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Full-length article

A new approach for modelling techno-economic performance of integrated energy systems on district scale for informed decision-making in a multi-stakeholder context

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ABSTRACT

To better support informed decision-making around renewable heating strategies on local scale, a new methodology was developed for simulating integrated heating scenarios. This paper proposes, describes and demonstrates the modeling methodology with a focus on a variety of KPIs, allowing a more inclusive evaluation of technical options, systems and scenarios. Key KPIs include system costs, CO_2 emissions, mitigation costs and end-user costs and investments. Key function of the model is an in-depth cost analysis by a breakdown of costs among types of measures (home equipment, insulation, local equipment and infrastructure), cost components (investments, O&M, taxes, subsidies) and stakeholders (system, government, owner-occupiers, renters, real estate owners, grid operators and local entrepreneurs). The methodology was applied to a fictive Dutch neighbourhood according to the urban and building typology provided in the paper. The results of six scenarios show large variety in costs among scenarios with significantly higher costs than the reference scenario in all scenarios, with scenario 'hybrid' and 'efficiency' presenting the best potential of becoming cost-competitive with the reference scenario in 2030. The method is suitable for evaluating a wide diversity of settings and contexts.

Abbreviations

KPI	key performance indicators
UTES	underground thermal energy storage
PTES	Pit Thermal Energy Storage
KNMI	Koninklijk Nederlands Meterorologisch Instituut (Royal Netherlands Meteorological Institute)
KEV	Klimaat- and Energieverkenning (Climate and Energy exploration)
PV	photovoltaics
MT	medium temperature

1. Introduction

The building sector faces major challenges in the coming years to be able to contribute to national and international targets for CO_2 emission reduction. Whereas much attention goes to renewable electricity generation, the largest share of energy consumption in the built environment in North-Western Europe is used for heating. However, renewable heating has received little attention from policy-makers in recent years compared to renewable electricity [1,2]. In the Netherlands, where the buildings sector is gas-dominated, national policy is aimed at natural gas free districts. Municipalities are legally bound to develop heating strategies for each district. National support is provided in the form of the 'Startanalyse', which gives municipalities a first indication of which heating strategy is most plausible for each district [3]. The search for more advanced planning tools that take into account the local physical characteristics at a detailed level based on which informed decision-making can take place is ongoing. To accommodate the transition of the building sector, more focus should be on renewable heating systems, infrastructure changes and improvement of the efficiency of building envelopes.

Various reviews have assessed the application of existing models on local scale, which are summarized by Bouw et al. [4]. This review has shown that models that are able to model all the necessary aspects to evaluate renewable heating systems in sufficient level of detail are

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scarce whereas the need for simple modeling tools and decision support systems for energy planning is large. This is especially a concern at the district level where many decisions concerning the transformation of the building stock are taken and for which planning tools are lacking, as also indicated by Allegrini et al. [5]. Existing models, such as Markal, LEAP and EnergyPlan are often identified in the literature as insufficient for energy planning on the local scale while suitable alternative models are lacking as well [6–10]. Current established models lack much of the techno-economic detail and multi-commodity focus to be able to adequately represent energy systems and evaluate key decisions on a local scale.

Recent academic insights in the requirements for planning models and decision-support tools that can guide the heat transition on local scale have identified multiple areas of model development. Firstly, an *integrated approach* is needed where heat and electricity are equally represented and at sufficient level of detail, as concluded by Bouw et al. [4]. This places a number of technical requirements on the selection and design of modeling components. Lyden et al. [11] identified limitations in district heating modeling and thermal storage in models for community scale energy systems, such as the exclusion of temperature variations, that need to be addressed for realistic modeling of hybrid systems. Jalil-Vega and Hawkes [12] stress the importance of including infrastructure and end-use-technologies to evaluate heat decarbonisation pathways. They recommend to include the three key different distribution networks (electricity, gas and heat) in models, as well as different temperature heat networks, and explicit infrastructure trade-offs, among others. Existing models focused on the built environment do not include infrastructure at a sufficient level of detail to allow the trade-off between individual building and district heat supply technologies and associated infrastructures [4,12]. Thermal components should also be included on the right scale to consider building measures and local spatial aspects. What is needed is a dedicated planning model that generates detailed scenarios with variations of system components, including various heat sources, different sizes and capacities of (end-use) equipment, various insulation levels, temperature levels, commodities, etc. A dedicated tool should also take into account both small time steps as well as long-time ranges, as stated by Connolly et al. [7,13], a requirement that is met by only very few existing models [7].

Secondly, a *stakeholder approach* is needed to provide the information needed to support decision-making that leads to the selection of options that are likely to be adopted by end-users. The difficulty of finding models and modeling tools that can effectively facilitate the heat transition, was addressed by Cowell and Webb [14], who say that knowledge generated by planning models is not well aligned with the decision-making context. Heat decarbonization models require a more open, reflexive approach they say, allowing a broad inclusion of actors because decisions concerning the heating of buildings take place on multiple levels. Bakhtavar et al. [15] stressed the importance of including stakeholder priorities in scenario selection and investigated the effects of changing decision-maker priorities on the outcomes for different stakeholder groups. The importance of effective communication of results for decision-making by tailoring to different stakeholders is also addressed by Yazdanie and Orehounig [16]. Creating insight in alternative technologies to all decision-makers that are involved at the local level, with more focus on end-users costs as identified by Henrich et al. [17], on multiple criteria, would be necessary to reach decisions on measures that can be successfully implemented. Solutions and recommendations resulting from the modeling process will most likely differ from optimal solutions found for individual companies or groups of interest [18]. Therefore, stakeholder dialogue should be supported with detailed information on the consequences of different strategies. Integrated planning methods require the inclusion of stakeholder decision-making [19], but current models are insufficiently capable to do so [8,19]. As Torabi Moghadam et al. [10] mention, a shared framework between stakeholders is needed to engage stakeholders in the planning process. Hence, the representation of different stakeholder groups forms an additional modeling challenge.

Thirdly, a *pragmatic approach* is needed in the form of simple modeling tools to support the planning practice rather than complex models whose output is difficult to interpret for practitioners [5,20]. Henrich et al. [17] studied the advantages and limitations of energy models used by municipalities concerning the natural-gas free heating transition in the Dutch context and concluded that perceived limitations include that models and modeling results were considered too abstract for analysis of local circumstances, too general or too simplified for local analysis. Bakhtavar et al. [15] also mention the need for practical tools in the energy planning domain, specifically by lowering the complexity and high computational times of the analysis. Instead, the focus should be on a richness of data output while the modeling framework itself remains relatively simple.

A new modeling methodology is proposed that deals with the aforementioned modeling challenges. In this paper, the methodology will be described and demonstrated. We will show how the techno-economic detail is improved in comparison to other tools, with a focus on heating and building characteristics. The multi-stakeholder context, which is central to the modeling approach, is addressed by providing the required input for supporting informed decision-making among involved stakeholders. The use a diverse set of KPIs is introduced which shows how solutions can be evaluated from a broader perspective, allowing a better compliance with stakeholder needs. Next to common KPIs, such as total costs and CO_2 emissions, the distribution of costs among stakeholders and future costs were added in the analysis as relevant KPIs.

The focus in this paper lies on the techno-economic model, that forms the basis of a participatory energy planning methodology. Eventually, the proposed model will be connected with social and other non-technical components related to the energy planning process. The model in this context should be seen as part of a broader modeling methodology, where the model is applied in combination with other tools and methods around district analysis, local data collection and stakeholder dialogue.

2. Methodology

With the aim of assessing the relevance of the identified model improvements for providing input for stakeholder dialogue, a new model was constructed in the MATLAB/Simulink environment. The developed modeling methodology aims to deal with the previously introduced challenges and bottlenecks. The model development has focussed on providing the information necessary to evaluate and compare renewable heating scenarios in both a detailed manner and from a broad perspective, including the evaluation of multiple KPIs.

Analysis was performed with the developed model to demonstrate how scenarios for renewable heating can be compared inclusively and how system effects are impacted differently between stakeholders and system components. Therefore, detailed cost data were generated by break-downs in different components: (1) breakdown in cost components (VAT, energy tax, subsidies), (2) breakdown in system components (equipment costs, building insulation costs, grid costs and fuel costs) and (3) breakdown in stakeholder groups (end-users, real estate owners, tenants, grid operators, local energy companies, government and the system). The proposed structure creates a clear overview of which costs are attributed to whom, and makes hidden costs, such as subsidies, visible so that system choices can be evaluated inclusively.

For long-term analysis, the model includes different sight years (2020-2050 in steps of 5 years), with adapted commodity prices (See Appendix A, Table A.1) and application of learning rates of technologies (see Appendix A, Table A.4). Future costs as result of energy price developments and cost reductions of renewable technologies were evaluated with a focus on 2030. Additionally, a sensitivity analysis was performed on the included data to further identity information gaps related to renewable heating technologies.

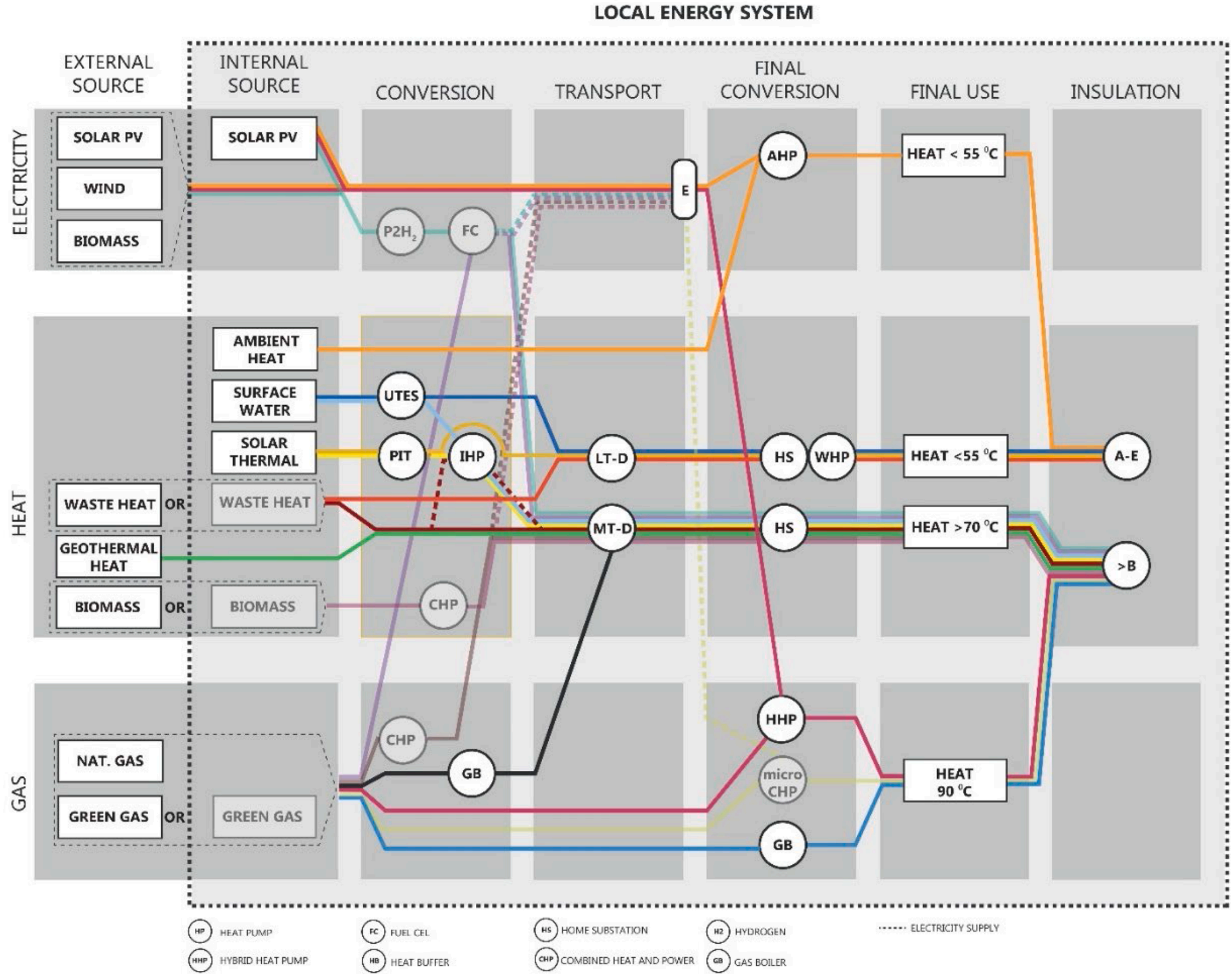

Fig. 1. Structure with modules. The technologies not included in the demonstration model are blurry.

Table 1
Heating technologies included in the modeling.

Heat sources	Conversion technologies	Infrastructure	Storage technologies
Solar thermal heat	Individual air source heat pump	Low-temperature district heating	Buffer tank (200-2000 l)
Heat from surface water		Mid/high-temperature district heating	Crawl space water bag (500-10.000 l)
Ambient heat	Individual water source heat pump	Reinforcement of electricity grids	Pit storage (5000-200.000 m3)
Geothermal heat	Hybrid heat pump	Removal or adaptation of gas grids	Aquifer storage (>50.000 m3)
Waste heat	Large-scale heat pump		
Biomass heat	Electric boiler		
Biogas	Gas boiler		

3. Model design

3.1. Modular approach

The model is built according to a modular structure, where combination of insulation level, equipment on house level to replace the gas boiler, renewable production technologies, storage facilities, equipment on district level to provide peak supply and upgrade low-temperature heat sources and changes to the existing gas and electricity grids and potential district heating grids can be combined to form a scenario. This allows the evaluation of combinations between building blocks and their internal variations (such as capacities and system sizes). The advantage of this approach is that multi-commodity interactions within the system can be more easily evaluated and compared by allowing different temperature levels, different scale levels and different conversion routes between gas, electricity and heat. Fig. 1 shows the possible combinations that can be assessed with this model structure.

3.2. Techno-economic components

The most promising alternative technologies for heating with gas boilers, as identified by [21–24], include district heating, electric heat pumps and in some cases individual heaters on biomass or solar heating. In the Dutch policy framework 5 strategies were identified: electric heat pumps, mid temperature district heating, low temperature district heating, hybrid heat pumps with biogas, and gas boilers with biogas [3]. District heating has the potential of integrating many different renewable sources, in particular biomass, geothermal energy and biogas [22].

