS, which is a commercial modelling language.

Table 6 provides a summary of the features and functionalities of the different modelling tools concerning the requirements of the analysis. The performance of the modelling tools is marked as low, medium or high based on the different criteria on the literature review. The spatial resolution of all the modelling tools except Calliope is low [141]. Some of the modelling tools have been soft linked with spatial analysis tools, to make up for the low spatial resolution. While DHNx has been developed within the Oemof framework to include spatial aspects of an energy system, it does not consider dispatch optimisation. The temporal resolution of the modelling tools is quite varied. The reviewed articles [69] suggested that OSeMOSYS has a low to medium time resolution. TIMES [92] and Balmorel [121] have been used at hourly resolutions with some additions to the source code to improve the computational capabilities. |While the exact simulation times in these studies are not available, these modelling tools can optimise models at high temporal resolutions. EnergyPlan [63,66] and EnergyPRO [48] have the default

Table 4
Interpretation of criteria ranges.

Criterion	Range	Interpretation
Temporal Resolution	Low to high	Low, for example, a Monthly resolution – 12 intra annual time steps High, for example, an hourly resolution – 8760/8784 intra annual time steps
Spatial resolution	Low to high	Low – Spatial aspects not considered High – Can consider the location of different supply and demand sites and determine cost-optimal locations for new supply and demand points
Flexibility	Low to high	Low – Modification to the tool is not documented High – The tool is modified extensively with several enhancements and additions that have been made in a reproducible manner
Interoperability	Low to high	Low – Not linked with other tools in previous studies High – Extensively linked with other tools using both soft and hard linking methods

time step of 1 h and EnergyPRO can also run models at higher resolutions than hourly. On the other hand, OSeMOSYS [51–60], TIMES [95], EnergyPRO [101] and Balmorel [98–106] can analyse models over longer periods, while EnergyPlan is used generally to simulate/optimise models only over one year. Oemof [137] and Calliope [147] have been used to simulate models both at higher time resolution and over larger periods. For the purpose of this study, the temporal resolution of the models has also been used as an indicator of model performance. In general, a high time resolution leads to large models that need heavy computational requirements and long simulation times. Thus, the tools that have been shown to solve models over large time periods at high (hourly or bi-hourly) time resolution are considered to have a high performance.

All the modelling tools have a linear or mixed-integer formulation and would be able to capture most of the techno-economic characteristics of the analysis. This is discussed in detail in Table 7. Some inherently non-linear aspects of components, for example, state of charge and variation of losses with the capacity of thermal storage are either represented using a mixed-integer formulation or are not considered by the tools. The flexibility of the tools is also quite varied. The literature on OSeMOSYS [55–57] indicates that the tool is easily modified and enhanced to suit specific requirements in most of the studies. This suggests that the modelling tool has high flexibility. Since EnergyPRO [48] is a commercial tool, the source code is not available and hence, the flexibility and modifiability of the tool are limited and no literature indicating otherwise could be found. EnergyPlan [77] has also been modified to suit the specific requirements in a few studies. However, the modifiability of the tool has not been found in scientific articles. Most modifications to the source code tool have been made by the community that manages the tool and the users can only contribute with independent add-ons in a semi-open way [77]. Hence, the flexibility of the modelling tool is assigned to be medium to high. TIMES [46,76] has been extensively modified to suit the specific requirements of various regions and has high flexibility, while Balmorel [117] has been modified in a few studies and is assigned to have medium to high flexibility. Oemof [108–111] has also been modified to create different versions of the tool in several previous studies to suit the requirements. Although no literature has been found on the flexibility of Calliope, several additions and changes have been made to enhance the functionality of the tool [141]. However, these changes and additions have only been documented on the tool website [48] and this seems to indicate that the tool has been developed by a more closed community than others. The ability of the modelling tools to interact with other tools is also similar to their flexibility. EnergyPRO is a standalone tool that has not been linked to other tools apart from excel. OSeMOSYS [14,58,59], TIMES [56,78–80] and Balmorel have been soft linked to several special-purpose tools in various previous studies. EnergyPlan [70,71] has also been linked to different tools, but most of the tools have been linked with the forwarding of results from EnergyPlan to another tool and no evidence was found of two-way data exchange with EnergyPlan and, thus it has a medium to high interoperability. Oemof [134] and Calliope [122–126] have also been linked to special-purpose tools.

