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Developing energy system scenarios for municipalities - Introducing MUSEPLAN

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ABSTRACT

The value of energy system scenarios is increasingly asserted in a decentralised and municipal context. There is, however, a lack of suitable tools for designing such scenarios, particularly tools that empower local planning practitioners in active participation. With this study, we introduce a novel tool designed specifically for municipal energy system modelling, thus bridging the gap between model developers and planning practitioners. The applicability and suitability of the new MUSEPLAN tool is investigated through its application in a case municipality, revolving around the needs of planning practitioners, supporting the build-up of modelling capacity, and focusing on the practical development of energy system scenarios. MUSEPLAN draws on the specialist simulation model EnergyPLAN but provides an environment for integrated design and comparison of multiple scenarios while reducing the complexity through discarding some of the more advanced options. In conclusion, MUSEPLAN resolves the identified challenges to the integration of energy system modelling in municipal energy planning, while simplifying the modelling and scenario evaluation process.

1. Introduction

Energy planning is inherently a complex issue due to the multidimensional nature of energy supply and demand across a multitude of energy sectors. Energy system modelling and energy system scenarios are tools that can aid energy planners in managing this complexity by providing a platform for assessing the effects and consequences of different energy system futures. Traditionally, energy planning, and in particular energy system modelling, has predominantly been conducted on a national scale, but recently municipalities and cities are showing a growing aspiration to carry out energy planning [1,2]. The importance of the local scale is evident from the growing body of literature on municipal energy planning, and Pasimeni et al. even argue that the municipal scale is the most suited spatial scale for investigating actions and strategies for reducing energy and environmentally related issues [3].

With the coming energy transition, the new energy paradigm calls for further focus on energy demands and the connection to appropriate energy supply technologies, also as an integrated part of local energy planning [4]. A natural prerequisite for this is that suitable energy system modelling tools exist that enable the evaluation of energy strategies and action plans and allow for the modelling of distinct alternatives considering local conditions and the values, preferences, and knowledge of local actors. Energy planners in cities and municipalities, however, generally prefer simple spreadsheet-based or "carbon calculator"-methods for assessing carbon emission reduction options, and such methods rarely account for more complex energy system interactions such as sector coupling and system dynamics [5,6]. Determining and exploiting cross-sector synergies are a pivotal part of the Smart Energy Systems concept [7], a framework for assessing and determining optimal energy system futures. Smart Energy Systems thinking seeks to mitigate the pitfalls of silo thinking and isolated projects that often plague traditional municipal energy planning. A paradigm shift towards integrated energy planning ensures that investments in energy infrastructure yield greater benefits for society as a whole and are aligned with the surrounding energy system [8], but necessitates that adequate practices and tools are in place.

Local governments are essential in the energy transition but face several critical challenges, including access to knowledge and appropriate tools and legal instruments for assessing and implementing

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national energy goals locally [9]. This perspective is supported by Krog, who investigated how municipalities deal with the transition to renewable energy (RE) systems through strategic energy planning [10, 11]. Krog found several strategic and practical barriers, including a lacking connection between the municipal and the national scale, resulting in unaligned expectations; a viewpoint also expressed by Thellufsen et al. [8].

Despite the benefits of integrating energy system modelling and scenarios in energy planning, cities and municipalities have not yet been able to integrate energy aspects in urban planning [12], emphasise short-term goals and actions, and often abandon energy system scenarios quickly [13]. This may, in part be due to limited energy system modelling capacity locally, as uncovered in a study by Schenone and Delponte who surveyed the Sustainable Energy Action Plans of ten cities [14]. They further concluded that planning and evaluation of renewable energy potentials are generally not based on a thorough evaluation of potentials but rather based on disjointed reasons and sporadic opportunities and that strategic decisions are primarily guided by national policies poorly adapted to the local context. These challenges are also supported by Chang et al. [15] who surveyed and reviewed 54 different energy system modelling tools used by municipal energy planners, amongst others, concluding that increasing complexity of modelling tools and linking of tools should not jeopardize interpretability and applicability of modelling for policy-makers.

1.1. Integration of energy system modelling in municipal energy planning

While modelling and scenarios are increasingly part of energy planning, existing research has identified several pertinent challenges to increased integration of energy system modelling in decentralised energy planning.

Yazdanie and Orehounig present key gaps and challenges in existing energy planning models for urban energy systems [16]. The challenges identified include lacking access and availability of data, model transparency and reproducibility, model complexity and a trade-off between model resolution and size, lacking knowledge on the interpretation of results and communication, and a continued need for capacity building. The authors suggest improving central frameworks and data collection to support local planning and improving modelling approaches to support the build-up of integrated scenarios. Similarly, Allegrini et al. review energy system modelling approaches for district-level energy systems, concluding that while there are many models and tools available, data availability, communication of results, and ease of use remain central challenges [17]. Ben Amer et al. [6] conducted a study on how municipal planners in Denmark apply software tools for energy planning purposes, finding little application of integrated energy system modelling due to a perceived complexity of such methods.

In a study on energy planning practices in municipalities, Johannsen et al. establish principles for the future development of energy system modelling tools relevant in a municipal context [18]. A generally positive attitude towards energy system modelling and scenario-based planning is determined among municipal planners, but also a discrepancy in the available tools and the energy planning capacity present in municipalities. The authors argue that future modelling tools need to support the build-up of internal modelling capacity, enable the utilisation of local knowledge, and provide understandable and actionable outputs.

Investigating the use of energy system models by municipal planners in Denmark, Ben Amer et al. conclude that municipal planners generally consider energy system models being too complicated and too narrowly focused [6]. They further find that municipal planners lack the expertise needed for establishing scenarios including the assessment of district heating (DH) potentials and this is therefore typically conducted by external experts. Chittum also established that while there are significant DH potentials in the USA, it "*remains well outside the typical energy policy discussions*" and thus beyond the energy planning [19]. Yu et al. also argue based on Danish case studies that a critical challenge to municipal energy planning is the dependency on DH consultants for heat planning [20]. Similarly, an observation from municipal planners is that the transport sector is insufficiently represented in energy system models [6], a concern also raised by Keirstead et al. [21].

In a literature review of studies employing energy system modelling for decentralised energy systems, Weinand et al. found that studies generally emphasise electricity demands and the residential sector, giving much less consideration to DH, industry, and transport sectors [22]. The authors conclude that methodologies that can involve local stakeholders in the modelling process should be developed so that local preferences can also be considered in the modelling.

Based on a review of practices in energy planning and modelling, Mirakyan and De Guio argue that uncertainty in energy models applied for energy planning in cities is not as well documented as model-based planning and decision-making in general [23]. They conclude that there is a need to further quantify the impact of different uncertainty aspects on energy planning, and secondly, that existing tools and methods have not supported the integrated energy planning processes and tasks in diverse energy scenarios, leading to limited uptake by planning practitioners.

The process of developing future energy system scenarios, including consideration of uncertainty, is generally closely connected to the modelling approach applied. Modelling approaches can broadly be categorised as either optimisation- or simulation-based, where "optimisation approaches" refer to models with endogenous investment optimisation (investment optimisation is done within the model) while "simulation approaches" refer to models with exogenous investment optimisation (investment optimisation is done outside the model) [24].