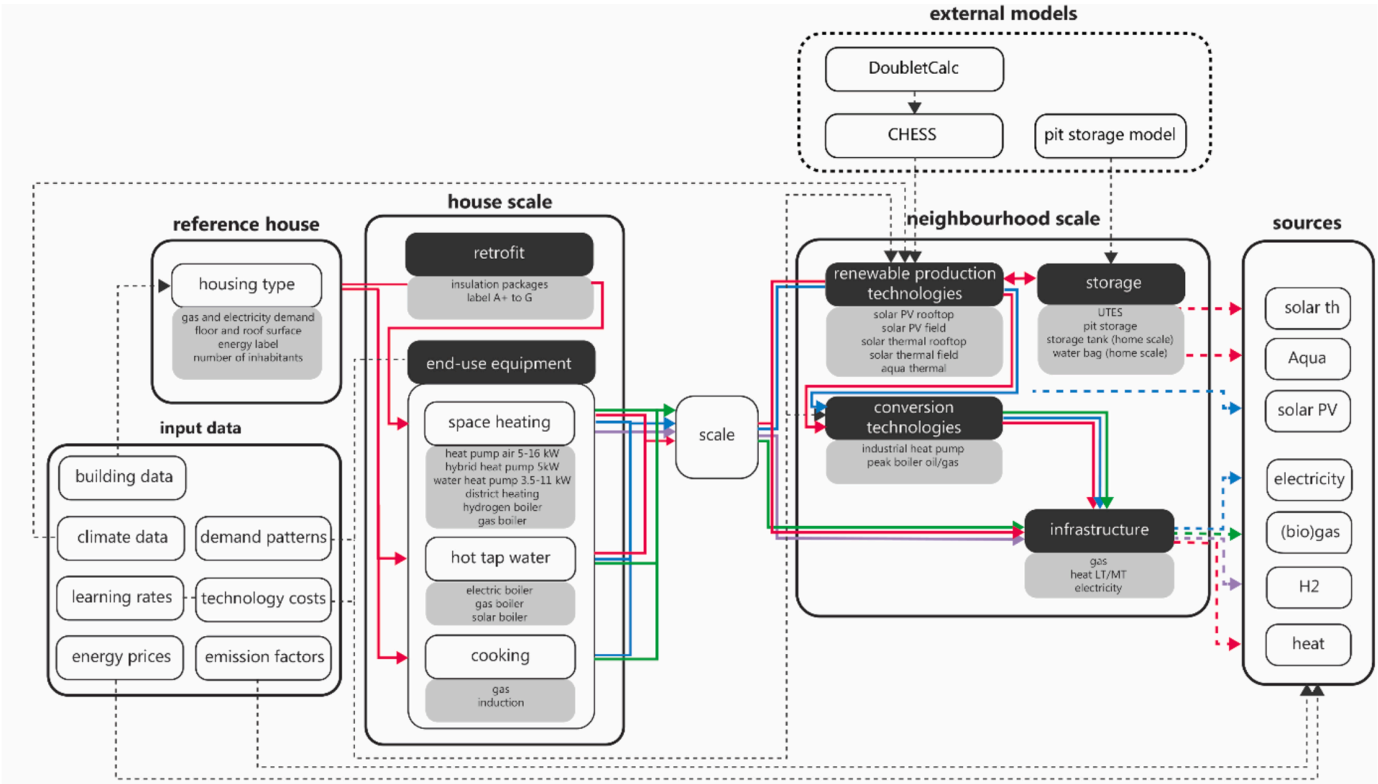

Fig. 2. Modeling framework with modules. For each archetype, the model first applies insulation, equipment for space heating, hot tap water (these are treated separately in the model) and cooking and after scaling up to district level, it applies local conversion technologies, local production technologies and infrastructure strategies. Grey dotted lines represent data streams, coloured lines represent energy flows (heat = red, gas = green, electricity = blue, hydrogen = purple).

The main energy sources and technologies relevant for the shift from natural gas to renewable alternatives are presented in Table 1.

Fig. 2 shows the setup of the model with the main modules. Each module uses predefined system components to allow sufficient variation in technologies and component sizes to be context-specific while maintaining workability by limiting the number of options. See Appendix A, Table A.1 for a list of components. The main modules can be described as follows:

Retrofit module: Energy efficiency is a key challenge for carbon emission reduction in the built environment [25]. The retrofit module takes the costs and efficiency gains of improvements to the building skin. Different levels of energetic performance have been distinguished rather than allocating specific measures, according to the Dutch energy label system, which allocates the building performance to a label with letter A+ to G. Each label comes with a percentage of efficiency performance and associated costs per m^2.

End-use equipment module: Several options for household conversion are included, divided between space heating, hot tap water and cooking purposes (see Fig. 1). Each technology includes a conversion efficiency, capital costs and operation & maintenance costs.

Conversion technologies module: On the district level, options for conversion include an industrial heat pump and peak boilers for district heating networks. Each technology includes a conversion efficiency, capital costs and operation & maintenance costs, heat pumps also include temperature levels (see Appendix B: relevant equations).

Renewable production technologies and storage modules: Basic thermodynamics were included to be able to evaluate the use of low-temperature renewable heat and storages, meaning that thermal components include at least an energy balance and temperature levels. The options for renewable production on district scale include rooftop solar PV, solar PV field, rooftop solar thermal, solar thermal field combined with pit storage and aqua thermal energy combined with an Underground Thermal Energy Storage (UTES). The Netherlands has good subsurface conditions for UTES and aqua thermal energy is increasingly considered as an option for renewable heating because of the many canals, lakes and rivers in the country [26]. The UTES module is based on more detailed calculations in the existing tools *DoubletCalc*[1] [27] and *CHESS*[2] of which the output was used as input to our model [28]. The solar thermal components are combined with a Pit Thermal Energy Storage (PTES). The pit heat storage is calculated with an external storage model[3] [29], and the output is linked to our model with a data file. The model calculates the state of the buffer for each hour based on a temperature-based control strategy.

Infrastructure modules: The switch from the current gas-based technological regime to alternative heating technologies, very much influences - and is accommodated by – infrastructure requirements. The model includes necessary electricity grid reinforcement and associated costs based on the calculated supply and demand peaks, different temperature levels of the district heating networks, different cost levels for district heating networks depending on the physical characteristics of the district (building density, type of road, etc.), and includes the costs of removal and maintaining the gas grid as well as adaptation to alternative gasses (see supplementary material: Model documentation).

[1] DoubletCalc is a 3D modelling environment for subsurface modelling. The model simulates the behaviour of a cold and warm well of a UTES as a result of injection from a heat source and extraction of heat supply.

[2] The CHESS model provides a thermal solver that provides dynamic modelling of the system based on the DoubletCalc model output. See further [77].

[3] The storage model uses a three-layer strategy with a cold layer, a warm layer and a thermocline. Total energy content, losses and the temperatures in the warm and cold layer are calculated for each time step.

Table 2
Building typology.

Building type	Construction period	Extracted characteristics
Detached	<1945	Living area
Semi-detached	1946-1964	Roof surface
Terraced middle	1965-1974	Number of occupants
Terraced corner	1975-1991	Current gas consumption
Maisonette	1992-2005	Current electricity consumption
Gallery flat	2006-2012	Energy label
Apartment (other)	>2012	

Table 3
Urban typology and housing types selected for further analysis.

Urban typology	Dominant housing type (percentage building stock)	Building density	Urban space
A. Pre-war city block	Porch < 1945 (3.8%)	High	Limited
B. Garden town	Row house <1945 (7.7%)	medium	Private gardens, parks
C. Open city block (stamp)	Gallery flat (2,6%)	medium/ high	Private gardens, public gardens, parks
	Porch 1965-1974 (1,7%)		
	Row house 1965-1974 (9,0%)		
D. Community neighbourhood	Row house 1975-1991 (12.9%)	medium	Private gardens, parks
E. Modern expansion	Semi-detached 1992-2005	medium	Private gardens
	Row house 1992-2005 (5.2%)		
F. Heterogenous, village	Detached <1964 (6.5%)	low	Much space between and around houses

3.3. System boundaries

The model takes the physical district or neighbourhood space as system boundaries, with virtual connections to the wider energy system on regional or national scale. Especially in urban districts, the spatial limitations can be quite substantial, in particular in relation to renewable production capacity. The model includes the exchange with the grid so that scenarios with production and conversion technologies focussed on the local scale can be compared with scenarios that depend more heavily on the larger system for energy import. Some energy sources, such as geothermal energy, biogas and biomass, generally need to be imported to the district as the scale at which they are optimally produced or the land use required typically takes place on larger scale. External sources are not modeled in detail, but are represented by a reference number for cost price and CO_2 emissions.

3.4. Data

The model requires data on the reference dwelling, the current consumption patterns, the climatic conditions of the site and price data of the technologies. Available data was mapped and analyzed, and the most appropriate data was selected and applied in the model. Although the aim was to make use of existing data as much use as possible, it was in some cases necessary to make assumptions or to complement available data with our own data sources. The data sources and quality of the data is discussed below. A full list of data is given in Appendix A: data.

Building characteristics: The characteristics of the reference dwelling, can be obtained from a data set of the most common Dutch housing types called 'Voorbeeldwoningen' [30]. This dataset gives average surfaces of building parts (walls, windows, floors, roofs), R-values of building parts, installed equipment, energy consumption (based on historic data) and energy index/energy label. The model needs the floor surface, roof surface, energy label, number of occupants and gas consumption to run.

Consumptions patterns: The reference dwellings only include annual energy demands. This annual use is attached to an hourly pattern of gas and electricity use to convert it to hourly use. These are retrieved from the national electricity hourly breakdown from a Dutch grid operator [31]. Consumption patterns for hot tap water are retrieved from [32]. Consumption patterns for cooking were not available and were constructed by the researchers based on the work of [33].

Energy price data: Tariffs for gas and electricity are retrieved from the Klimaat- and Energieverkenning (KEV) 2019 [34]. This data is available until 2040 and the year 2050 is supplemented in the data set by extrapolation. The data includes the major policy developments such as the expected increase in energy tax on natural gas, but is not in line with some of the most profound analysis on long-term developments in infrastructure costs and cost of major renewable energies, neither does it include scenarios as is common for future prices. It is however the most common national energy price data set available and was therefore applied. The costs for external heat sources (geothermal heat, waste heat, biomass heat) was based on the Dutch subsidy calculations, in which the costs and performance of reference systems are provided [35].

Technology costs: The national cost inventory [3] includes investment costs and operation and maintenance costs for major heating technologies, as well as other tools used in practice provide, see for instance [36]. These data are predominantly based on market consultation. The data do however have limitations, especially in relation to the variation of technologies for different system sizes. The variations in the available data were substantial for some technologies. For some technologies (solar thermal boilers, heat pumps, district heating) a new dataset was constructed allowing more variation in technology type and size with data retrieved from various sources as indicated in Table A.1. The costs of various renewable production and conversion technologies on district scale was retrieved from internal sources (see Table A.1). For insulation, data are available from a data tool from [37], based on data from [38–40], except for higher levels of insulation (label A-A+), which were estimated based on [41,42] to complement the dataset. A limitation of the data is that it is based on calculated data, indicating the technical potential rather than the actual savings that are realized in practice after renovation.

Learning rates: Typical learning rates are expressed in the cost reduction for each doubling of production capacity. Learning rates from major renewable technologies (solar PV, wind, etc.) are available from various sources. However, we are rather interested in the future cost reduction of small-scale technologies such as heat pumps and insulation packages. Here, the available data is lacking, both for to market projections up until 2050 and total expected cost reductions, and only rough estimations for expected cost reductions are available from a national inventory [3]. Those data are considered to be most complete and are therefore included in the dataset, see further Section 4.3.

Climate data are retrieved from the Dutch national weather institution KNMI and represent a climate (average) year. Other patterns can be loaded, for instance for a very hot or cold year.

3.5. Model operation

3.5.1. House and district-scale urban typology

The use of archetypes has been proposed to deal with the heterogeneity of the building stock without getting lost is unnecessary details [43,44]. Our methodology makes use of archetypes as starting point of the modeling process. The applied dataset includes 27 predefined archetypes that can be adapted to create a reference dwelling that is representative for the district (see Table 2). The model takes the (existing) individual dwelling as basis for a district or neighbourhood of approx. 100-3000 dwellings. Within this district, there can be multiple clusters with a different reference dwelling that is multiplied by the number of houses in the cluster. Analysis of the study area to map the

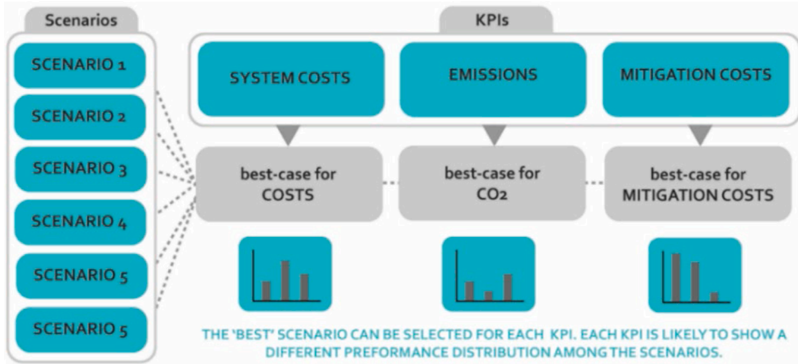

Fig. 3. Illustration of how to select best-case scenarios for different KPI's (example).

heterogeneity of the building stock with different states of maintenance, modifications and insulation levels of similar buildings and dwellings can be used additionally to refine the archetypes.

Districts or neighbourhoods can be characterized by one or more typical housing types. However, housing types alone do not suffice as a starting point for a scenario, as the local context, including available space for renewable generation and building density, effect the scenario results. Therefore, a typology on district-scale has been provided as well (see Table 3). Using such a typology, it is possible to show which scenarios are preferred in different segments of the building stock. We defined six district types that represent sufficient spread in characteristics, deducted from Dutch urban typologies defined in [45,46]. Each type was assigned a (combination of) typical housing type(s), according to the categorization of the Dutch housing stock (see Table 2). After defining the reference dwelling(s), measures are selected and applied on the level of the individual dwelling as well as on district scale (see Section 3.2).

3.5.2. Simulation and scenario selection

Most established models for the built environment on local scale are optimization models, mostly optimized for costs, as shown by Bouw et al. [4]. However, giving one optimal solution does not suffice as input for stakeholder dialogue, where various system choices and effects need to be evaluated. A full optimization is not relevant nor manageable for stakeholder dialogue, especially with focus on end- users as an important stakeholder group. Techno-economic optimization is not a precondition for successful implementation of renewable energies, but the social process evolving around it and its interlinkages with technologies determine its success [47]. It is rather the stakeholders that determine which techno-economic and other parameters are considered important during the stakeholder evaluation process. Different approaches to the issues of considering multiple stakeholders and multiple KPI's exist. Best practices include participative multi-criteria optimization (e.g. [48,49]) which enables the consideration of multiple KPI's and also supports a stakeholder process, as well as game theory inspired approaches using multi-objective optimization (e.g. [50]) which enables the evaluation of stakeholder impacts by considering benefit allocation.

These approaches have in common that the evaluation takes primarily place within the model by a modeling expert at a detailed level while our aim is to provide stakeholder dialogue with the information prior to evaluation, allowing an evaluation of a broad range of options with different consequences. The context of interventions in the built environment is associated with discrete choices with large differences concerning the realization in practice and the distribution of stakeholder costs, and requires something other than solely an optimization. With the aim of showing the effects of possible system choices to support the decision-making process by providing information on multiple system aspects, our methodology therefore uses a scenario approach.