Table 5
Comparison of the tools – Software, Language and access.

Tools/ Criteria	Access			Modelling language
	Model	Solver	Shell	
OSeMOSYS	Open	Open	Open	Multiple languages
EnergyPlan	Open	Open	Open	Single language - Delphi Pascal
TIMES	Open	Commercial	Commercial	Single language - GAMS
EnergyPRO	Commercial	Commercial	Commercial	Source code unavailable
Balmorel	Open	Commercial	Commercial	Single language - GAMS
Oemof	Open	Open	Open	Single language - Python
Calliope	Open	Open	Open	Single language - Python

All the modelling tools can model the different technical and economic parameters that must be analysed for the case of industrial heat recovery as shown in Table 7. Multi-objective optimisations can be run using EnergyPlan and TIMES. All tools are able, in different ways, to represent industrial EHC sources and their techno-economic characteristics adequately, given the possibility to either use pre-defined model objects or introduce fully-customized user-defined technological options. EnergyPlan is the most user-friendly, from this perspective, because it has pre-defined objects specifically for industrial EHC sources. EnergyPRO is the least user-friendly in this case because it is the least flexible in terms of user-defined technologies. The accuracy of the tool is determined based on its level of detail in representation of technologies and error arising from the representation. Oemof uses process and equipment-based models for each technology and thus has a high accuracy whereas EnergyPRO uses such models only for a few technologies and thus have a 'Medium to High' accuracy. All other tools use techno-economic parameters to represent the technologies and thus only have a Medium accuracy.

The functioning of the DST is designed based on the comparison of the tools. An application of the DST is described in the section 4.

4. Example application of DST

The decision support tool has been built based on Tables 5–7 presented in section 3. The DST was tested by using a real-life case study from the Horizon 2020 project 'REUSEHEAT' [150]. The DST was tested by assigning requirements for the criteria. In the REUSEHEAT project, several case studies of industrial EHC recovery and use in DHS have been analysed and documented [149]. The case considers the project Warmtelevering Leidse Regio (WLR) which involves the recovery and transmission of industrial EH from the port of Rotterdam to DHS in the greater Leiden area. The project aims to connect the Industries to the DHS through an extension of the network and use of the EH to supply heat to about 13000 households and 200 companies. A long-term exploratory scenario is considered to determine the minimal socio-economic cost of extending the DHS over 10 years. The case also considers the competitiveness of the DHS compared to other technological solutions such as decentralised heating, and the policies and the regulatory framework of the region. Thus the analysis requires a tool that is capable of modelling with a long-term perspective and optimizing investments in the energy system. Furthermore, the project requires a 43 km long pipeline connection between the DHS and the industries. The spatial layout planning of the pipeline has already been conducted. Hence, the spatial resolution of the tool can be low. However, the tool must be able to interoperate with the spatial analysis tools. Open-source tools are chosen in order to conduct a transparent and reproducible analysis. A medium accuracy is deemed to be satisfactory since the main objective of the analysis is to conduct long term planning and further detailed analysis can be conducted based on results of this analysis. The criteria are defined as shown in Table 8.

In this case, the models that meet all the criteria are OSeMOSYS and Oemof. To make the final choice of the tool, the criteria are ranked as shown in Table 10. The ranking of the criteria is arbitrary and is used by the user to indicate the most important objectives. The ranking chosen here is for illustration purposes and is chosen in line with the narrative of the case.

Since the objective of the example analysis is to explore long term investment planning, a low time resolution is sufficient. Further, the tool will be linked with other tools to carry out special-purpose analysis for planning the spatial layout of the network and analysing the business cases. This explains the rank for spatial resolution, flexibility and interoperability. The calculation based on the ranking of criteria is

Table 6
Comparison of the tools – Spatial and temporal resolution, structure and linking.