Johannsen et al. compared the implications of applying simulation and optimisation approaches respectively for a municipal energy system [25]. The authors found that the applied simulation approach could arrive at results comparable in terms of CO_2 emissions and total system costs based on a simple set of preestablished principles. Because of the iterative modelling process of simulation approaches and thereby inherent build-up of system understanding and knowledge and easier communication of results, Johannsen et al. argue simulation approaches may be preferable to municipal energy planners [25].

Based on the above review four primary challenges to the integration of energy system modelling in municipal energy planning are identified in Table 1.

These challenges serve as design and evaluation criteria for the presented MUSEPLAN.

1.2. Scope and structure

There are many benefits of conducting energy system analysis and developing scenarios also on a municipal scale, but such analyses and

Table 1
Primary challenges to the integration of energy system modelling in municipal energy planning.

Challenges	Description	References
Access to data	Obtaining the required model inputs is challenging (energy demands, technology data and costs, RE resources, etc.).	[16,17,26, 27]
Scenario design and evaluation	Establishing and evaluating multiple feasible future scenarios is challenging and is not sufficiently embedded and supported in traditional energy system modelling tools.	[18,23]
Knowledge and awareness of DH	The local potential for DH is often unknown to municipal planners, without the capability to make such an assessment of the future potential.	[6,19,20]
Tool complexity	Existing energy system modelling tools are overly complex and not well-suited for application by non-experts.	[6,21]

scenario work remain a challenge to most municipalities. The tools available for energy system modelling are not adapted to be used by planners without extensive modelling expertise or are not developed with a local, decentralised context in mind. In response to this gap, the MUSEPLAN energy system modelling tool was developed, a novel tool designed specifically for a decentralised and local context.

The main objective of this study is to evaluate how MUSEPLAN mitigates the four primary challenges *Access to data, Scenario design and evaluation, Knowledge and awareness of DH, and Tool complexity.* This is done through an application of MUSEPLAN in a case municipality to demonstrate the ability of the tool to develop energy system scenarios in a municipal context. The novelty of this study stems from the introduction and evaluation of an energy system modelling tool designed specifically to mitigate the specific challenges of energy system modelling observed in a decentralised context, for which few suitable tools exist.

In Section 2 MUSEPLAN is introduced as an alternative modelling tool for municipal energy system scenario design and analysis. This section focuses on the functioning of MUSEPLAN including integration with existing models, operation and use of the tool, and input and output data structure. Section 3 presents the results and practical experiences from the tool application in the case area Oud-Heverlee. Section 4 includes a discussion and evaluation of how the tool mitigates the challenges established. Finally, the main conclusions are presented in Section 5 alongside proposed areas for further research and development.

2. MUSEPLAN tool methodology

MUSEPLAN is an energy system modelling tool targeted at local energy systems, particularly cities and municipalities. The tool was developed based on insights from municipal planning practitioners [18] to provide a tool that supports municipal energy planners in developing local energy system scenarios to be used in their municipal energy planning. The tool including manual and documentation is freely available online [28]. This section introduces MUSEPLAN, fundamental design principles, and its general functioning including main data inputs, assessment and help tools, and scenario modelling process.

2.1. Tool design and modelling approach

MUSEPLAN is based on an existing energy system modelling tool, EnergyPLAN [29]. Both EnergyPLAN and MUSEPLAN allows for temporal evaluation of the operation of energy system scenarios, thereby including aspects such as peak demands, variable electricity production of renewable technologies, and energy storage technologies. This is done by simulating hourly energy balances in all the sectors of an energy system, including the heating, power, gas, transportation, industry, and water desalination sectors. The energy system is represented as a copper-plate model in terms of the electricity and gas system with no spatial specification of the location of demands and supply within the modelled system.

The advantage of using an existing documented and tested energy system tool is that it has been tested extensively and is well-documented. A 2022 paper discussing the validation and application of EnergyPLAN identified 315 journal papers in which EnergyPLAN was applied and argued for validation through application [30]. EnergyPLAN was developed mainly for large-scale energy systems, e.g., national energy systems, though previous studies have shown that EnergyPLAN can be useful for local energy system scenarios [31], as seen in case studies for the municipality of Aalborg [8], Varaždin County [32], the municipality of Altavilla Silentina [33], and the cities of Zagreb [34], Osimo [35], Utrecht [36], Bolzano [37], and Corvo [38]. However, even though EnergyPLAN is relevant for local energy system analyses, it was not designed for this purpose. Not all technologies are typically found in analyses for the municipal scale. As shown by Weinand et al. [22], a subset of technologies are relevant for municipal energy system modelling, while some technologies are more relevant in large-scale energy system analyses, and hence, for a local context, several adaptations are relevant.

Based on the primary challenges identified in Table 1 a series of model adaptations were outlined to mitigate these challenges and ensure that that MUSEPLAN is applicable and relevant specifically for a municipal energy planning context. An overview of the specific model adaptations outlined during the tool design process can be seen in Table 2. Further details on the specific adaptations of the EnergyPLAN tool is available in the included Appendix.

MUSEPLAN is a tool for analysing different energy transition pathways, based on what is referred to in the energy modelling community as "exogenous system optimisation" [24]. This means, that MUSEPLAN leaves it to the user to define the scenarios that are to be analysed thereby engaging the user directly in the choice of technologies and more. MUSEPLAN is based on defining a reference system and thereafter designing and analysing future pathways towards a desired goal. Such pathways are designated as scenarios. A scenario is a combined set of changes to the energy system – usually, something that can be combined under a common header for instance "High wind and electricity savings". Furthermore, MUSEPLAN works with "variations". In this example, variations could for instance be different combinations of wind expansion and electricity savings. Another scenario example could be "DH expansion" where variations could be different technology options for supplying DH. Due to its nature with user-defined scenarios, scenario development is a reiterative activity as indicated in Fig. 1.

MUSEPLAN simulates a local energy system, which can be connected to an external market e.g., a national transmission system based on a user defined capacity limitation, thereby allowing both modelling of island operation and interconnected operation of energy systems. Methane generation and other forms of power-to-X generation are excluded from the tool.

The user can compare and assess scenarios based on several criteria – economic, CO_2 emissions, fuel usage, and electricity exchange and depending on the specific objective of the energy transition process, the user will use one or more of these to modify the scenarios and variations. Typically, CO_2 emissions and costs are the main decision parameters [39], however, if for instance, the location is an island, in an area with a weak grid, or if self-sufficiency is of the essence, then a technical parameter like electricity exchange is relevant to observe. Electricity exchange indicates to what extent the modelled system relies on the surrounding world to maintain the balance between electricity production and demand. Thus, through the reiterative definition of scenarios and variations and the analysis of the simulation results, the user

Table 2
Primary challenges and associated model adaptations for MUSEPLAN.