An advantage of the scenario approach is that it allows the inclusion of a larger set of KPIs more easily, including more qualitative KPIs (such as ratings) as well, whereas optimization may become highly complex when including many different KPIs. This enables a broader vision of a scenario without weighting each indicator of the scenario in advance, which results in more open judgement based on more complete information.

A downfall of the scenario approach is that a selection of scenarios to include in the analysis needs to take place, which can be complicated as the number of combinations of measures may become very large, and evaluation in practice can only take place for only a limited number of scenarios. Then the challenge is to find a method for scenario selection, as presenting one optimized scenario is too narrow because of the aforementioned reasons, and showing all possible scenarios for all KPI's is so broad it becomes impractical. We therefore need to define a procedure for scenario selection.

As a first step in the selection process, logical combinations of measures are defined. To create an overview of possible solutions, first 'main technologies' are selected, referring to the dominant fuel or technology. In line with the national policy framework, those main technologies for the built environment with a focus on sustainable heating can be categorized as: *all-electric, mid-temperature district heating, low-temperature district heating, hybrid (biogas), efficiency* and *solar thermal.* Within these main scenarios, various subvariants may exist, with combinations of insulation levels, solar PV and heat sources. The possible scenarios are checked for potential space restrictions and resource restrictions in the study area. Infrastructure limitations in historical city centres, retrofitting limitations in monumental buildings and limited space in and around buildings for storages and equipment in urban areas are examples of relevant spatial limitations. Additionally, scenarios are checked for consistency, for instance in an all-electric scenario the option of gas cooking will be eliminated. Then, options are checked for a chosen policy aim, which may again limit options. In this case we chose an 80% CO_2 emission reduction target. However, the policy target can be chosen differently as well. All scenarios that do not meet the target are removed from the selection. The remaining scenarios can be filtered with a second criteria, such as cost efficiency, to further limit the options for analysis. The result of the pre-selection process is an overview of scenarios, which can be further analyzed (see Fig. 3).

3.5. Model output

The model calculates the economic, energetic and environmental performance for the chosen scenario in comparison to a reference scenario. The reference scenario is the current situation of a gas connected dwelling, with a certain energy demand and associated energy costs. The model produces three main output tables for economic, energetic/technical and environmental performance: (1) an overview of outputs per KPI, including carbon emissions and mitigation costs (environmental analysis), (2) an energy balance with all demands, supplies and

Table 4
Summary of technologies included in the scenarios.

Scenarios	Retrofit level	End-use equipment	Renewable production	Conversion technologies	Infrastructure	Storage technologies
Scenario 1: All-electric	Label B	Individual air-source heat pump, induction cooking	Rooftop solar PV	-	Electricity grid reinforcement Disconnection from gas grid	-
Scenario 2: Hybrid	Label B	Hybrid heat pump	Rooftop solar PV	-	Electricity grid reinforcement	-
Scenario 3a: MT heat – waste incineration	Label B	Induction cooking, home substation	Rooftop solar PV	-	District heating Electricity grid reinforcement Disconnection from gas grid	-
Scenario 3b: MT heat – solar thermal	-	Induction cooking, home substation	Rooftop solar PV Solar thermal field	Central heat pump Peak boiler (gas)	District heating Electricity grid reinforcement Disconnection from gas grid	Pit thermal storage
Scenario 4: LT heat	-	Individual water-source heat pump, induction cooking, home substation	Rooftop solar PV Aqua thermal heat	-	District heating Electricity grid reinforcement Disconnection from gas grid	UTES
Scenario 5: Efficiency	Label B		Rooftop solar PV Biogas (grid)	-	Electricity grid reinforcement	-

losses of the system (energy analysis) and (3) an overview of all the costs components per stakeholder (economic analysis), see Appendix C.

4. Model results

To further demonstrate the modeling of a district, we selected the most common Dutch district type, which is the community neighbourhood with row houses from the period 1975-1974, at a scale level of 500 similar houses. A policy goal of 80% emission reduction was chosen. The results presented below illustrate the findings for this specific housing type. Note that the results can differ for other housing types.

4.1. Selected scenarios

From the six main scenarios that were defined (see Section 3.5.2), a longlist of possible scenarios that meet the goal of 80% CO_2 emission reduction was constructed (Appendix D: Scenarios longlist). From this longlist, the scenarios with the lowest system costs per main scenario were selected for further analysis, which are summarized in Table 4. For solar PV, an East-West orientation was assumed, with a standard package of 20 panels (10 on the east-oriented roof and 10 on the west-oriented roof). For insulation two options were included, one with moderate insulation values, resulting in energy label B and one with high insulation values, resulting in energy label A+. The insulation packages include adaptations to the ventilation system, but excludes any other energetic measures. The heat pump option represents a package including low-temperature radiators, adaptation of the internal electrical installation and control- and measurement systems.

No scenarios were selected within the main technology ‘solar thermal’ that comply with the 80% reduction goal. A large solar boiler for space heating and long-term storage on house scale did not hit the goal, also not in combination with insulation packages.

It is worth noticing that rooftop solar PV is included in all the scenarios. None of the scenarios without rooftop solar PV reaches the 80% emission target. Although in some scenarios the emission target can almost be reached without rooftop solar PV; the combination of biogas and insulation to label A+ in the hybrid, efficiency and solar thermal scenario reaches around 70% reduction and some of the district heat scenarios combined with insulation to label A+ reach a reduction of around 70% as well. In scenarios with no or limited increase in electricity use (hybrid, district heating, efficiency), there is a small overproduction of electricity. In the solar thermal scenario (3b), the overproduction at house level largely covers the electricity use of the central heat pump.

It is also worth noticing that scenarios with no additional insulation often have minor differences with or are even less cost-efficient than the scenarios with the moderate insulation package (see scenarios with biogas, geothermal district heat, solar thermal district heat). Scenarios with higher levels of insulation appeared to be less cost-effective than the selected scenarios. When fuel costs are high, additional insulation earns itself back well. Variation in fuel prices and their effects will be further discussed in section 4.3 (sensitivity analysis).

4.2. Scenario results

4.2.1. Energetic analysis

Fig. 4 shows the energy flows in each scenario divided by scale level. To achieve the goal of 80% emission reduction, measures can be taken on different scale levels. Starting from the current situation, emission reduction can be achieved by efficiency gains at building level, with use of heat pumps and insulation, by local renewable energy production, and by purchasing external (renewable) energy. In the heat pump scenarios (all-electric and hybrid) and efficiency scenario, a significant share of the measures takes place on building level, whereas in the district heating scenarios the emission reduction is achieved by measures outside of the building scale. In the external heat scenario, the largest share of the reduction is achieved outside of the system boundary compared to the local heat scenario where most of the reduction is achieved on local scale. The scale at which measures are taken directly affects the type of stakeholders involved and how costs and benefits are distributed (see Section 4.2.3). Scenarios with insulation and air-source heat pumps have a significant demand reduction while district heating scenarios have an increased demand due to e.g., losses in the distribution network, losses in storages and pumping energy. The required production of local renewable energy is in that case significantly higher, as can be seen from scenario ‘MT heat B’.

4.2.2. KPIs

Table 5 shows the results of the simulations of the defined scenarios for the fictive neighbourhood for the chosen KPIs per household per year. According to the proposed methodology for scenario evaluation, the best-case can be selected for each KPI (see grey hatched cells). The

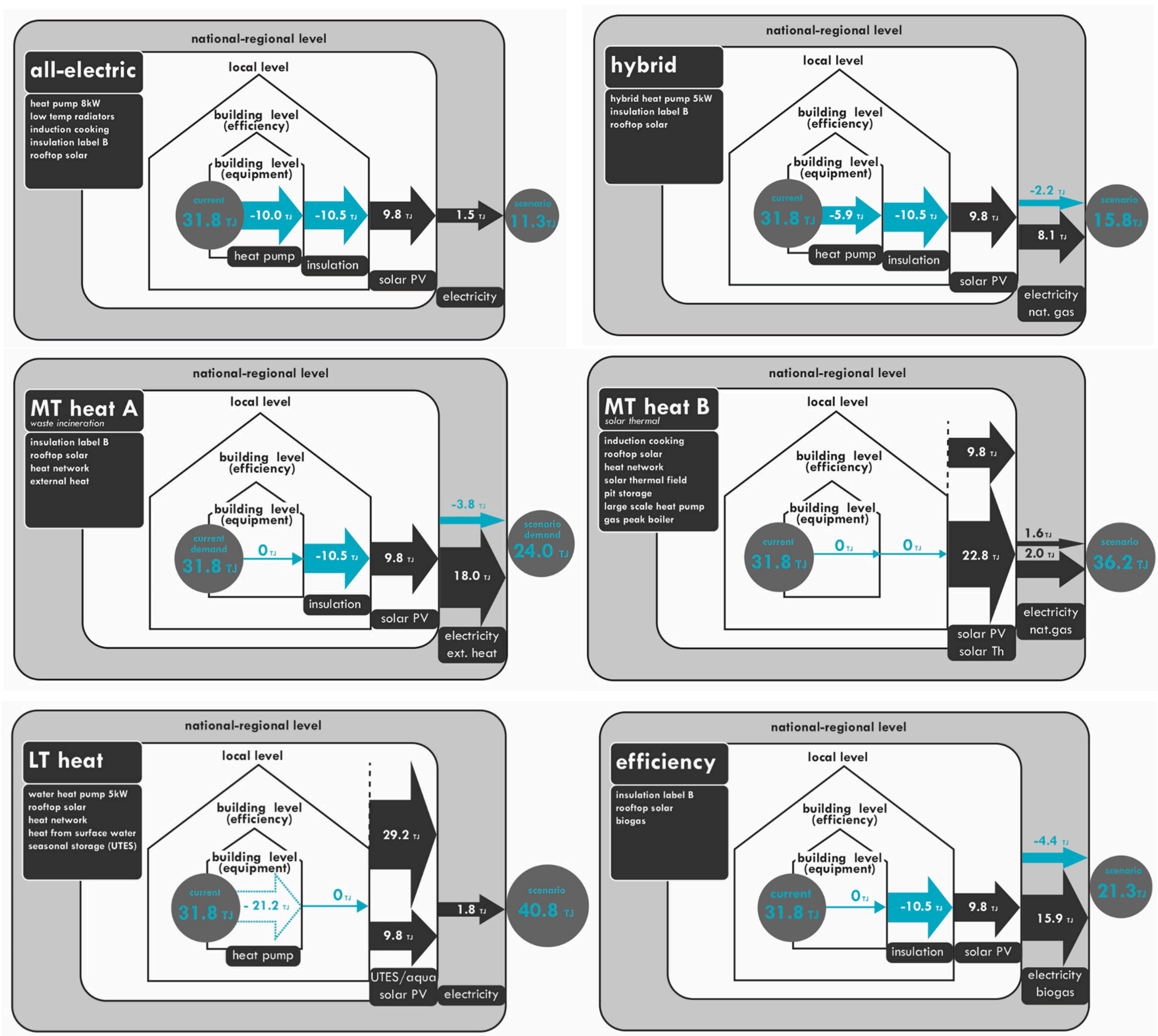

Fig. 4. Representation of the energy flows per scale level. Blue arrows represent savings on energy demand, grey arrows represent energy supply by energy source. Both current and scenario energy demand are given. The sum of the energy flows represented by both the blue and the grey arrows give the energy demand in the scenario.

Table 5
Scenario results for six scenarios and six KPIs. Results are shown for one house of the selected type. Costs represent annualized costs per household.

Scenario			System KPIs			End-user KPIs		
	Main technology	Subtype	System costs per house (€)	CO_2-emission reduction (%)	Mitigation costs per house (€/tonne)	End-user costs (€)	End-user Investments (€)	Payback period (year)
1	All-electric	-	2337	93%	229	1996	29975	15
2	Hybrid	-	1852	86%	149	1473	20058	12
3a	MT district heat	Waste incineration	2858	92%	292	1493	15934	12
3b	MT district heat	Solar thermal	4035	87%	602	1762	7963	10
4	LT district heat	-	4001	92%	575	3577	25157	72
5	Efficiency	-	2033	100%	194	1234	16334	10

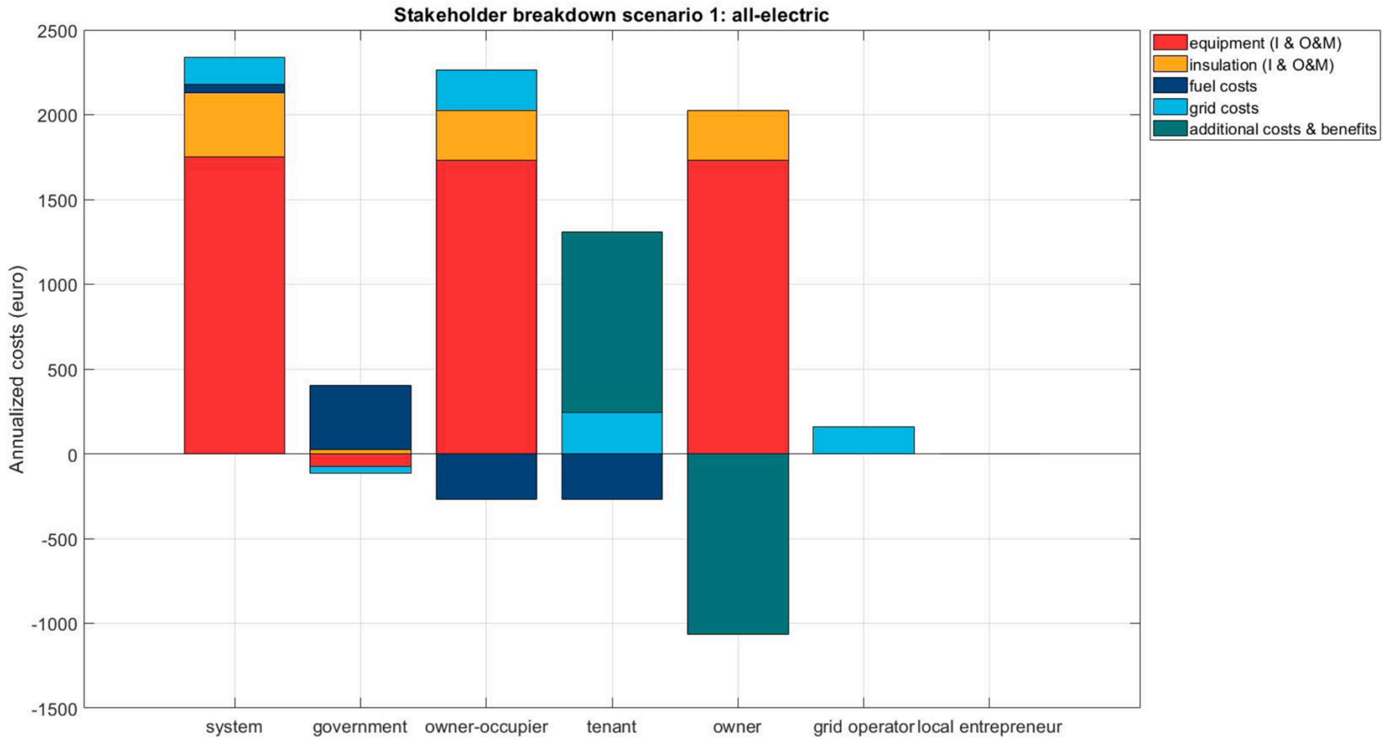

Fig. 5. Annualized costs of the all-electric scenario for one house distributed over the stakeholders that are potentially involved. The additional costs and benefits for the tenant and real estate owner consist of rent increase that housing corporations are allowed to charge to compensate for the investments in sustainable energy measures.