Tools/Criteria	Spatial resolution	Temporal resolution	Optimisation problem	Flexibility	Interoperability
OSeMOSYS	Low	Low	Linear and mixed-integer problem	High	High
EnergyPlan	Low	High - Hourly	Linear and mixed-integer problem	Medium to High	Medium to High
TIMES	Low	Medium to high	Linear and mixed-integer problem	High	High
EnergyPRO	Low	High - Hourly	Linear and mixed-integer problem	Low	Low
Balmorel	Low	Medium to high	Linear and mixed-integer problem	Medium to High	High
Oemof	Low	High - Hourly	Linear and mixed-integer problem	High	High
Calliope	High	High - Hourly	Linear and mixed-integer problem	Medium to High	High

Table 7
Techno-economic parameters and objective function.

Tools/ Criteria	Technical and economic parameters					Objective function	Accuracy
	Thermal storage	Market	Policy	Modelling Industrial EHC	Emissions accounting		
OSeMOSYS	Yes	Yes	Yes	New technology and fuel addition	Yes	Single	Medium
EnergyPlan	Yes	Yes	Yes	Predefined technology structures	Yes	Single and Multi	Medium
TIMES	Yes	Yes	Yes	New technology and fuel addition	Yes	Single and Multi	Medium
EnergyPRO	Yes	Yes	Yes	Customisation using predefined technology structures	Yes	Single	Medium to High
Balmorel	Yes	Yes	Yes	New technology and fuel addition	Yes	Single	Medium
Oemof	Yes	Yes	Yes	New technology and fuel addition	Yes	Single	High
Calliope	Yes	Yes	Yes	New technology and fuel addition	Yes	Single	Medium

shown in Table 9 and Table 10.

The scores for the tools in the different criteria are shown in Table 10. These scores are assigned based on the performance in these criteria shown in Table 6. The scores are assigned from 1 to 5 based on the performance in each criterion with '5' being the highest and '1' the lowest. The score of the tool and the ranking of the criteria are multiplied by each other to find the final score. In this case, the final score is calculated as shown in Table 11.

Based on the above criteria and the calculation, the result of the DST was 'Oemof'. While none of the tools can meet all the criteria in the DST, all criteria are satisfied by at least one model, indicating that most combinations of criteria will be met. In a case where no tool can meet the specified criteria, the output will be **'No suitable tool found from the considered set of tools'**. However, there is a possibility to modify the DST to identify sub-optimal solutions. The decision support tool enables decision making by industrial stakeholders by presenting a simple means of choosing a TEOM.

5. Conclusion

This paper presents a literature review and a critical analysis of energy system optimisation tools for modelling the case of an industrial EHC recovery system. Seven TEOMs are chosen for an in-depth review from a larger pool of tools, owing to their capability of modelling at least partially EHC recovery systems. The review critically analyses the performance of the modelling tools and their suitability to model EHC recovery and use at four different levels of analysis. A simple DST is designed, to determine their suitability.

The review, the comparison of the tools and the DST indicate that none of the reviewed models can satisfy the requirement and have a high performance in all the criteria. Thus, the choice of the tool is mostly dictated by the objective of the analysis. While most tools are capable of representing the techno-economic characteristics of technologies and storage involved in EHC recovery systems, the performance of the tools differs to a large extent in their capability to model at high temporal and spatial resolutions and in their interoperability. These criteria are found to have a large influence on the choice of the tool, based on the needs that were identified from the literature.

Furthermore, the review indicates that not all tools are capable of analysing the inclusion of industrial EHC into DHCS at the different levels of analysis. While a few tools are capable of representing the techno-economic characteristics of every actor in detail, only one tool can capture the spatial aspects of the network. Most tools are capable of analysing the market perspective and modelling the inclusion of EH as a part of the larger energy system. Each tool uses a different methodology to represent industrial EHC sources. While some tools use direct predefined structures, others provide flexibility to the user to add new technologies for industrial EHC recovery. Only for one tool i.e. EnergyPRO, neither of the mentioned methods are applicable and the user must use and make changes to predefined structures to represent EHC sources. For example, the predefined structure for a boiler can be assigned a 100% efficiency to represent an industrial EHC source.

In addition, the level of detail to which the tools represent the

Table 8
Inputs for each criterion in the decision support tool.