Challenges	Model adaptations
Access to data	- Incorporation of help tools for data collection (energy demands, climate, and renewable energy generation data) - Online documentation and manual for data collection
Scenario design and evaluation	- Simulation-based modelling approach leading to a user-guided scenario design procedure - Embedded design, evaluation, and comparison functionalities for multiple scenarios - Immediate summation of key scenario outputs and results
Knowledge and awareness of DH	- Integration of geographical tools for assessment of DH potentials, including generation of cost curve, heat loss estimation, and total heat demand
Tool complexity	- Targeted limitation of technologies and model inputs - Descriptive explanations for all model inputs - Simplification and centralisation of model inputs - Familiar interface as a Microsoft Excel-based application

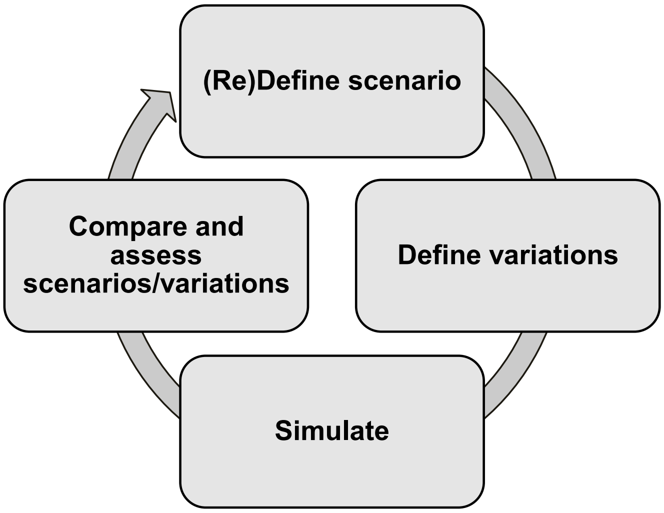

Fig. 1. Reiterative scenario development process in MUSEPLAN.

will identify appropriate transition strategies that meet the local objectives.

2.2. Model overview and inputs

Many inputs and data are needed to model an energy system. Generally, the most important inputs are various forms of energy demands, characteristics of energy supply technologies, and related cost parameters - investment costs, fuel costs, and operation and maintenance costs. This is also the case for energy system modelling in MUSEPLAN, and an overview of the main data inputs is shown in Fig. 2.

MUSEPLAN is an hourly model and requires hourly demand and supply data for one year. This allows the model to balance supply and demands of all energy sectors for all hours throughout the year. Import and export of electricity can be included both at a fixed price and as hourly variable electricity prices. More information about the different inputs as well as how to collect data can be found in Nielsen et al. [40]. External databases and resources such as e.g., the Hotmaps toolbox [41] can naturally also be used to source the required model inputs, however, this is not directly integrated in the tool and needs to be operated by the user externally.

Because the primary purpose of MUSEPLAN is to model energy transition scenarios with an emphasis of cross sector integration as opposed to detailed modelling of individual technologies, certain technology-specific details are omitted from the model. For example, detailed operational characteristics of power plants such as start and stop times and associated costs, or part-load capabilities. Similarly, power-to-X generation technologies are excluded from the tool, as modelling of these technologies require more detailed modelling approaches as was done in studies by Nastasi et al. [42,43], and as these technologies should be evaluated not only from a local perspective but rather from a broader perspective. Because the tool is intended for municipal energy planners, the need to generate holistic energy system scenarios outweighs ambitions for having highly detailed modelling of individual technologies, which would ultimately increase both the complexity of the modelling tool and process and increase the necessary technological know-how of users.

2.3. Assessment and help tools

An important finding from Section 1 was that obtaining the required data for energy system analyses in municipalities remains a significant challenge. To accommodate this a range of different assessment and help tools were developed and integrated into MUSEPLAN. This section

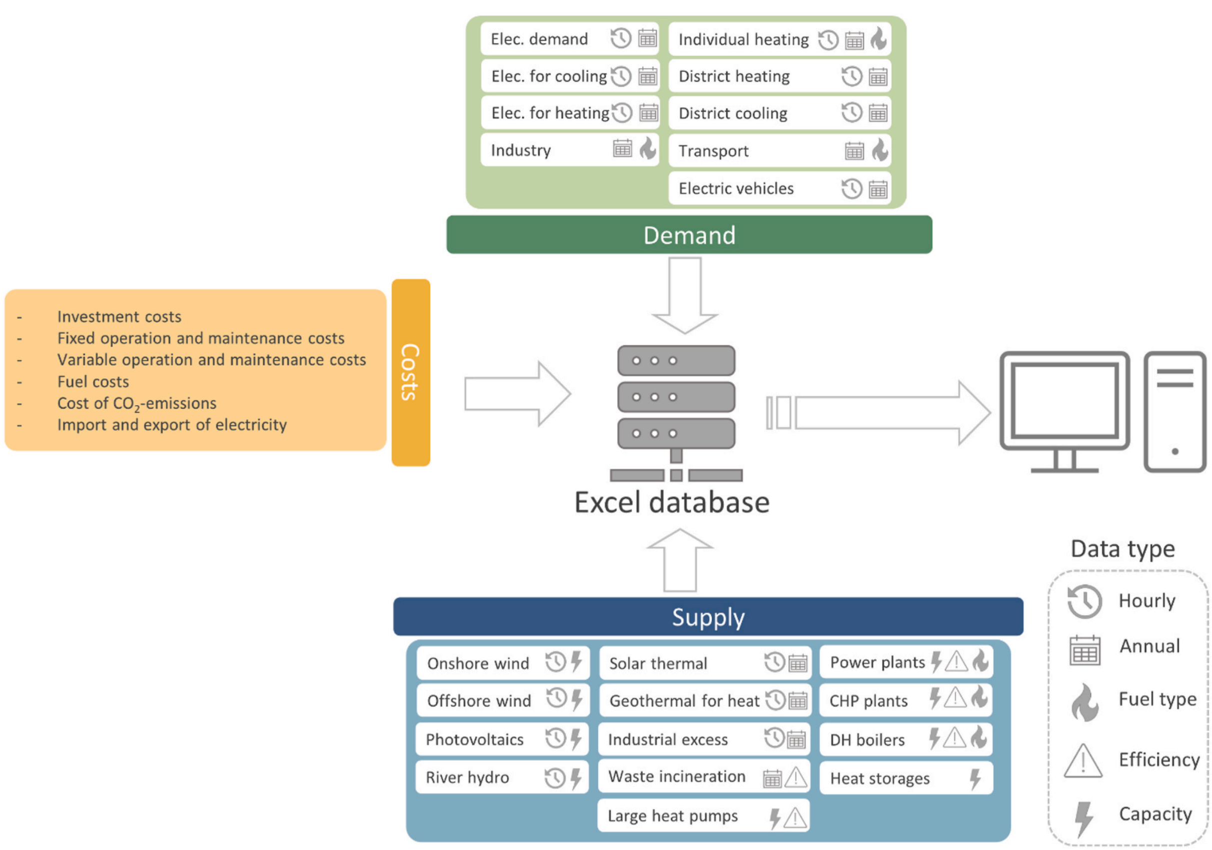

Fig. 2. General overview of the data inputs utilised by MUSEPLAN.

presents a brief overview of these assessment and help tools and how these can aid the user in collecting the required data for modelling.

2.3.1. Importing wind and photovoltaic (PV) production distributions

MUSEPLAN requires hourly production profiles for wind power and PV if these technologies are included in the scenario. This can be obtained within MUSEPLAN based on coordinates for a geographic location, based on which wind power and PV production profiles can be imported from Renewables.ninja [44,45]. The user needs to indicate the type of wind turbine to be included and PV technology details such as panel orientation.