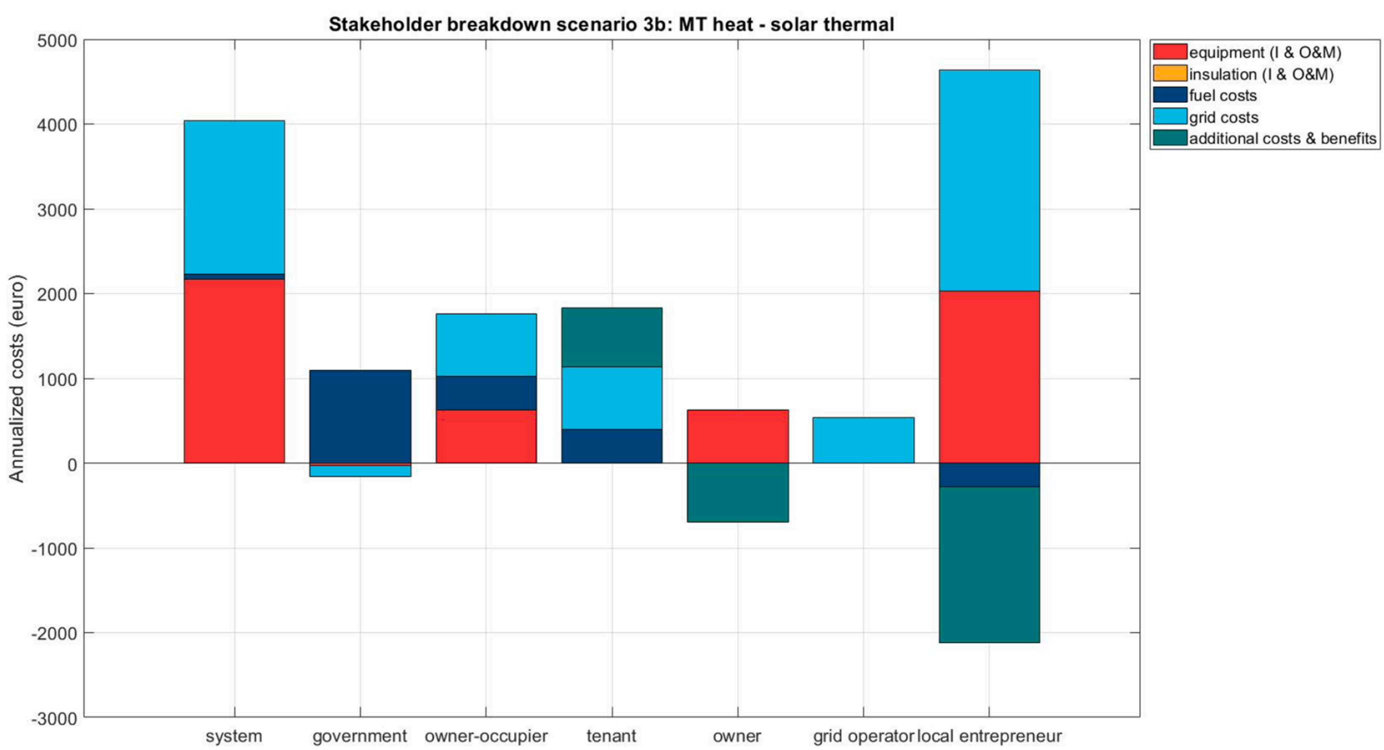

Fig. 6. Annualized costs of the MT heat scenario for one house distributed over the stakeholders that are potentially involved. The additional costs and benefits for the tenant and real estate owner consist of rent increase that housing corporations are allowed to charge to compensate for the investments in sustainable energy measures. The benefits of the local entrepreneur consist of maximum income from consumers according to the current price cap regulation.

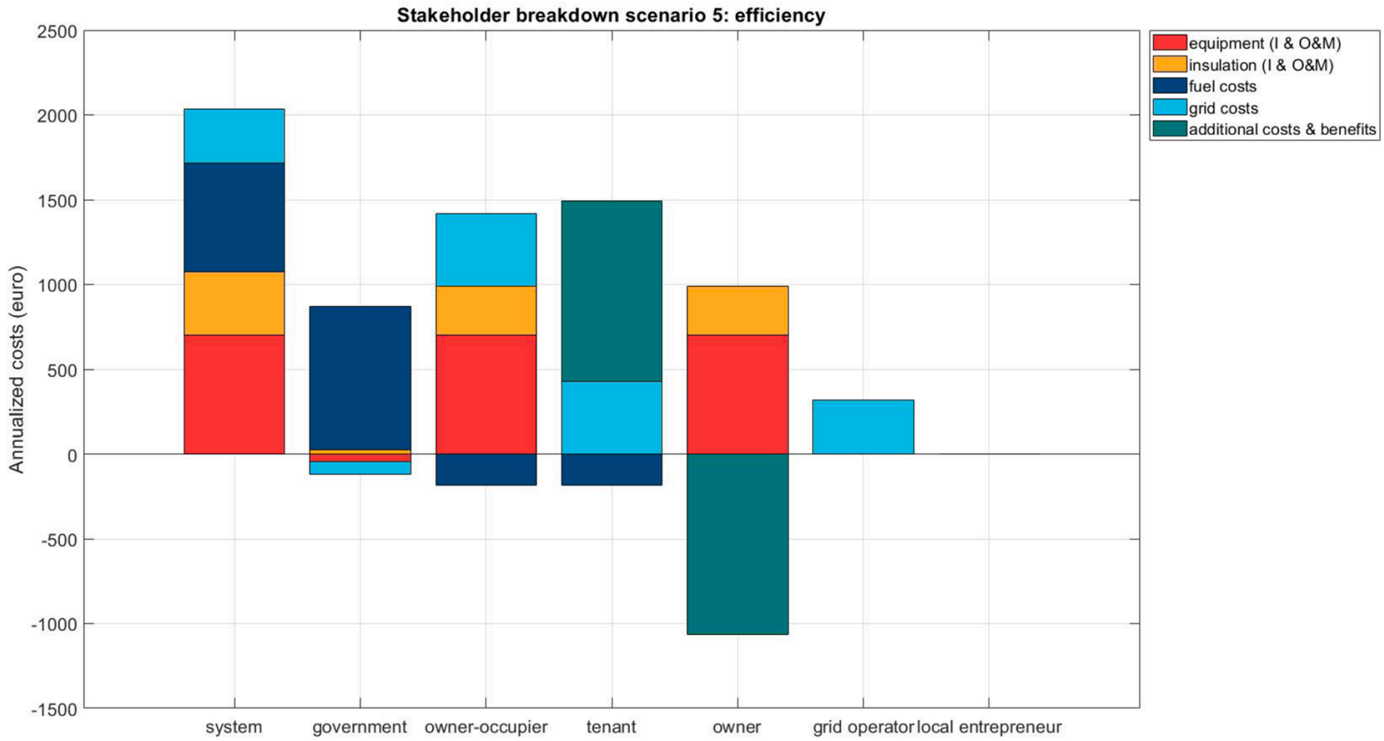

Fig. 7. Annualized costs of the efficiency scenario for one house distributed over the stakeholders that are potentially involved. The additional costs and benefits for the tenant and real estate owner consist of rent increase that housing corporations are allowed to charge to compensate for the investments in sustainable energy measures.

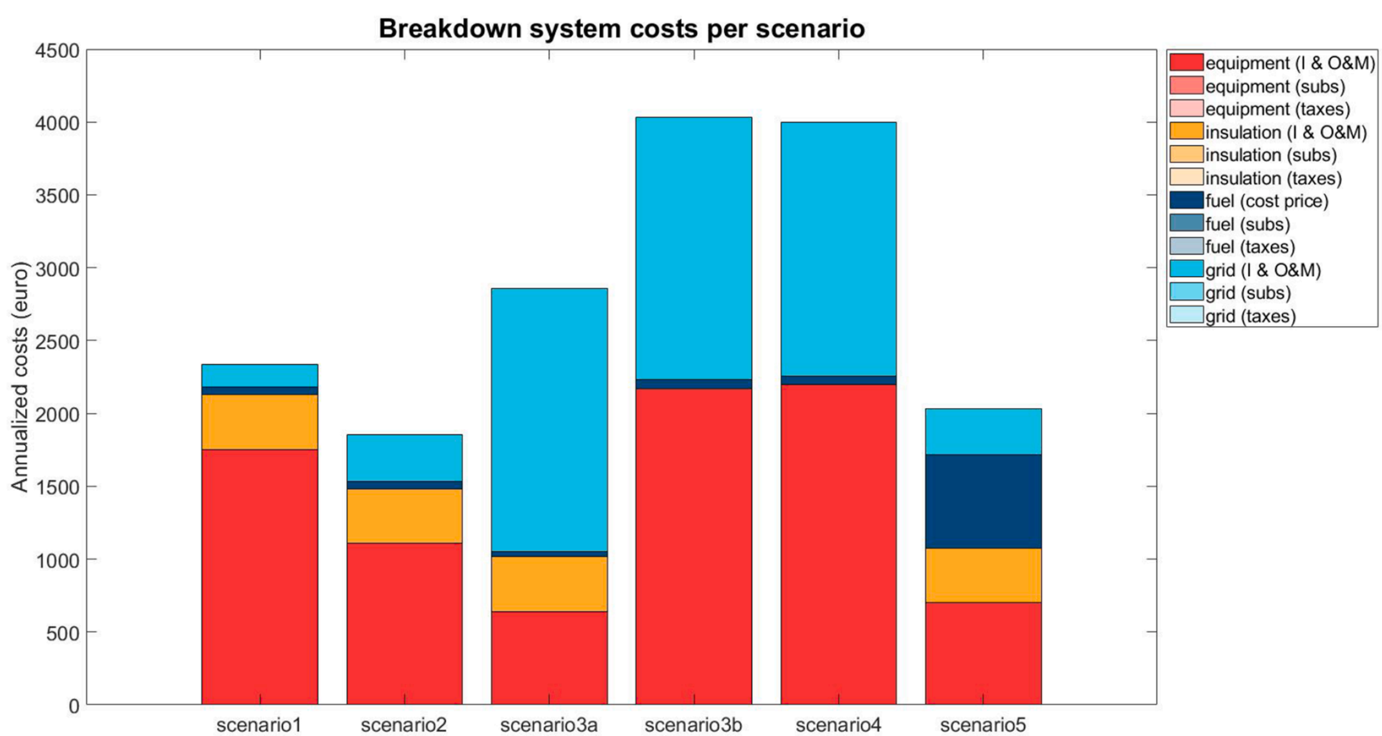

Fig. 8. Annualized system costs per house for six scenarios. Costs show a breakdown in equipment, insulation, fuel and grid. An additional breakdown is given in investments and operation and maintenance costs, subsidies and taxes.

results show that the best-case scenario differs per KPI. The results show a large variation in outcomes, for which it is ambivalent to point out the preferred scenario. In scenario 'hybrid' for instance, the system costs are the lowest, whereas the district heat scenario with a solar thermal source have significantly lower end-user investments. The highest CO_2-emission reduction can be achieved in the efficiency scenario, which also has the lowest end-user costs. Not only does the performance of the scenarios differ per KPI, also the spread within KPIs is significantly large;

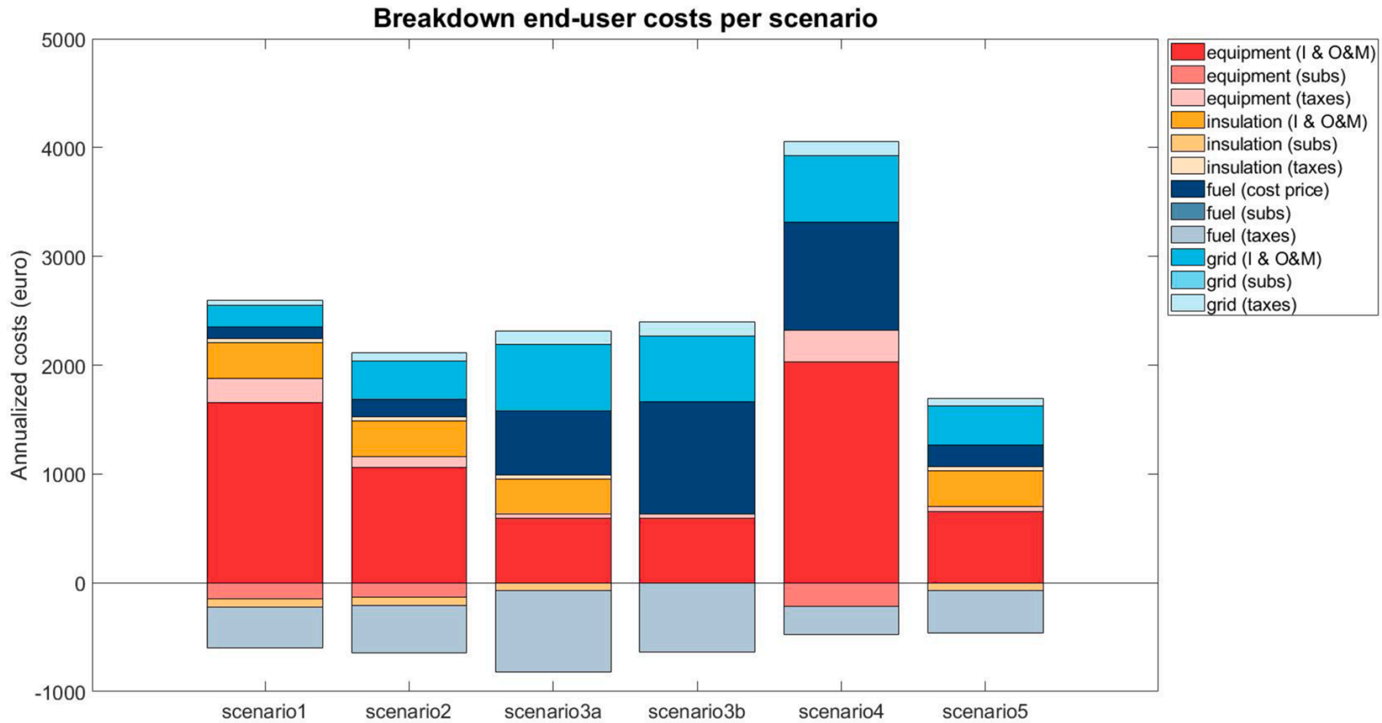

Fig. 9. Annualized end-user costs per house for six scenarios. Costs show a breakdown in equipment, insulation, fuel and grid. An additional breakdown is given in investments and operation and maintenance costs, subsidies and taxes.