Criteria	Answer
Access	Open-source
Solver access	Open-source
Shell	Open-source
Performance with high time resolutions	Low
Language	No preference
Spatial resolution	Low
Temporal resolution	Low to medium
Modelling method	No preference
Accuracy	Medium
Flexibility	High
Interoperability	High
Technological richness	Yes
Thermal storage	Yes
Market	Yes
Policy measures	Yes
Emission accounting	Yes
Objective function	Single objective

Table 9
Input for the criteria.

Criteria	Ranking
Temporal resolution	1
Spatial resolution	2
Flexibility	3
Interoperability	4

Table 10
Score for the tools in DST.

Criteria/tool	OSeMOSYS	EnergyPlan	TIMES	EnergyPRO	Balmorel	Oemof	Calliope
Temporal resolution	2	4	3	4	3	5	5
Spatial resolution	1	1	1	1	1	1	5
Flexibility	5	4	5	1	4	5	4
Interoperability	5	4	5	2	5	5	5

Table 11
Calculation of the scores.

Criteria/tool	OSeMOSYS	Oemof
Temporal resolutions	2	5
Spatial resolution	2	2
Flexibility	15	15
Interoperability	20	20
Final score	39	42

technologies is also considered in the review by evaluating the different methods of technology representation. Detailed process and equipment-based models have a high accuracy while a techno-economic representation has medium accuracy. While the different methods are mentioned, the ease of using these tools to represent EHC recovery is not discussed in this study as it is subjective to the user, case under consideration as well as available resources. Furthermore, the performance of the tools is deemed to be partially represented by the time resolution that it can consider. Tool that can optimise at high time resolution are deemed to also have a high performance. However, in reality, these reviewed tools also have different performance and failure points for a given model and a computational facility. However, the computational requirements and the availability of resources and the simulation time is subjective and dependent on the objective of the user. Therefore, the study only considers time resolution as a representative of the tool performance. This can be further expanded by studying the time and computational effort for each model for a particular case in detail. Thus, based on the findings from the review and the results of the DST, it is clear that all aspects of the analysis cannot be represented by using just one of the tools in their present form.

The importance of using modelling tools to analyse EHC recovery from an industrial perspective is well established. The modelling tools provide information about the potential of EHC recovery thus reducing uncertainties around such projects. Hence, it is critical to have an accurate analysis of EHC recovery from the models in order to support decision making. Since none of the reviewed modelling tools can satisfy all the criteria by itself, it is vital that energy system optimisation models are developed in a manner that the modelling tool can be linked with other tools and have the flexibility to be modified to suit the requirements of the analysis. Thus, research should focus on the development of tools to enable industrial stakeholders to model and analyse the case of EHC recovery. This would ensure the development of tools in close collaboration with the industrial stakeholders and capture all the requirements needed for such analysis from an industry's perspective. Research needs to be inter-disciplinary with the aim of developing interoperable tools. Funders can then reward the use of tools that are open-source and, meet interoperability criteria, and promote partnerships between academia and industry in funding programmes. There are few instances of implementations of such policy in EU Horizon 2020 projects such as EMB3RS and REUSEHEAT, where industries work in collaboration with academic institutions to build tools for the industrial EHC recovery capturing all requirements of the industrial stakeholders [63,150]. Such a policy would be complementary to other direct and indirect economic incentives to promote EH recovery and enable willingness of the industrial actors to invest in EHC recovery.

A direct policy indication from this review and experiences from attempts to develop multi-model and inter-operable toolkits is that it is beneficial to make such important investment decisions with the support of a portfolio of modelling analyses looking at the different layers of the problem. This helps to contextualize the results of the modelling studies and present them in terms that can be interpreted by industrial stakeholders and policy makers.

Furthermore, as the selected TEOMs are continuously being developed to add new functionalities, their suitability for the analysis of EHC recovery could change in the future. Most of the tools have a large community of users and developers and the available literature may change quickly. In addition, a significant share of the industrial EH requires an exergy based analysis to determine feasibility of using the EH in a DHS based on the quality of the heat. Thus, in the future, there is a potential to apply the methodology and the DST to exergy based optimisation tools.

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.

Data availability

No data was used for the research described in the article.

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