2.3.2. Estimating local heat and cooling demands

If the user does not have access to local heat and cooling demands, these can be estimated within MUSEPLAN based on a built-in geoprocessing tool that estimates building typology and geometry for the investigated area. The user-required input is a GeoJSON file containing building geometry, which is open access and can be downloaded from Open Street Maps [46], and an hourly temperature time series from MERRA-2 data [47]. Heat and cooling demands are then estimated both per building and as aggregate for the investigated area, and hourly heating profiles are produced. For heating, both the space heating and hot water consumption are included. For DH and district cooling the grid loss is added as a constant. Climate change scenarios, i.e., changing temperatures with corresponding changing heat and cooling demands are not considered in this study. While it is unproblematic to model and simulate energy systems with changing heat and cooling demands in MUSEPLAN, the user would need to produce such demand projections externally.

2.3.3. Estimating the potential for DH expansion

The estimation of DH expansion potential is connected to the previous estimation of heat demands and includes an assessment of associated DH grid costs. The tool outputs a georeferenced TIF file containing aggregated heat demand data on a 100 × 100 m resolution for the defined geographical area. This file is then used to evaluate the end-user heat demand and calculates costs and losses using 10 % incremental steps of DH coverage. Because the DH tool does not know the current level of DH in the area its initial assumption is that no DH exists in the area. If DH does exist in the area the tool can be used to estimate grid loss and investment cost of the existing DH system by identifying the share of the end-user heating demand that is currently served by DH.

2.3.4. Estimating local roof-top PV potential

This tool can estimate the potential for roof-top PV for a geographic area based on a georeferenced file with building geometries, as was the case for the estimation of local heat and cooling demands. The user must estimate how much of the building footprint is available for PV panels, based on e.g., the typical angle of roofs and local planning restrictions for the investigated area.

2.3.5. Estimating local transport energy demands

Inputs for the transport demands can be estimated based on the population of the modelled area and standard values for transport demand, efficiencies, and load factors for passenger and freight transport. Transport demands are limited to passenger transport and freight transport by lorries due to the municipal scope of MUSEPLAN. To determine transport demand, the user needs to specify transport demand in terms of average km/person for both car and bus transport, and for freight transport in terms of ton-km/person. Load factors are also specified in terms of persons/vehicle, and for freight transport in tons/vehicle. The transport demand assessment tool assists the user in estimating and converting transport demands into energy consumption as inputs for MUSEPLAN. The model and energy system analysis does not differentiate between energy consumption for cars, busses, or lorries.

Further information on the included assessment and help tools is available in Refs. [40,48].

3. Case application

This section introduces the case area Oud-Heverlee (Belgium) and presents the results from the energy system modelling. The main purpose of the analysis is to investigate and demonstrate the capability and applicability of MUSEPLAN in mitigating the established primary challenges to integrating energy system modelling in energy planning in a municipal context; hence only a selection of relevant scenarios is explored as opposed to modelling all possible energy system futures. The modelled scenarios investigate the potential for transitioning the heat sector through electrification and DH, implementing renewable transportation, and combining these scenarios with increased local renewable electricity production.

3.1. Case introduction: Oud-Heverlee

Oud-Heverlee is a municipality in the Flemish region of Belgium with approximately 11,000 inhabitants. Oud-Heverlee already has a small amount of rooftop PV, some electric vehicles, and some households have heat pumps (HPs) for heating. However, the energy system of the municipality is still largely based on fossil fuels for heating and transportation, and electricity is mainly supplied from the national electricity grid.

Oud-Heverlee consists primarily of single-family houses (88 % of residential buildings in 2020), with the remaining housing facilities being mostly apartments. The municipality has experienced a slight growth in population from 2011 to 2020 of 0.9 %, and a gradual increase in housing facilities, increasing by 5.4 % in the same period. However, both growth rates are lower than the average of the Flemish region. The building stock consists of 44.3 % of buildings from before 1970, 20.5 % of buildings from the period 1971–1981, and the remaining 35.2 % being buildings constructed after 1981 [49].

A reference scenario for 2020 was established, functioning as a baseline for comparison for later scenarios. Because the focus is on modelling the local energy system and context, efforts were focused on modelling demands and technologies with the largest local impact such as the individual heating and transportation sectors. Industrial activity in Oud-Heverlee is limited, and there are no local power plants, hence these inputs are based on national statistics and a population-based share. This way, the scenarios account for the benefits Oud-Heverlee receive from national industries and power plants while accounting for a population-based share of the CO_2 emissions related to such production. Data and assumptions for individual and heat demands, transport demands, and renewable energy generation were collected through the assessment tools integrated in MUSEPLAN, while electricity demands were determined based on national statistics. Details on model inputs are available in the Appendix.

3.2. Modelled energy system scenarios

A reference scenario is modelled along with future scenarios for the heat sector and the transport sector. Scenarios for heat and transport are not combined; this is to test the influence of the heat and transport measures separately, allowing for more details to be included in the investigation of the heat and transport sectors, respectively. However, it is possible to model scenarios integrating changes across multiple sectors in MUSEPLAN.

In Table 3 an overview of the modelled heat scenarios can be seen. These 10 scenarios explore pathways for the transition of the heat sector and test the capabilities of MUSEPLAN. The modelling of these scenarios utilises many of the options and assessment tools included with MUSEPLAN, and the results and experiences from the application are therefore valuable to any further potential development of the tool.

Heating in the Reference Scenario is supplied solely through individual heating and mainly produced on natural gas boilers. With the heat scenarios in Oud-Heverlee, pathways for transitioning the heating

Table 3
Heat transition scenarios for Oud-Heverlee.

#	Scenarios - heating	Heating sector	Heat production	Storage	RE production
0	**Reference**	Individual heating	Present level	Present level	Present level
1	**Individual HPs**	100 % Indiv. electric HP	Electric HPs (individual)	No changes	No changes
2	**30 % DH**	30 % DH	Electric HP (indiv./DH) biomass boilers	24 h storage	No changes
3	**60 % DH**	60 % DH	Electric HP (indiv./DH) biomass boilers	24 h storage	No changes
4	**90 % DH**	90 % DH	Electric HP (indiv./DH) biomass boilers	24 h storage	No changes
5	**50 % indiv. HPs/DH**	50 % DH 50 % indiv. HP	Electric HP (indiv./DH) biomass boiler (DH)	24 h storage	No changes
6	**50 % indiv. HPs/DH**	50 % DH 50 % indiv. HP	Electric HP (indiv./DH) biomass boiler (DH)	24 h storage	+2 MW wind/PV
7	**50 % indiv. HPs/DH**	50 % DH 50 % indiv. HP	Electric HP (indiv./DH) biomass boiler (DH)	24 h storage	+4 MW wind/PV
8	**50 % indiv. HPs/DH**	50 % DH 50 % indiv. HP	Electric HP (indiv./DH) biomass boiler (DH)	24 h storage	+6 MW wind/PV
9	**50 % indiv. HPs/DH**	50 % DH 50 % indiv. HP	Electric HP (indiv./DH) biomass boiler (DH)	24 h storage	+8 MW wind/PV
10	**50 % indiv. HPs/DH**	50 % DH 50 % indiv. HP	Electric HP (indiv./DH) biomass boiler (DH)	24 h storage	+10 MW wind/PV