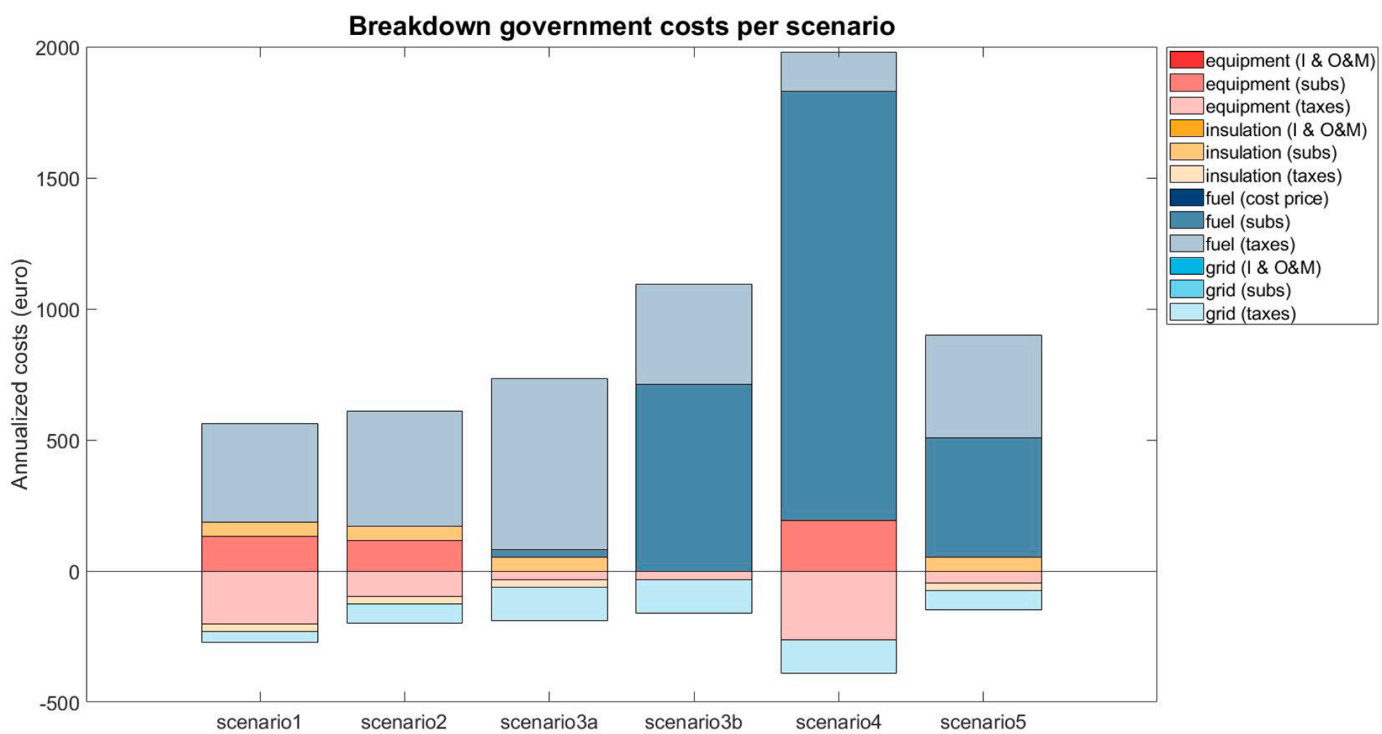

Fig. 10. Annualized government costs per house for six scenarios. Costs show a breakdown in equipment, insulation, fuel and grid. An additional breakdown is given in investments and operation and maintenance costs, subsidies and taxes.

system costs differ at a factor 2,2 between the highest and lowest scenario result, and for mitigation costs this is even a factor 4,4. The results for this neighbourhood indicate that the efficiency scenario results in the lowest costs for end-users, whereas the hybrid scenario has better results for system KPIs. Nevertheless, the results may be quite deviant for a different neighbourhood, for instance one with older dwellings. Overall, it becomes clear that choices for one scenario over another can have large impact on certain stakeholders, especially with such large differences between scenarios, which pleads for a careful evaluation of scenarios and ultimately for joint decision-making.

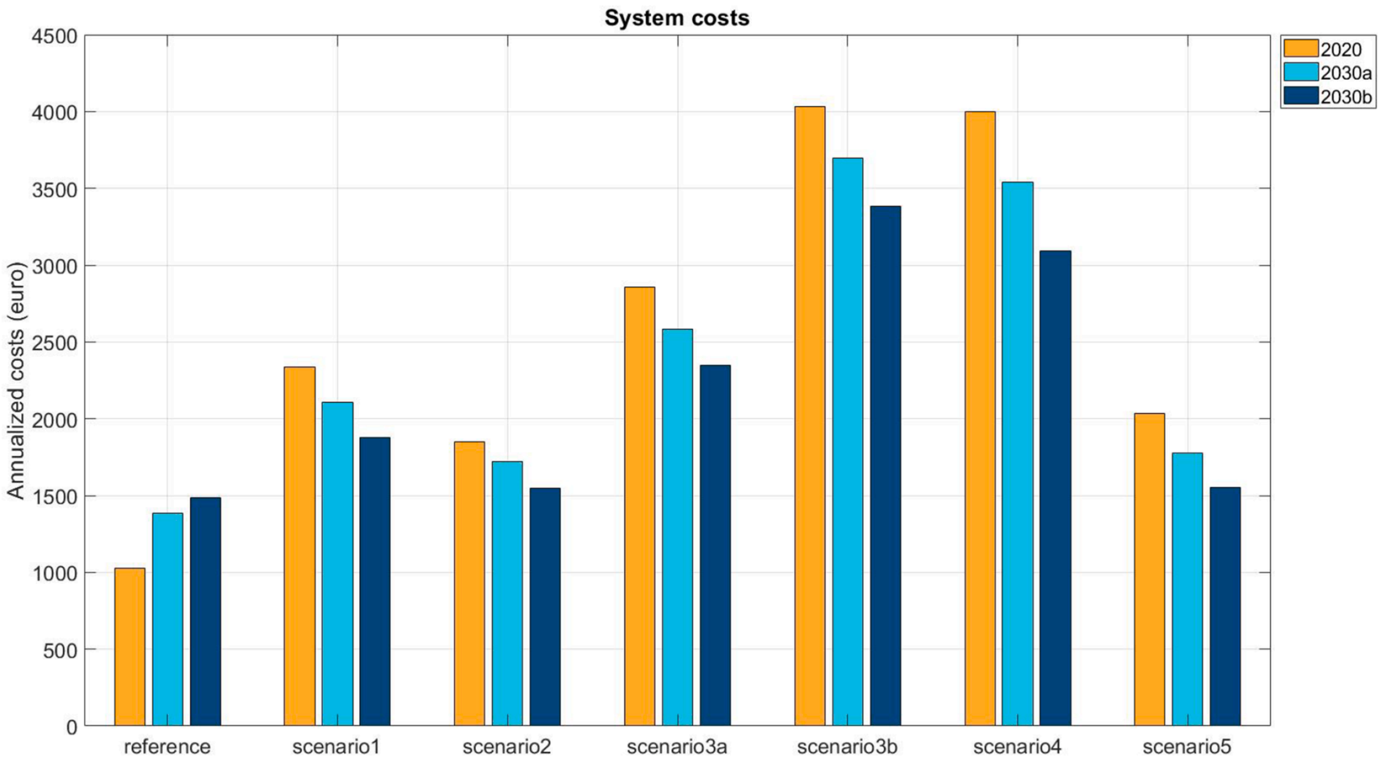

Fig. 11. Annualized costs in 6 scenarios for the reference year (2020) and two scenarios for 2030, one conservative (2030a), one optimistic (2030b).

Table 6
Bandwidth of key variables in absolute numbers and relative deviations from the default model variables for a row house of the period 1975-1991.

Variables	Unit	min abs	model abs	max abs	min rel	model rel	max rel	Refs.
District heating investment	€	12000	29322	-	-58%	0%	-	CE Delft [36]
Insulation investment (label B)	€	6200	9964	12900	-38%	0%	29%	Brouwer [58]
Heat pump investment (8kW)	€	7919	10940	12705	-28%	0%	16%	PBL [3]; Thuisbaas [59]
Biogas price consumer*	€	-	0,82	1,61	-	0%	96%	-
COP of heat pumps (label B)	-	3,12	3,08	4,49	1,29%	0%	38%	PBL [3]
Interest rate – social discount rate**	€	1.0	3.0	5.0	-67%	0%	67%	[60–62]
Interest rate – household***	€	0.0	2.0	5.0	-100%	0%	150%	ECB [63]

*The bandwidth of biogas price has been established by comparing the consumer tariff with (model value) and without SDE++ subsidy (upper value). The SDE++ component is set at 71% of the production costs.
**Discount rates used in European policies lay between 1 and 3% according to Löffler [60], recommended values for individual European countries lay between 3.0 and 5.5% according to Florio & Sirtori [62] which is also in line with Moore, Boardman & Vining [61]. A range of 1-5% is therefore defendable.
***Household interest rates are based on the savings interest, which were roughly between 0 and 5% in the period 2000-2020.

4.2.3. *Cost analysis*

To show how a cost analysis that is specified per stakeholder is performed with the model, three scenarios were selected that vary in the way costs are divided among stakeholders: ‘all-electric’, ‘MT heat – solar thermal’ and ‘efficiency’ (see Figs. 5–7). The annualized costs for those three scenarios are split in costs for equipment, insulation, fuel, grid and additional costs & benefits, such as income through rent. Each stakeholder has its own individual cost components, and differences among stakeholders can exist for the same system component due to variance in tax tariffs on fuels and investments, specific tariffs and charges and interest rates used to annualize cost components. For instance, households pay a connection fee for the gas, electricity and heat grids, but those consumer tariffs are not included in system costs, as those only include the real costs of operating and maintaining the grid. Similarly, end-users pay taxes over the fuels consumed with different tariffs for households and for businesses, depending on the consumption level. Interest rates, specifically reflected in commercial investments, for instance by a local entrepreneur, lead to substantially higher costs than system costs, as can be seen in district heating investments (see Fig. 6). Thus, the costs cannot be added up to create total system costs. However, some cost components are directly reflected in the costs of another stakeholder, such as additional income through rent increase which is subtracted from the tenant and added to the real estate owner.

Figs. 5–7 illustrate how differently costs can be distributed among stakeholders, for instance in the scenarios in which measures are taken at building scale (‘all-electric’ and ‘efficiency’), most of the investment costs are shifted to the end-user, both to *owner-occupiers* and *tenants* (indirectly through increase of the rent), whereas in scenario ‘MT heat – solar thermal’ in which measures are taken on local scale, investment costs for end-users are low.

In ‘MT heat – solar thermal’, where renewable heat is produced locally, most of the costs shift to the *local entrepreneur*, for whom it can be challenging to obtain a positive business case, as income through (regulated) energy tariffs is limited and the investments costs are significantly higher due to the construction of a heat source (solar thermal collector, storage, heat pump and peak boiler) and the heat grid. The fuel costs are low in this scenario due to the own production (incl. rooftop solar PV on household level), with fuel costs for the peak (gas)

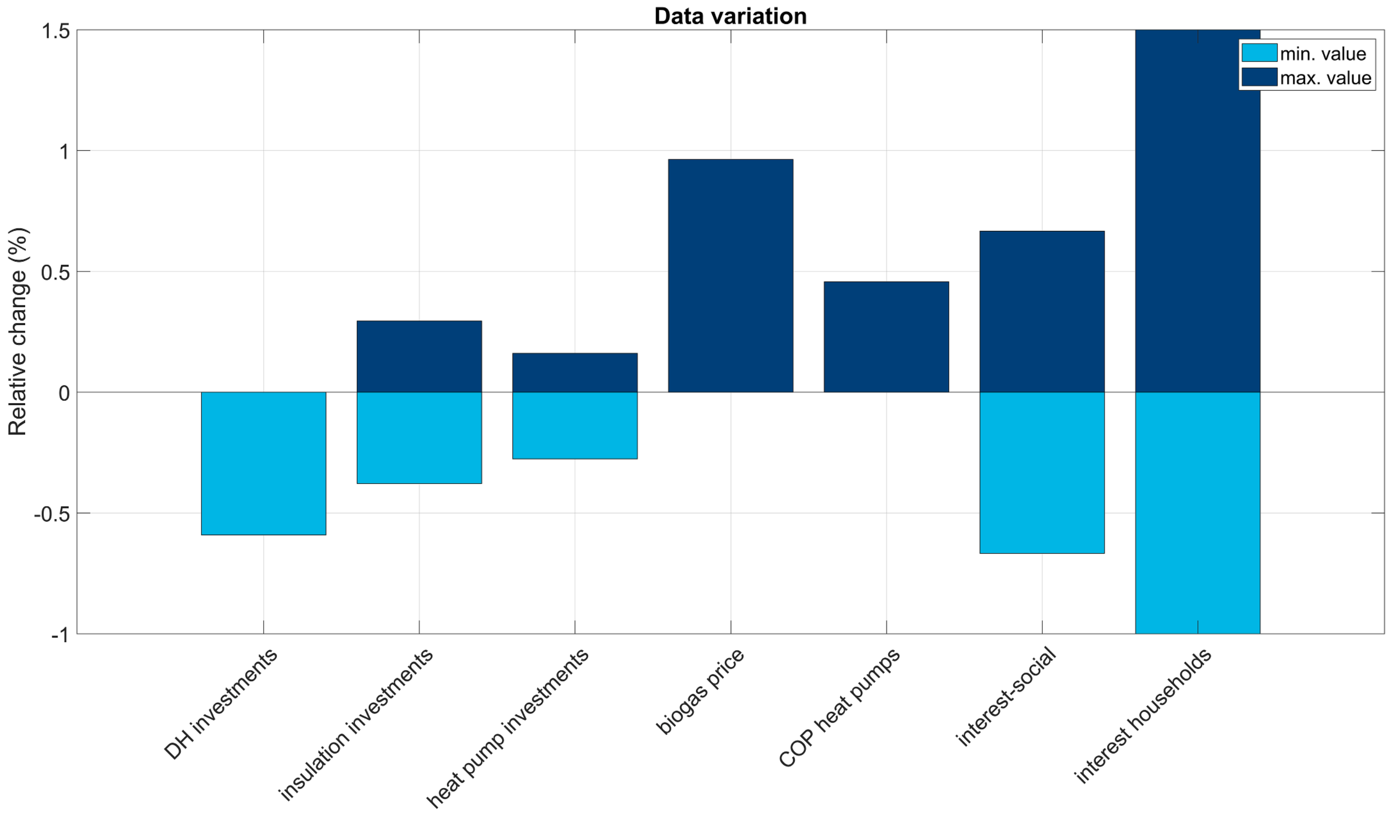

Fig. 12. Bandwidth of key variables.