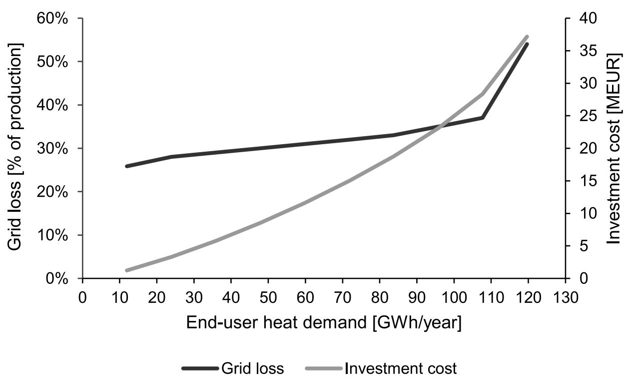

Fig. 3. Cost curve and grid loss for DH expansion in Oud-Heverlee. A demand of 10 GWh/year corresponds to approximately 365 houses.

sector are explored and the assessment tools included with MUSEPLAN are used for estimating the potential for DH. In Fig. 3, the established cost curve for DH expansion in Oud-Heverlee can be seen. This cost curve is based on a mapping of heat demand densities, established from a combination of building geometric data from OpenStreetMap [46], building tabula data from the Building Stock Observatory [50] and climate data from MERRA-2 [47]. Further information on the methodology is available in Nielsen et al. [40]. Long-term energy storage is not considered in the case as there are no seasonally restricted heat generation available, e.g., solar thermal heating. Hence heat storage is mainly relevant for balancing daily and weekly fluctuations.

From Fig. 3 it is evident that grid costs and grid losses gradually increase as an increasing share of the municipality is converted to DH. Observed grid losses are relatively high because of the generally scattered houses in the municipality; this naturally becomes more critical as the DH implementation rate increases.

In Table 4 the main inputs for the heat scenarios can be seen. Here the distribution of individual heating relative to the DH demand is shown, and how peak demands, production capacity and storage capacity increase as the DH demand increases.

For the transport sector, 10 scenarios are also investigated, as shown in Table 5. The transport scenarios investigate different transition pathways including different combinations of vehicle types, smart charging, and renewable electricity generation capacity.

Pathways for renewable transportation in Oud-Heverlee are explored in transport scenarios. The scenarios revolve around converting the current fleet of fossil fuel passenger vehicles to electricity and the conversion of busses and lorries to hybrid alternatives.

MUSEPLAN furthermore includes options for testing dumb-charge relative to smart-charge strategies for electric vehicles. Dumb-charge assumes that no intelligent controlling of charging strategy is applied, while smart-charging seeks to reduce the excess electricity production and electricity production from power plants by smart-charging of electric vehicles. Smart-charge vehicles are given the option to do vehicle-to-grid discharging, thereby assisting in balancing the grid.

It should be noted that the transport demands (in terms of passenger kilometres and ton kilometres) do not change throughout the analyses; only the energy consumption varies, as a result of using different combinations of vehicle types with different engine efficiencies and thus energy consumption.

In Table 6 the main inputs for the transport scenarios can be seen, illustrating how diesel and petrol consumption decreases as an increasing number of electric vehicles and hybrid vehicles are implemented. Furthermore, the balance between dumb-charge and smart-charge vehicles and battery capacity available for vehicle-to-grid (V2G) charging is shown.

Table 4
Overview of main inputs for heat transition scenarios for Oud-Heverlee.

	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
DH demand [GWh]	0.00	0.00	35.89	71.78	107.68	59.82	59.82	59.82	59.82	59.82	59.82
Individual heating demand [GWh]	119.64	119.64	83.75	47.86	11.96	59.82	59.82	59.82	59.82	59.82	59.82
DH peak load [MW]	0.00	0.00	17.44	34.87	52.31	29.06	29.06	29.06	29.06	29.06	29.06
DH storage capacity [MWh]	0	0	194	388	582	388	388	388	388	388	388
Fuel boiler capacity [MW]	0.00	0.00	20.92	41.85	62.77	34.87	34.87	34.87	34.87	34.87	34.87
Electric HP capacity [MW_e]	0.00	0.00	2.69	5.38	8.08	4.49	4.49	4.49	4.49	4.49	4.49

Table 5
Transport transition scenarios for Oud-Heverlee.

#	Scenarios - transport	Cars	Bus/freight	Smart charge (SC)	RE production
0	**Reference**	Conventional	Conventional	None	Present level
1	**EVs 25 %**	25 % EVs	Conventional	None	No changes
2	**EVs 50 %**	50 % EVs	Conventional	None	No changes
3	**EVs 75 %**	75 % EVs	Conventional	None	No changes
4	**EVs 100 %**	100 % EVs	Conventional	None	No changes
5	**EVs and hybrid bus/freight**	100 % EVs	100 % hybrid	None	No changes
6	**SC EVs and hybrid bus/freight**	100 % EVs	100 % hybrid	80 % SC	No changes
7	**SC EVs and hybrid bus/freight (RE)**	100 % EVs	100 % hybrid	80 % SC	+2 MW wind/PV
8	**SC EVs and hybrid bus/freight (RE)**	100 % EVs	100 % hybrid	80 % SC	+4 MW wind/PV
9	**SC EVs and hybrid bus/freight (RE)**	100 % EVs	100 % hybrid	80 % SC	+6 MW wind/PV
10	**SC EVs and hybrid bus/freight (RE)**	100 % EVs	100 % hybrid	80 % SC	+8 MW wind/PV

Table 6
Overview of main inputs for transport transition scenarios for Oud-Heverlee.

	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
Diesel consumption [GWh]	27.71	22.2	16.69	11.18	5.67	2.36	2.36	2.36	2.36	2.36	2.36
Petrol consumption [GWh]	28.57	21.43	14.29	7.14	0	0	0	0	0	0	0
Biofuel consumption [GWh]	4.21	3.26	2.31	1.36	0.4	0	0	0	0	0	0
Dumb-charge demand [GWh]	0	2.63	5.26	7.88	10.51	10.51	2.1	2.1	2.1	2.1	2.1
Smart-charge demand [GWh]	0	0	0	0	0	0	8.41	8.41	8.41	8.41	8.41
Battery storage capacity[a] [MWh]	0	0	0	0	0	0	215.60	215.60	215.60	215.60	215.60

[a] Combined battery storage capacity of smart-charge vehicles available for V2G charging.

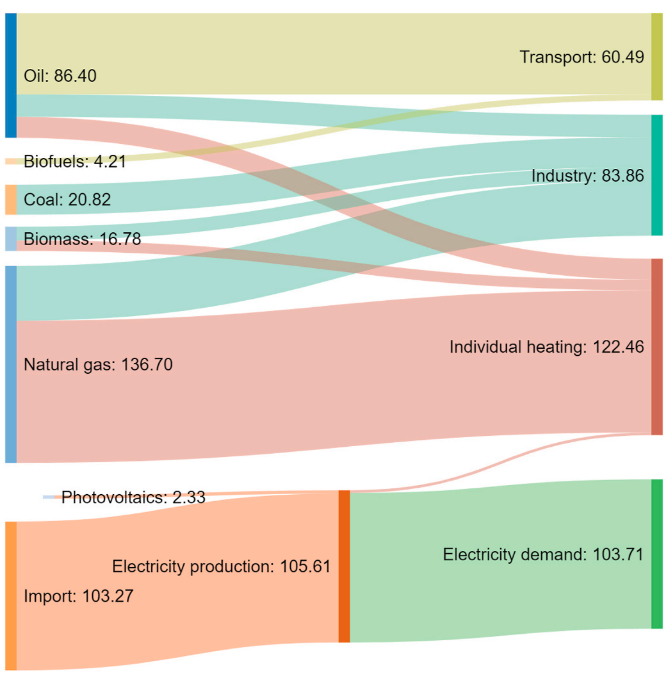

Fig. 4. Reference Scenario energy flows [GWh] for Oud-Heverlee.

Common for both the heat and transport scenarios is that the scenarios test the ability of MUSEPLAN to run multiple scenario iterations based on a reference scenario while implementing various changes e.g., increasing RE capacity. This makes it possible to compare results across different scenarios while ensuring that all scenarios and results are confined to one data file.

3.3. Scenario outcomes

Energy demands in the Reference Scenario per energy sector and fuel type can be seen in Fig. 4. Individual heating is the most energy-consuming sector, consisting largely of a natural gas demand due to the prevalence of natural gas boilers in households. The electricity demand is almost entirely supplied through import from the national electricity grid due to little local production capacity without any power plants, while the industrial energy demand is supplied through a combination of coal, oil, natural gas, and biofuels. The transport demand is almost entirely supplied from oil due to the prevalence of conventional fossil-fuelled vehicles, and to a limited extent supplemented by biofuels due to the addition of bioethanol.

The resulting energy consumption for the heat transition scenarios can be seen in Fig. 5. For all scenarios, the total energy consumption decreases compared to the Reference Scenario. This is mainly because HPs are implemented in both individual heating and DH, and these are more efficient than the existing natural gas boilers. In scenarios with high shares of DH conversion, the total energy consumption increases as the grid loss increases. Finally, it can be seen that with increasing local renewable electricity generation capacity the electricity import is decreased, as an increasing amount of electricity is produced locally.

The resulting energy consumption for the transport transition scenarios can be seen in Fig. 6. It is seen that compared to the reference scenario, implementing electric and hybrid vehicles decreases the total energy consumption, mainly because of the higher efficiencies of electric vehicles and hybrid bus and freight transport. This most notably causes a reduction in oil consumption, and increases electricity import due to increased electricity demand. As the heating sector is not changed in these scenarios a large natural gas consumption remains for individual gas boilers.

In Fig. 7 the renewable share of fuel in the heat and transport scenarios can be seen. In the heat scenarios, it can be observed that increasing the share of DH increases the RE share, mainly because of the increased use of biomass in DH fuel boilers. Electricity imported from

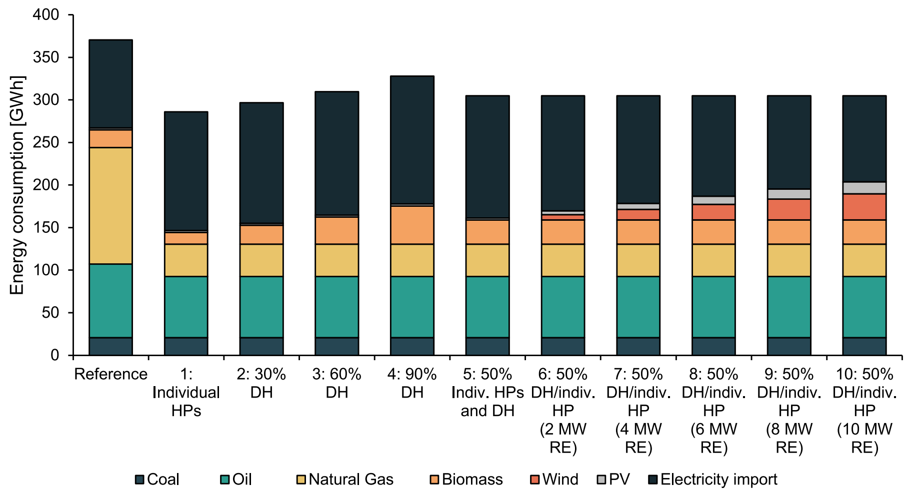

Fig. 5. Energy consumption in heat transition scenarios for Oud-Heverlee.

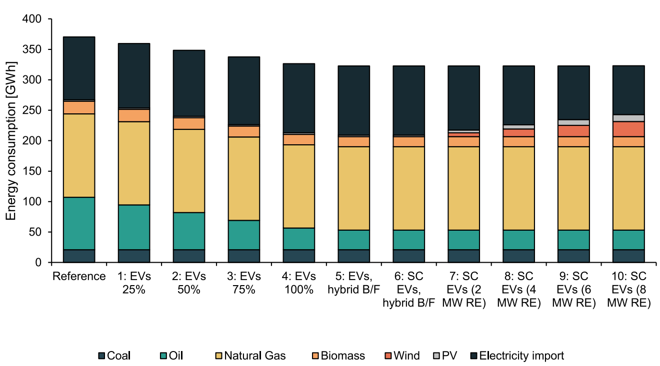

Fig. 6. Energy consumption in transport transition scenarios for Oud-Heverlee.

the national electricity grid accounts for an average CO_2 emission factor of 0.285 t CO_2/MWh, equal to the average emission factor for grid electricity in Belgium in 2020 [51]. Local electricity produced from PV and wind power is considered to have an emission factor of 0 t CO_2/MWh, hence the RE share increases further when combined with local renewable electricity production. In the transport scenarios, it can be observed how simply shifting to electric vehicles does not increase the RE share due to the assumed CO_2 emission factor. In the transport scenarios, electric vehicles need to be combined with increased renewable electricity production capacity to increase the renewable share of fuel.

In Fig. 8 changes to CO_2 emissions can be seen. Similarly, results can be observed for both heat and transport scenarios – generally increased electrification, whether that is from electric HPs or electric vehicles, reduce CO_2 emissions because of increased efficiency. This effect becomes more pronounced as the renewable electricity production capacity increases.

In Fig. 9 net electricity import can be seen. A similar trend is observed for the heat- and transport transition scenarios where local renewable electricity production capacity reduces the amount of electricity imported from the national grid. This effect is, however, partially offset by the increasing electrification occurring in most of the scenarios (HPs in DH and individual heating, EVs), resulting in increased electricity demand. The combination of smart charging EVs and local renewable electricity production is most capable of reducing electricity imports due to the flexibility of the charging for the EVs.

In Figs. 10 and 11 total annual system costs can be seen for the heat- and transport transition scenarios. For both the heat- and transport-transition scenarios, investment costs constitute the most significant cost, and specifically for the heat transition scenarios, the investment

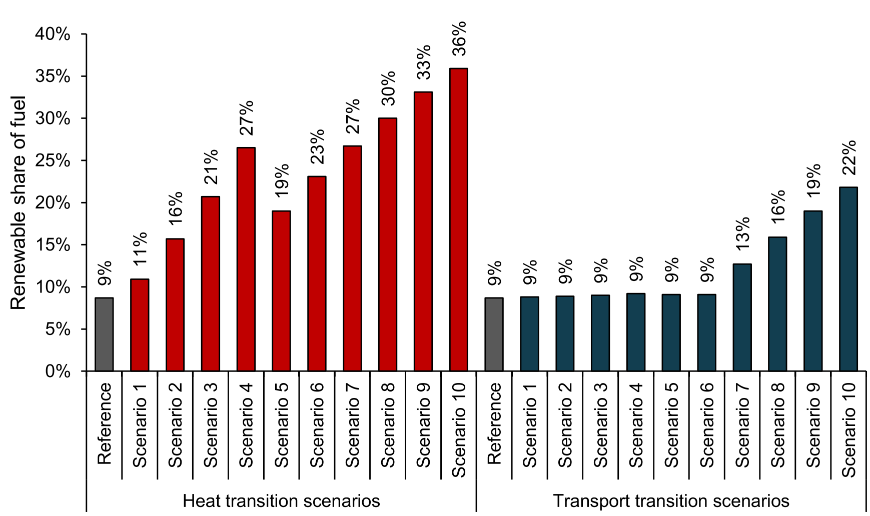

Fig. 7. Renewable share of fuel in heat- and transport transition scenarios for Oud-Heverlee.