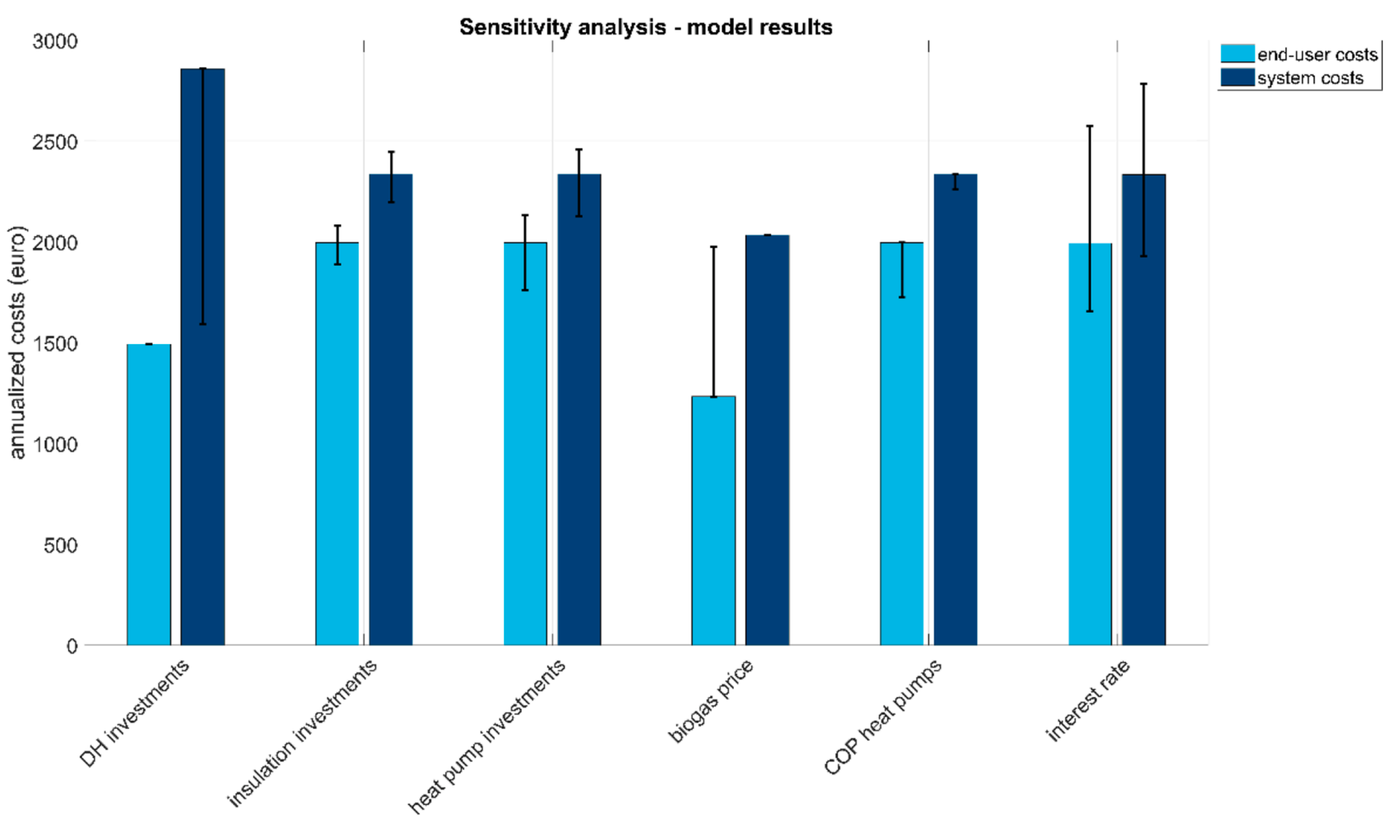

Fig. 13. Results of the sensitivity analysis showing end-user costs and system costs for the five selected variables. Error bars show the change in result with the determined minimum and maximum input values.

Table A1
Overview of investment costs, O&M costs and subsidies for all included technologies.

Technology	unit	investment costs (incl. tax and installation)	subsidy fixed	subsidy variable (SDE)	fixed O&M costs (per year)	variable O&M costs (per year)	Source
Solar flate plate set 2,5 m²/150 m³ (min)	€	3073	768	0,000	0,5%	0,0	Own dataset*
Solar flate plate set 10 m²/300 m³ (max)	€	7129	2444	0,000	0,5%	0,0	Own dataset*
Solar vacuum tube set 20/150 m³ (min)	€	3257	1163	0,000	0,5%	0,0	Own dataset*
Solar vacuum tube set 90/500 m³ (max)	€	10777	2541	0,000	0,5%	0,0	Own dataset*
Hydrobag 500 l iso (min)	€	1568	0	0,000	0,0	0,0	[64]
Hydrobag 10000 l iso (max)	€	10536	0	0,000	0,0	0,0	[64]
Close-in boiler 10 l (min)	€	500	0	0,000	0,0	0,0	estimation
Close-in boiler 200 l (max)	€	1000	0	0,000	0,0	0,0	estimation
Heat pump combi water-water 3,5 kW (min)	€	14273	2800	0,000	0,0	0,0	Own dataset*
Heat pump combi water-water 12 kW (max)	€	15270	3300	0,000	0,0	0,0	Own dataset*
Heat pump combi air 5kW (min)	€	8452	1700	0,000	135,0	0,0	Own dataset*
Heat pump combi air 16kW (max)	€	12856	2500	0,000	135,0	0,0	Own dataset*
Heat pump hybrid air 5 kW	€	5424	1700	0,000	150,0	0,0	Own dataset*
Heat pump electrical adjustments	€	1000	0	0,000	0,0	0,0	estimation
Low-temperature internal heating system	€/piece	1000	0	0,000	0,0	0,0	Own dataset*
Natural gas boiler	€	1400	0	0,000	165,0	0,0	estimation
Hydrogen boiler	€	2500	0	0,000	165,0	0,0	estimation
District heating – internal network ground bound house	€/connection	6500-7000	0	0,000	2,5%	0,0	Own dataset*
District heating – internal network multistorey indv.	€/connection	4500-5000	0	0,000	2,5%	0,0	Own dataset*
District heating – internal network multistorey coll.	€/connection	2000-2500	0	0,000	2,5%	0,0	Own dataset*
District heating - distribution network	€/m	723	0	0,000	1,0%	0,0	[65]
District heating – secondary network	€/m	936	0	0,000	1,0%	0,0	[65]
District heating - substation	€/connection	530	0	0,000	3,0%	0,0	[65]
Electricity grid reinforcement light	€/connection	3000	0	0,000	0,0	0,0	Own dataset*
Electricity grid reinforcement heavy	€/connection	1500	0	0,000	0,0	0,0	Own dataset*
Industrial heat pump	€/kW_{th}	1140	0	0,038	2,0%	0,0	[66]
Solar PV - rooftop individual (variable)	€ /Wp	1,1	0	0,000	0,0	0,0	[67]
Solar PV - field >1MW	€ /kWp	580	0	0,069	12,8	32,0	[66]
Solar thermal 140kW$_{th}$-1MW$_{th}$	€ /kW_{th}	525	0	0,095	1,9	0,0	[66]
Solar thermal >1MW$_{th}$	€ /kWp	420	0	0,080	4,0	0,0	[66]
Peak boiler gas	€ /kW	800-1800	0	0,000	2,0%	0,0	[3]
Thermal storage (pit)	€/m^3	30	0	0,000	1,0%	0,0	[68]
UTES per doublet	€/m^3/hr	3500-4500	0	0,000	2,5%	0,0	[69]
Aqua thermal 50 m/hr (min)	€/m^3/hr	€ 50000	0	0,101	10000 €/y	0,0	[70]
Aqua thermal 200 m/hr (max)	€/m^3/hr	€ 200000	0	0,101	10000 €/y	0,0	[70]

*see supplementary material (model documentation) for further explanation

boiler and heat pump only. Grid costs for maintaining the natural gas grid and reinforcement of the electricity grids remain relatively low in all scenarios.

The *government* is providing subsidies on insulation, heat pumps and other equipment, and collects taxes on fuel and investments as income. Due to the application of solar energy, which results in a small or negative electricity use, the taxes gained are negative for the government under the current regulation as the yearly discount on the energy tax for households is granted, whereas little or no taxes are generated as income.

The costs for each scenario can be broken down into more specified cost components. To show the variety in the distribution among scenarios, we selected three stakeholders: owner-occupiers, system and government (see Figs. 8–10). A breakdown between investment and operation & maintenance costs, subsidies and taxes create additional insight in how costs are built up. The low fuel costs for owner-occupiers can now be explained by the fact that the discount in energy taxes, which is negative due to a high production of solar electricity, counteracts the fuel costs. The positive stacked bar minus the negative stacked bar represents the total costs for the stakeholder, while showing all included components. For scenario 3b, the end-user breakdown in Fig. 9 shows that, despite of the low overall fuel costs shown in Fig. 6, the paid fuel is substantial but is counteracted by the negative discount on the energy tax. The grid costs can be compared similarly, showing substantially higher costs for the heat grid in scenarios 3a, 3b and 4, whereas scenario 1 has the lowest grid costs with only costs for reinforcing the electricity grid, and scenario 2 and 5 also include costs are for maintaining the gas grid in addition to electricity grid reinforcement. Operation & maintenance costs for electricity are not considered as these are not relevant in the scenario comparison.

The stakeholder breakdown also shows the effect of subsidies on fuels. From Fig. 7 for instance, it can be seen that in scenario 5

Table A2
Commodity prices.

Energy prices	Component	2020	2025	2030	2035	2040	2045	2050
Electricity households	Variable delivery rate incl. taxes (€/kwh)	0,228	0,235	0,239	0,226	0,251	0,251	0,251
	Wholesale price (€/kwh)	*0,063*	*0,079*	*0,085*	*0,075*	*0,095*	*0,095*	*0,095*
	ODE, incl. VAT (€/kwh)	*0,033*	*0,044*	*0,044*	*0,044*	*0,044*	*0,044*	*0,044*
	Energy tax, incl. VAT (€/kwh)	*0,118*	*0,096*	*0,092*	*0,092*	*0,092*	*0,092*	*0,092*
	Fixed delivery rate, incl. VAT (€/year)	67,5	67,5	67,5	67,5	67,5	67,5	67,5
	Transport rate, excl. VAT (€/year)	241,9	241,9	241,9	241,9	241,9	241,9	241,9
	Tax reduction (€/year)	527,2	527,2	527,2	527,2	527,2	527,2	527,2
Electricity commercial 50.000 - 10.000.000 kWh	Variable delivery rate incl. taxes (€/kwh)	0,100	0,121	0,128	0,118	0,137	0,137	0,137
	Wholesale price (€/kwh)	0,052	0,064	0,069	0,059	0,078	0,078	0,078
	Variable component (€/kwh)	*0,010*	*0,010*	*0,010*	*0,010*	*0,010*	*0,010*	*0,010*
	ODE, incl. VAT (€/KWh)	*0,025*	*0,033*	*0,035*	*0,035*	*0,035*	*0,035*	*0,035*
	Energy tax, incl. VAT (€/KWh)	*0,014*	*0,014*	*0,014*	*0,014*	*0,014*	*0,014*	*0,014*
	Transport rate, excl. VAT (€/year)	66,0	66,0	66,0	66,0	66,0	66,0	66,0
	Fixed delivery rate, incl. VAT (€/year)	59589,0	59589,0	59589,0	59589,0	59589,0	59589,0	59589,0
	Connection fee, excl. VAT (€)	9080,0	9080,0	9080,0	9080,0	9080,0	9080,0	9080,0
Electricity commercial > 10.000.000	Variable delivery rate incl. taxes (€/kwh)	0,049	0,060	0,065	0,056	0,073	0,073	0,073
	Wholesale price (€/kwh)	*0,047*	*0,058*	*0,063*	*0,054*	*0,071*	*0,071*	*0,071*
	Variable component (€/kwh)	*0,001*	*0,001*	*0,001*	*0,001*	*0,001*	*0,001*	*0,001*
	ODE, incl. VAT (€/KWh)	*0,000*	*0,001*	*0,001*	*0,001*	*0,001*	*0,001*	*0,001*
	Energy tax, incl. VAT (€/KWh)	*0,001*	*0,001*	*0,001*	*0,001*	*0,001*	*0,001*	*0,001*
	Transport rate, excl. VAT (€/year)	66,0	66,0	66,0	66,0	66,0	66,0	66,0
	Fixed delivery rate, incl. VAT (€/year)	105540,0	105540,0	105540,0	105540,0	105540,0	105540,0	105540,0
	Connection fee, excl. VAT (€)	43095,0	43095,0	43095,0	43095,0	43095,0	43095,0	43095,0
Natural gas households (€/m^3)	Variable delivery rate incl. taxes (€/m^3)	0,819	1,120	1,167	1,194	1,221	1,248	1,275
	Wholesale price (€/m^3)	*0,267*	*0,434*	*0,456*	*0,478*	*0,501*	*0,523*	*0,545*
	ODE, incl. VAT (€/m^3)	*0,094*	*0,124*	*0,133*	*0,133*	*0,133*	*0,133*	*0,133*
	Energy tax, incl. VAT (€/m^3)	*0,403*	*0,470*	*0,482*	*0,482*	*0,482*	*0,482*	*0,482*
	Fixed delivery rate, incl. VAT (€/year)	66,5	66,5	66,5	66,5	66,5	66,5	66,5
	Transport rate, excl. VAT (€/year)	185,4	185,4	185,4	185,4	185,4	185,4	185,4
Natural gas commercial 5000-170.000 m^3	Variable delivery rate incl. taxes (€/m^3)	0,742	0,900	0,938	0,958	0,978	0,998	1,018
	Wholesale price (€/m^3)	*0,315*	*0,387*	*0,407*	*0,427*	*0,447*	*0,466*	*0,486*
	Variable component (€/m^3)	*0,000*	*0,000*	*0,000*	*0,000*	*0,000*	*0,000*	*0,000*
	ODE, excl. VAT (€/m^3)	*0,094*	*0,124*	*0,133*	*0,133*	*0,133*	*0,133*	*0,133*
	Energy tax, excl. VAT (€/m^3)	*0,333*	*0,389*	*0,399*	*0,399*	*0,399*	*0,399*	*0,399*
	Fixed delivery rate, excl. VAT (€/year)	66,0	66,0	66,0	66,0	66,0	66,0	66,0
	Transport rate, excl. VAT (€/year)	8775,8	8775,8	8775,8	8775,8	8775,8	8775,8	8775,8
	Connection fee, excl. VAT (€)	31481,8	31481,8	31481,8	31481,8	31481,8	31481,8	31481,8
District heat	Variable delivery rate incl. taxes (€/GJ)	26,1	26,1	26,1	26,1	26,1	26,1	26,1
	Fixed delivery rate incl. taxes (€/GJ)	469,2	469,2	469,2	469,2	469,2	469,2	469,2
	Measurement rates incl. taxes (€/GJ)	26,6	26,6	26,6	26,6	26,6	26,6	26,6

Table A3
Production costs renewable heat.

Energy prices	Component	2020	2030	2050	SDE++ (2020)
Biogas (€/MWh)	Biogas	90,0	76,7	50,0	0,0514
District heat (€/kWh)	Geothermal heat	0,0705	0,0705	0,0705	0,0467
	Biomass heat	0,0465	0,0465	0,0465	0,0318
	Biogas heat	0,0661	0,0661	0,0661	0,0514
	Waste heat	0,0173	0,0173	0,0173	0,0026
Hydrogen (€/m^3)	Green hydrogen	0,472	0,263	0,156	-
	Blue hydrogen	0,140	0,195	0,150	-
	Grey hydrogen	0,372	0,202	0,156	-

(efficiency), the system costs for fuel are high due to high production costs of biogas, whereas the end-user costs for biogas are low. In the breakdown (Figs. 8–10) it can be seen that the fuel is subsidized and as a result of the subsidy and other regulations, end-user costs remain low. Similar effects can be seen for solar thermal heat (scenario 3b) and aqua thermal heat (scenario 4). Concerning investment subsidies, Fig. 9 shows the minor role of subsidies for end-user investments.

Table A4
Learning rates technologies.

Technology	2050	2030-optimistic	2030-mid	2030-pessimistic
District heating - distribution	21%	21%	11%	0%
District heating internal network	25%	25%	13%	0%
District heating home substation	20%	20%	10%	0%
Close-in boiler	0%	0%	0%	0%
Heat pump air	38%	38%	19%	0%
Heat pump water	38%	38%	19%	0%
Heat pump hybrid	45%	45%	23%	0%
Heat pump large-scale	45%	45%	23%	0%
Gas boiler	0%	0%	0%	0%
Hydrogen boiler	20%	20%	10%	0%
Solar PV field	21%	21%	11%	0%
Solar boiler	21%	21%	11%	0%
UTES	45%	45%	23%	0%
Aqua thermal energy	30%	30%	15%	0%
Insulation label up until A	18%	18%	9%	0%
Insulation label A+	41%	41%	21%	0%
Low-temperature internal heating system	12%	12%	6%	0%

Table A5
Emission factors.

	2020	2030	2050	Source
Electricity (kg/kWh)	0,30	0,09	0,00	[34]
Natural gas (kg/m³)	1,89	1,89	1,89	[71]
Biogas (kg/GJ)	13	13	13	assumption
District heat – geothermal (kg/GJ)	20	20	20	[72]
District heat – biomass (kg/GJ)	13	13	13	[72]
District heat – waste heat (kg/GJ)	26	26	26	[72]
Hydrogen (grey) (kg/m³)	12,53	3,76	0,00	[71]

4.3. Future costs scenarios and effects of learning

As a result of technological learning, technologies may become cheaper and more efficient in the future. At the same time, the production costs of renewable electricity and other renewable energies may decrease whereas fossil fuel-based energy sources may increase as a result of CO_2 taxes, scarcity or geopolitical conflict. When taking these factors into account, it is relevant to evaluate what the advantage would be between taking measures now or in the future. Taking measures now will have the benefit of profiting from prolonged savings in energy costs and CO_2 emissions, whereas taking measures in the future (potentially) benefit from lower investment costs.

To assess the potential cost decline, the system costs for 2030 are calculated using cost reduction rates. The cost reduction rates for 2030 are taken from [3]. Costs decline of technologies in the heating transition in the Dutch market in this data set have been estimated using market consultation and expert opinion. The data consists of an optimistic, middle and pessimistic scenario, in which the optimistic scenario is based on what the market assumes feasible, the pessimistic scenario is always 0% (no learning) and the middle scenario is the average of the optimistic and pessimistic scenario. The data set was found to be the most complete data available from one source or method. The technologies that were not included in this database (solar PV, aqua thermal) have been complemented with other data sources [51,52].

Weaknesses of the dataset are the limited explanation of the assumptions behind the cost reduction and foundation of the data (such as market prognoses and learning rates), and the absence of a quantified minimum boundary which limits the use of the middle and pessimistic scenario. To check whether the data is reliable we have calculated the cost reduction using market information and learning rates for some of the key technologies: heat pumps, district heating and insulation. For air source heat pumps for residential applications, the current market grows at a rate of approx. 35% annually with a current volume of 159.402 heat pumps installed [53] and the learning rate is estimated at 10% [54]. With a learning rate calculation (see Appendix B for equations), the cost reduction in 2030 is 36%, which is fairly close to the optimistic scenario in the database (38%). For district heating the Dutch market is expected to grow from 24 PJ total heat supplied in 2020 to 40 PJ in 2030 [55]. With an average learning rate of 19% [56], the cost reduction can be calculated at 14%, which is a bit lower than the database suggests. Our conclusion is that the data is optimistic, but fairly adequate.

Fig. 11 shows the results for the six scenarios for reference year (2020) and two scenarios for 2030, one using the middle scenario (2030a), one using the optimistic scenario (2030b). Included in the future cost scenario are: cost decline of investment costs of the main technologies, energy prices of energy carriers in 2030 (gas and electricity), efficiency improvements of selected technologies (heat pumps) and changes is some policies (net metering scheme for solar PV). The input variables for learning rates and future energy costs can be found in Table (Appendix A: data).

Results show that as a consequence of learning, the system costs decrease in all scenarios at a rate of about 7-13% in the middle scenario and 16-24% in the optimistic scenario. The highest cost reductions are achieved in scenario 4 (low-temperature heat) and scenario 5 (efficiency). Scenario 4 consist of elements with a high learning: heat pumps

Table B1
List of relevant equations used in the modelling.

Equations	Symbols
Efficiency improvements insulation $E_{dem,\ new} = E_{dem,\ old} * \eta$	$E_{dem,\ new}$ = heat demand after insulation[J] $E_{dem,\ old}$ = original heat demand [J] η = efficiency gain per label step
Solar thermal Collector: $Q_{col} = I_0 * \eta_c * A_c$ $I_0 = I_{hor} \cdot \cos\alpha + I_{vert} \cdot \sin\alpha$ $\eta_c = \eta_0 - k_1 \cdot \frac{(T_c - T_a)}{I_0} - k_2 \cdot \frac{(T_c - T_a)^2}{I_0}$ Heat balance buffer: $c_w * m_w * \frac{dT_s}{dt} = Q_{col} - Q_{dem} - Q_{loss}$ $Q_{loss} = A_s * U_s * (T_s - T_a)$	I_0 = total irradiation [W/m²] I_{hor} = irradiation on the horizontal plane [W/m²] I_{vert} = irradiation on the vertical plane [W/m²] α = tilt angle η_0 = optical efficiency k_1 = heat loss correction value 1 k_2 = heat loss correction value 2 T_c = collector temperature [°C] T_a = ambient temperature [°C] Q_{col} = collector heat gain [J] Q_{loss} = system heat loss [J] A_c = collector surface [m²] A_s = storage surface [m²] c_w = specific heat capacity of water [J/kg K] m_w = mass of the storage medium [kg] T_s = storage temperature [°C] T_a = ambient temperature [°C] U_s = heat loss coefficient [W/K]
Solar PV $E_{col} = I_0 * \eta * A_c$ $I_0 = I_{hor} \cdot \cos\alpha + I_{vert} \cdot \sin\alpha$ $A_c = round\left(\frac{A_{roof} * a}{A_{panel}}\right) * A_{panel}$	E_{col} = energy produced by the collector [W] A_c = collector surface [m²] A_{roof} = roof surface [m²] A_{panel} = panel surface [m²] a = available roof surface [%] η = collector efficiency I_0 = total irradiation [W/m²] I_{hor} = irradiation on the horizontal plane [W/m²] I_{vert} = irradiation on the vertical plane [W/m²] α = tilt angle
Heat pumps $E_{el} = \frac{E_{dem} * load}{COP} * \frac{1}{3,6 * 10^6}$ Water-sourced heat pump: $COP_{water} = \frac{T_h}{T_h - T_c} * \eta_t * \eta_r$ $T_h = \frac{T_{supply} - T_{return}}{\ln\left(\frac{T_{supply}}{T_{return}}\right)}$ $T_c = \frac{T_{source} - T_{cooled}}{\ln\left(\frac{T_{source}}{T_{cooled}}\right)}$ Air-sourced heat pump: $COP_{hh,\ air,sh} = 1,5 + 0,0875 * (20 + T_a)$ [73] $COP_{hh,air,htw} = 1 + 0,0425 * (20 + T_a)$ [73]	E_{el} = Electricity demand heat pump [kWh] E_{dem} = Energy demand for heating [J] $load$ = Share of demand that is covered by the (hybrid) heat pump COP_{water} = coefficient of performance water-source heat pump (Lorentz efficiency) $COP_{hh,air,\ sh}$ = coefficient of performance air-source heat pump for space heating in households $COP_{hh,air,htw}$ = coefficient of performance air-source heat pump for hot tap water in households T_h = supply temperature at house level T_c = temperature of the disposed water T_a = ambient temperature η = theoretical heat pump efficiency η_r = real heat pump efficiency
Boilers $E_{out} = E_{in} * \eta$	E_{out} = incoming energy E_{in} = outgoing energy η = boiler efficiency

(continued on next page)

Table B1 (*continued*)

Equations	Symbols
District heating $Q_s = Q_p * q_{hl}$ $P_{pump} = p_{pump} * Q_p$ $C_{DH} = (C_{int} + f_c * ((L_{distr} * C_{distr}) + (L_{con} * C_{con}))) * N_{house}$	Q_p = heat delivered to the network [GJ] Q_s = heat delivered to the consumer [GJ] q_{hl} = relative heat loss in the DH network [%] P_{pump} = power required for pumping [kWh] p_{pump} = reference value for pumping power relative to heat transported [kWh/GJ] Q_p = heat demand [GJ] C_{DH} = total costs of district heating [€] C_{int} = costs of the internal network in buildings [€/connection] f_c = correction factor for building density, historical context and temperature level L_{distr} = length of the distribution pipes [m/connection] C_{distr} = costs of the distribution pipes [€/m] L_{con} = length of the connection pipes [m/connection] C_{con} = costs of the connection pipes [€/m] N_{house} = number of houses connected to the network
UTES/aqua thermal $Q_{UTES} = q * m * c_w * dT$ $P_{pump} = p_{pump} * Q_p$ $Q_{Aqua} = Q_{dem} * \left(1 - \frac{1}{COP}\right)$	Q_{UTES} = heat delivered by the aqua thermal source [J] q = time specific flow rate [m^3/h] m_w = mass of the storage medium [kg] c_w = specific heat capacity of water [J/kg K] dT = temperature difference between the extracted and injected water P_{pump} = power required for pumping from aquifer [kWh] p_{pump} = reference value for pumping power relative to heat transported [kWh/GJ] Q_p = heat demand [GJ] Q_{Aqua} = direct supply of aqua thermal heat to the network [GJ]
Grid balance $P_{max} = V * I$ $P_{NET} = E_{grid} - P_{max} * t$	P_{max} = maximum power (grid capacity) [W] V = voltage [V] I = maximum current per connection[A] P_{NET} = net grid load [W] E_{grid} = energy transported over the grid [J]
Emissions $\Delta M_{CO_2} = (E_{current} - E_{new}) * \alpha$ $C_{CO_2} = \frac{\sum \frac{I}{L} + C - B}{\Delta M_{CO_2}}$	ΔM_{CO_2} = emission reduction $E_{current}$ = reference energy use E_{new} = scenario energy use α = emission factor C_{CO_2} = mitigation costs I = investment costs L = lifetime B = yearly benefits C = yearly costs
Cost analysis Investment costs: $I_{year} = I * (1 - LR_{year})$ Annual costs: $C_{tot} = C_{fuel} + C_{grid} + C_{OM} - B$ $C_{fuel} = E * P_{var} + P_{fix}$ $C_{elec,\ cons} = E_{direct} * P_{var} * (1 - f_{NM}) + E_{surplus} * f_{NM} * P_{subs} + P_{fix} - P_{disc}$ Net present value: $NPV = -I + \frac{B - C}{\alpha}$ $\alpha = \frac{r}{1 - (1 + r)^{-L}}$ Rate of return $ROI = \frac{B - I + C}{I - C}$ Payback period $PBP = \frac{I}{B - C}$	I = investment costs B = yearly benefits C = yearly costs C_{tot} = total yearly costs C_{fuel} = yearly costs C_{grid} = yearly grid costs C_{OM} = yearly operation and maintenance costs $C_{fuel,comm}$ = yearly fuel costs C_{cons} = yearly electricity costs for consumers (net metering) f_{NM} = the percentage of production that can be supplied to the grid against a subsidy P_{subs} = subsidy fee [€/kWh] P_{fix} = fixed tariff P_{disc} = yearly discount on energy bill α = capital recovery factor r = interest rate L = lifetime ROI = rate of return [%] PBP = payback period
Learning rates $C(x_t) = C(x_0) \cdot \left(\frac{x_t}{x_0}\right)^{-b}$ [56] $LR = 1 - 2^{-b}$ [56]	$C(x_t)$= cost of technology at time = x $C(x_0)$=cost at time = 0 x_t = cumulated production x_0= cumulated production at time = 0 LR = learning rate b = positive learning parameter

(19%), aqua thermal energy (14%), UTES (23%) and district heating (11%). The order in which the scenarios perform largely remains the same in 2030, except that the efficiency scenario in the optimistic variant performs equally well as the hybrid scenario which had lower system costs in 2020. Overall, scenario 2 (hybrid) and scenario 5 (efficiency) have the best potential of becoming competitive with the reference scenario in 2030 in the optimistic scenario.

In the reference scenario, where no measures are taken, the system costs increase as a result of increasing gas prices. Scenarios with natural gas are the most sensitive to cost reduction, as can be seen from scenario 2 (hybrid) and the scenario 3b (solar district heating) which still have some dependency on natural gas (8.1 TJ resp. 2.0 TJ) in contrast with the other scenarios. It should be noted that the comparison with a scenario on natural gas is unsteady since the gas price is volatile in future years, even on the short-term as has become evident recently with gas prices rapidly increasing in the winter of 2021-2022. Additionally, household energy costs in future years are sensitive to the carbon price, which is not included in the calculation, but may become relevant in the future. This would influence the comparison with the reference scenario and eventually the attractiveness of sustainable alternatives.