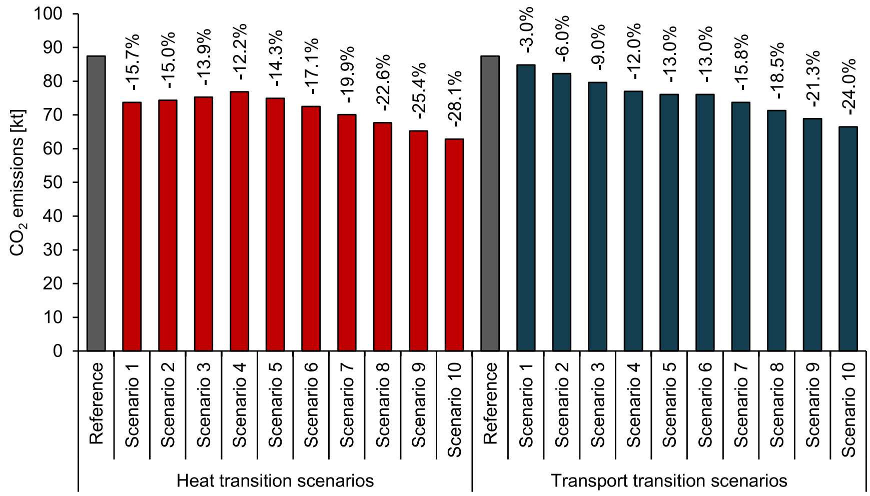

Fig. 8. CO_2 emissions in heat- and transport transition scenarios for Oud-Heverlee.

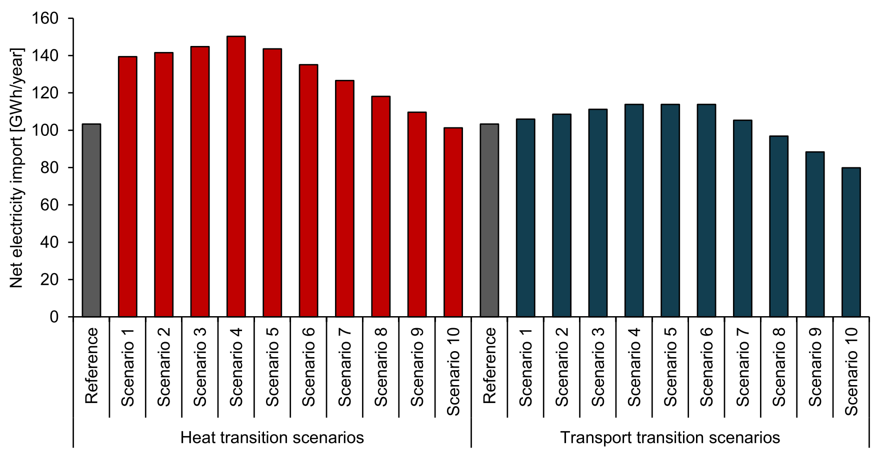

Fig. 9. Net electricity import in heat- and transport transition scenarios for Oud-Heverlee.

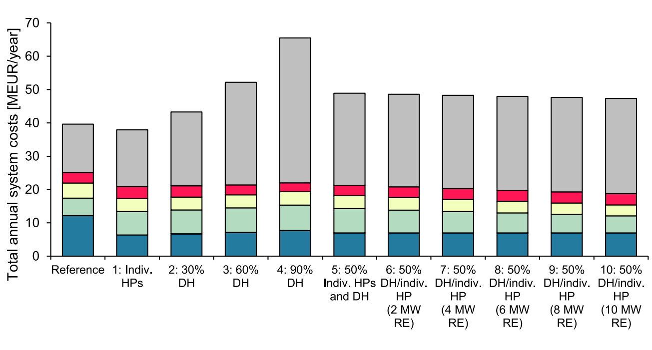

Fig. 10. Annual system costs for heat transition scenarios by category for Oud-Heverlee.

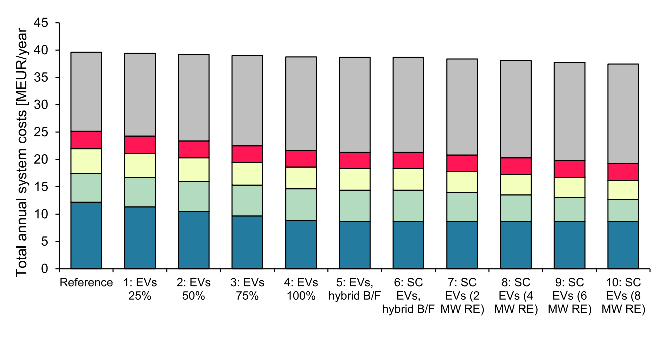

Fig. 11. Annual costs for transport transition scenarios by category for Oud-Heverlee.

cost increases significantly as the DH implementation rate increases. A complete conversion to individual electric HPs provides a lower-cost alternative compared to the reference, while a combination of individual electric HPs and DH is more expensive than the reference. For the transport transition scenarios, it is seen that shifting from conventional fossil fuel-based vehicles to electric vehicles results in lower total annual costs for the system. Finally, a general observation for both the heat- and transport transition scenarios is that local renewable electricity production reduces total system costs, increases the local RE share, and thereby reduces CO_2 emissions.

4. Discussion

Ten different heat- and transport transition scenarios were modelled for Oud-Heverlee to demonstrate the capabilities of MUSEPLAN in modelling municipal energy system scenarios. The scenarios explored different combinations of individual HPs, DH, electrification of passenger vehicles and renewable electricity generation capacity. This section discusses how the four challenges to energy system modelling in municipal energy planning established in Table 1 in Section 1.1 are mitigated in MUSEPLAN.

4.1. Access to data

Access to data was established to be a critical challenge to the modelling of municipal energy system scenarios. MUSEPLAN includes several assessment tools for estimating both demands (heating, cooling, and transportation) and renewable energy production (PV and wind). This simplifies the modelling process, but still, many data points are required, and good access to (local) data significantly helps the user develop scenarios. Municipalities with limited internal modelling capacity are likely not used to perform continuous data collection and agreements for data exchange may not be in place with local utility companies and TSO/DSO.

Muñoz et al. developed a methodology for integrated modelling of city energy systems and concluded that the main flaws of their methodology are the need for increased efforts in data-gathering and the difficulty of characterizing the transport sector and implementing new mobility measures [52]. Pérez et al. developed a methodology for establishing energy balances in municipalities, and like Muñoz et al., emphasised the pivotal limitation of data access in modelling [53]. There is no reason this task should be left solely at the responsibility of the planning practitioners seeking to use energy scenarios in planning; rather modelling tools should support the collection of the required data.

4.2. Scenario design and evaluation

Scenario design and evaluation are embedded in MUSEPLAN which supports evaluation and comparison of multiple energy system scenarios concurrently. These functionalities were used extensively in the case of Oud-Heverlee and constitute a significant advantage over existing energy system modelling tools, such as EnergyPLAN, for modelling municipal energy system scenarios. The scenarios developed focus on the heating and transportation sector and were mostly evaluated based on CO_2 emissions, thus allowing for an assessment of mitigation impact of planned policy measures. Such assessments are becoming increasingly relevant as part of energy planning in cities and municipalities, and as argued by Koldo et al., energy transition-related decisions should to a greater extent be backed by detailed energy models and scenarios [54].

However, there is a need for adequate tools and models for this purpose specifically for the municipal level, as established by Poggi et al.: *"(…) a considerable gap in the elaboration of practice-oriented approaches capable of aiding local authorities in the preparation of development plans where energy efficiency goals are covered."* [55]. According to Poggi et al., this gap is evident in all planning processes from problem formulation, analysis, diagnostic, and implementation. Sillak et al. assessed co-creation processes in cities' strategic energy planning to determine whether co-creation can accelerate energy transitions, finding that there is a need for more methods facilitating co-creation in the initiation, design, and implementation phases [56]. Future studies could investigate how MUSEPLAN can support co-creation processes in municipal energy planning as part of developing relevant local energy system scenarios for the energy transition.

4.3. Knowledge and awareness of DH

Knowledge and awareness of DH are important in holistic energy planning due to the potential for the integration of variable renewable electricity generation [57]. DH is generally not integrated sufficiently in energy planning at the urban and municipal scale [12], in part due to a lack of appropriate tools and methodologies for coupling urban planning and heat planning [20]. MUSEPLAN includes tools for estimating local heat demands and estimating future district heating potentials including costs and heat losses based on spatial heat density analysis, providing valuable inputs to municipal energy system analyses. Similar methodologies have been applied in previous research, e.g., in analyses of the future DH potential of Denmark [58,59], Switzerland [60], and France [61], but the methodologies established in these studies are country-specific and not an integrated part of a holistic energy system modelling tool.

One advantage of the DH potential assessment methodology included with MUSEPLAN is that it is not delimited to a specific country as it is based on OpenStreetMap data and thereby available in most regions. Secondly, the DH potential can immediately be included in a holistic energy system modelling and -analysis, thus allowing for an assessment of the impact on the energy system. The country-specific methodologies established in previous research employ country-specific data potentially of higher accuracy than universally available OpenStreetMap data. With MUSEPLAN the primary motivation was to establish something that is universally available, and naturally, some trade-off in terms of accuracy is expected.

4.4. Tool complexity

Tool complexity, and specifically how to limit complexity, is not a trending topic in the field of energy system modelling tools. This is evident in a review of tools conducted by Chang et al.: *"We identify three main trends of increasing modelling of cross-sectoral synergies, growing focus on open access, and improved temporal detail to deal with planning future scenarios with high levels of variable renewable energy sources"* [15]. From this, it appears that the focus in energy system modelling tools is more on increasing the technical ability rather than on user experience and utility for planners.

The opposite has been the primary concern in MUSEPLAN – reducing complexity by limiting the technical ability in areas not relevant to municipal energy scenarios and improving the user experience by providing a simplified modelling interface with integrated assessment and help tools. MUSEPLAN applies a simulation approach which, as argued in Ref. [25], due to the iterative nature of the approach supports a build-up of system understanding and technology interactions that is not immediately present in optimisation-based approaches.

Simulation-based approaches also generally more easily allow for more diverse evaluation criteria relative to optimisation-based approaches which traditionally primarily target costs and CO_2 emissions [62]. It is possible to combine optimisation-based modelling with additional evaluation criteria [63], but such approaches generally increase the modelling complexity and widespread application by planning practitioners is likely infeasible.

5. Conclusion

Municipalities are increasingly involving themselves in integrated energy planning and seek to employ energy system modelling and energy scenarios for this. There is a lack of suitable tools and models designed specifically for energy system modelling and assessment of cross-sector interactions in municipal energy planning for planning practitioners.

This study presented four critical challenges to increased integration of energy system modelling in energy planning at the municipal scale, namely 1) Access to data, 2) Scenario design and evaluation, 3)

Knowledge and awareness of DH, and 4) Tool complexity. In response to these challenges, the MUSEPLAN energy system modelling tool, a modified and simplified version of the advanced energy system analyses tool EnergyPLAN was designed specifically for the municipal context and applied to a European case study.

The four primary challenges are mitigated through a series of novel functionalities embedded in MUSEPLAN.

1) Access to data: An array of help tools assist the user in gathering necessary data, including energy demands and demand profiles, solar PV potential, and renewable energy generation profiles.
2) Scenario design: Built-in functionalities for simulating multiple scenarios and variations starting from a reference scenario provides an intuitive platform for designing future energy system scenarios.
3) Knowledge and awareness of DH: An integrated tool for estimating DH potential for a local area based on heat demand density provides the user with opportunities for making own assessments of local DH potentials.
4) Tool complexity: An intuitive modelling interface, a reduction in technologies and technical options given the local scope, combined with comprehensive assessment tools reduce the functional tool complexity.

The case application and analysis in the municipality of Oud-Heverlee show significant decarbonisation potential combinations of individual HPs, DH, electric vehicles, and local RE production capacity (wind and PV). The main purpose of the analysis is to test the capability of the tool and the results that can be provided; hence the results should not be considered as an indisputable and elaborate depiction of energy system futures in Oud-Heverlee. Additional energy system scenarios can, and should, be established as part of developing a comprehensive energy strategy. MUSEPLAN evaluates the energy system considering cross-sector interactions and thus benefits across energy sectors stand out. This is both in terms of changes in energy demands, e.g., the conversion from natural gas to electricity-based heating or observed discrepancies of local renewable electricity production and electricity consumption caused by increased electrification. In conclusion, MUSEPLAN helps to mitigate the established challenges to increased use of energy system modelling and energy scenarios in municipal energy planning. This is done by improving access to required data, simplifying the process of modelling and evaluating multiple future scenarios, enabling the assessment of DH potentials, and reducing tool complexity by simplifying both the range of technologies included and their implementation in line with the municipal context. Energy system scenarios developed with MUSEPLAN can provide valuable inputs to municipal energy planning and the process of modelling scenarios can contribute to a build-up of local energy system modelling capacity and system knowledge.

Future research could explore the practical application of MUSEPLAN by municipal energy planners as part of continued advancement of energy planning practices, integration of energy system modelling and scenarios, and further development of modelling methodologies for the municipal context. Further research and development of the MUSEPLAN tool, as well as other municipal energy system modelling tools, could pursue further integration of additional external tools and data sources, such as e.g., the Hotmaps toolbox, in addition to methods for estimating local energy efficiency potentials.

CRediT authorship contribution statement

Rasmus Magni Johannsen: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Peter Sorknæs:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Poul Alberg Østergaard:** Conceptualization, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing. **Diana Moreno:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **Steffen Nielsen:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Sara Abd Alla:** Conceptualization, Writing – original draft, Writing – review & editing. **Giorgio Bonvicini:** Conceptualization, Writing – original draft, Writing – review & editing.

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

Data included in the appendix.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2024.100141.

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