Whether the cost reduction will be achieved in the future depends on many factors such as a steady development of the market, as learning curves depend on the cumulative market volume, R&D investments and sector efforts to achieve targets agreed in the Dutch Climate Agreement [57]. Not all components of a technology have the same degree of learning for which the total learning rate may be lower for the technology as a whole, as pointed out by [56]. Especially in maturing technologies, this effect may be substantial.

4.4. Sensitivity analysis

As a guide for decision-making, the reliability of the data is essential. Unfortunately, many different numbers for the same technologies circulate among practitioners. Often, the exact origin of the data is unknown, as well as an explanation of which components are exactly included and excluded in the numbers. The data presented in this paper represents the state of the art of the included technologies. In addition, we have explained the origin of our data. However, when data on individual technologies and measures are collected and compared with data that is being used in other studies, we observe quite large differences for a number of key variables.

Table 6 presents an overview of the bandwidth of these data,

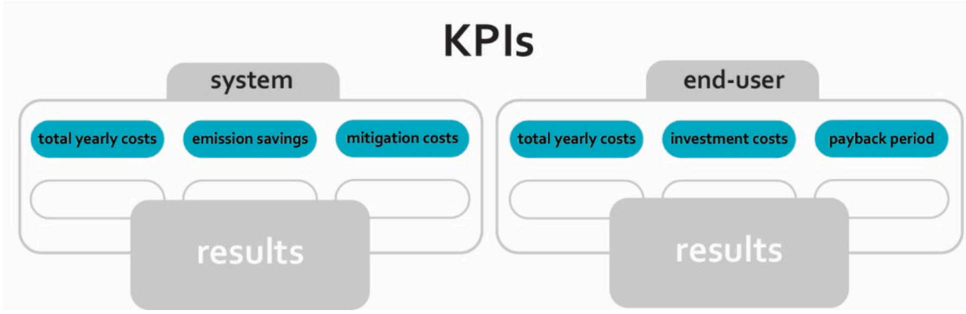

Fig. 14. Overview table with KPI's.

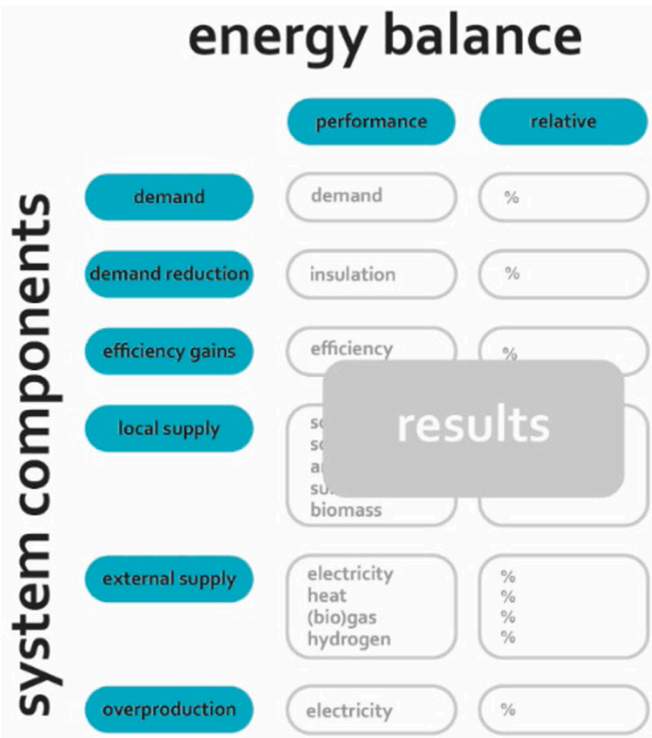

Fig. 15. Example energy balance table.

including the data sources, which is also graphically presented in Fig. 12. For district heating only a lower limit was defined due to very limited data availability of data expressed as total investment costs per house, including the costs of connecting existing houses. Next, we performed a sensitivity analysis to investigate the effect of the variables on the scenario results. As a reference we took again the terraced house from the period 1975-1992 (which is the most common housing type in the Dutch housing stock) and calculated the effects on end-user costs and system costs for each of the selected main scenarios that the measure applies to. Insulation investment, heat pump investment heat pump COP and interest rates were applied to the all-electric scenario (scenario 1), district heating investment was applied to the external heat scenario (scenario 3a) and biogas price was applied to the efficiency scenario (scenario 5).

Fig. 13 presents the model results for the bandwidth of input data. Although the variation of individual variables (see Fig. 12) are tempered by the summation of measures in the scenario calculation, the effects can be quite substantial. Looking at the bandwidth of the variables (see error bars), we can see that there is an overlap between costs in certain ranges, making the decision between scenarios based on costs, less firm. The scenario with biogas for instance, is sensitive to the provision of subsidies, and without them the end-user costs match that of the all-electric scenario (systems costs are unaffected). The largest sensitivity was found in the district heating scenario, in which may become competitive with the other scenarios at less than the minimum value for system costs, especially when the identified sensitivities in the all-electric scenario are at its maximum. However, since the uncertainty is so high, more insight in the costs of district heating systems is needed to be able to evaluate cost effectiveness even at a basic level. Other substantial effects were found in the interest rates applied to both system and end-user costs. This is line with findings by Löffler [60], who demonstrated the importance of social discount rates used in energy modeling.

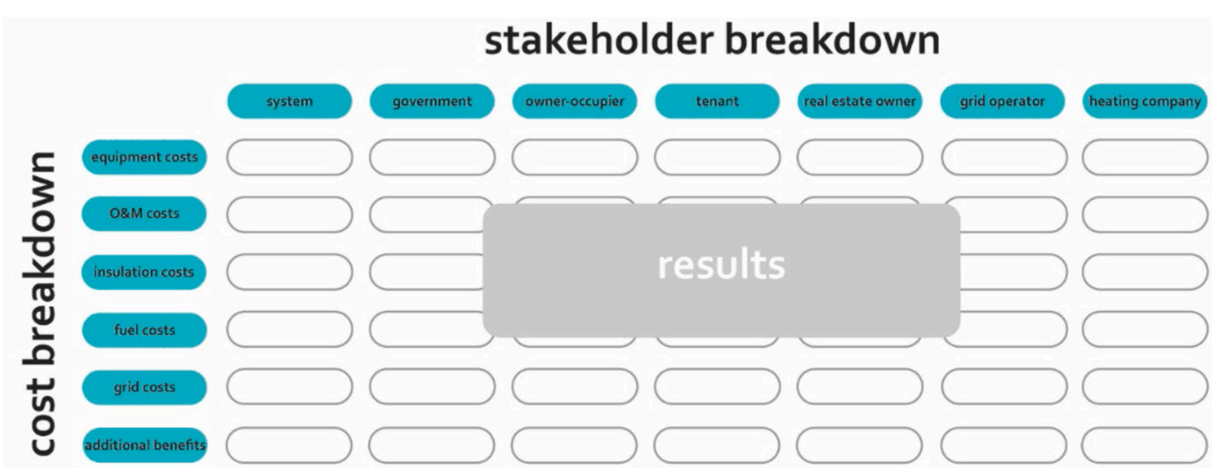

Fig. 16. Example cost breakdown table.

Table D1
Longlist of scenarios selected based on emission reduction and system costs.

Main scenario	Source	Neighbourhood measures	Individual measures	Renewable generation	Insulation level	CO_2	System costs
All-electric	Ambient air	-	Heat pump (air), induction cooking	-	-	37%	1957
	Ambient air	-	Heat pump (air), induction cooking	Rooftop PV	-	79%	2078
	Ambient air	-	Heat pump (air), induction cooking	Rooftop PV	A+	104%	3195
	Ambient air	-	Heat pump (air), induction cooking	Rooftop PV	B	93%	2337
	Ambient air	-	Heat pump (air), induction cooking	-	A+	61%	3074
	Ambient air	-	Heat pump (air), induction cooking	-	B	51%	2216
Hybrid	Natural gas	-	Hybrid heat pump	-	-	21%	1429
	Natural gas	-	Hybrid heat pump	-	A+	59%	2509
	Natural gas	-	Hybrid heat pump	-	B	43%	1666
	Natural gas	-	Hybrid heat pump	Rooftop PV	-	64%	1615
	Natural gas	-	Hybrid heat pump	Rooftop PV	A+	102%	2695
	Natural gas	-	Hybrid heat pump	Rooftop PV	B	86%	1852
	Biogas	-	Hybrid heat pump	-	-	44%	1889
	Biogas	-	Hybrid heat pump	-	A+	67%	2656
	Biogas	-	Hybrid heat pump	-	B	57%	1945
	Biogas	-	Hybrid heat pump	Rooftop PV	-	87%	2076
	Biogas	-	Hybrid heat pump	Rooftop PV	A+	109%	2843
	Biogas	-	Hybrid heat pump	Rooftop PV	B	100%	2131
District heat MT	Solar thermal field	Heat grid, heat pump, gas boiler, pit storage	Induction cooking	-	-	44%	3784
	Solar thermal field	Heat grid, heat pump, gas boiler, pit storage	Induction cooking	-	A+	72%	4920
	Solar thermal field	Heat grid, heat pump, gas boiler, pit storage	Induction cooking	-	B	63%	4033
	Solar thermal field	Heat grid, heat pump, gas boiler, pit storage	Induction cooking	Rooftop PV	-	87%	4035
	Solar thermal field	Heat grid, heat pump, gas boiler, pit storage	Induction cooking	Rooftop PV	A+	114%	5171
	Solar thermal field	Heat grid, heat pump, gas boiler, pit storage	Induction cooking	Rooftop PV	B	106%	4284
	Geothermal	Heat grid	Induction cooking	-	-	41%	3236
	Geothermal	Heat grid	Induction cooking	-	A+	65%	3734
	Geothermal	Heat grid	Induction cooking	-	B	55%	3138
	Geothermal	Heat grid	Induction cooking	Rooftop PV	-	84%	3487
	Geothermal	Heat grid	Induction cooking	Rooftop PV	A+	108%	3985
	Geothermal	Heat grid	Induction cooking	Rooftop PV	B	98%	3389
	Waste incineration	Heat grid	Induction cooking	-	-	32%	2358
	Waste incineration	Heat grid	Induction cooking	-	A+	62%	3453
	Waste incineration	Heat grid	Induction cooking	-	B	50%	2607
	Waste incineration	Heat grid	Induction cooking	Rooftop PV	-	74%	2610
	Waste incineration	Heat grid	Induction cooking	Rooftop PV	A+	105%	3704
	Waste incineration	Heat grid	Induction cooking	Rooftop PV	B	92%	2858
Warmtenet LT	Aqua thermal	Heat grid, heat pump (water)	Induction cooking	-	-	50%	3750
	Aqua thermal	Heat grid, heat pump (water)	Induction cooking	-	A+	67%	4930
	Aqua thermal	Heat grid, heat pump (water)	Induction cooking	-	B	60%	4045
	Aqua thermal	Heat grid, heat pump (water)	Induction cooking	Rooftop PV	-	92%	4001
	Aqua thermal	Heat grid, heat pump (water)	Induction cooking	Rooftop PV	A+	109%	5181
	Aqua thermal	Heat grid, heat pump (water)	Induction cooking	Rooftop PV	B	102%	4297
Efficiency	Natural gas	-	-	-	A+	52%	2060
	Natural gas	-	-	-	B	30%	1236
	Natural gas	-	-	Rooftop PV	-	43%	1276
	Natural gas	-	-	Rooftop PV	A+	95%	2311
	Natural gas	-	-	Rooftop PV	B	73%	1487
	Biogas	-	-	-	-	45%	1927
	Biogas	-	-	-	A+	67%	2349
	Biogas	-	-	-	B	58%	1782
	Biogas	-	-	Rooftop PV	-	88%	2179
	Biogas	-	-	Rooftop PV	A+	109%	2600
	Biogas	-	-	Rooftop PV	B	100%	2033
Solar thermal	Natural gas	-	Solar boiler	-	-	23%	2530
	Natural gas	-	Solar boiler	-	A+	66%	3616

(*continued on next page*)

Table D1 (*continued*)

Main scenario	Source	Neighbourhood measures	Individual measures	Renewable generation	Insulation level	CO_2	System costs
	Natural gas	-	Solar boiler	-	B	49%	2765
	Biogas	-	Solar boiler	-	-	55%	3155
	Biogas	-	Solar boiler	-	A+	72%	3740
	Biogas	-	Solar boiler	-	B	65%	3087

Further, the results are also sensitive to the accuracy of the measures chosen. The scenarios can be finetuned by allowing more variations. In this case, we chose one package for rooftop solar PV with the maximum of 20 panels at East-West orientation. When allowing variation in the number of panels, results closer to the 80% emission target are possible. For instance, at a level of 11 number of panels in the efficiency scenario and 18 panels in the hybrid scenario, the minimum of 80% emission reduction will be hit while also avoiding excessive overproduction of electricity. The conclusion that solar PV is necessary to reach the emission target in the scenarios still holds and the order of preference does not significantly change, despite the fact that end-user costs slightly increase with smaller amounts of PV. For efficiency measures, including target label C would slightly lower the results for costs while still hitting the emission target. For instance, in the MT heat scenario with waste incineration, 81% emission reduction can be achieved with label C compared to 92% with label B.

5. Conclusion and discussion

The paper has demonstrated how an integrated model for energy planning on the local scale, with the primary goal of creating input for a participatory planning process, may function. A scenario methodology was proposed with sufficient level of detail to evaluate renewable heating technologies and to evaluate scenarios that show a diversity in performance on different KPIs in an inclusive and pragmatic way. To demonstrate the model, the methodology was applied to a fictive neighbourhood of 500 houses of housing type 3D in district type D, according to the typology we have provided for this methodology.

The paper has shown how the scenario selection process takes place based on selection criteria. First, a longlist of scenarios was created by outlining logical combinations of measures. For the chosen criterium of 80% CO_2 emission reduction, most scenarios in the case-study do not reach the target. The selected scenarios heavily depend on rooftop solar PV to reach the target, which is marked as the measure with the lowest cost against high savings under the current policy regime (net metering), whereas insulation only played a minor role in the selection of scenarios with a high emission reduction and low system costs.

The analysis of KPIs (system costs, CO_2 emissions, mitigation costs, end-user costs, end-user investments and payback period) for the six selected scenarios shows large mutual differences. The scenario with the highest costs is more than twice as expensive than the scenario with the lowest costs. For mitigation costs, the difference is even higher. On average systems costs are around € 2850 compared to the reference of € 1025. The scenarios are more expensive than the reference scenario in 2020, and most of them remain above the reference costs in 2030 despite of increased costs for the reference scenario and decreased scenario costs of around 20% in the optimistic scenario. Two scenarios, namely 'hybrid' and 'efficiency', have a good potential of becoming competitive with the reference scenario in the optimistic scenario for 2030.

Implications also differ among stakeholders, with scenario 'LT heat' being an expensive scenario for all stakeholders and the scenarios 'hybrid' and 'efficiency' representing the lowest costs for both system and end-users. The difference in the scale at which measures are taken (on house level, on district level or outside the system boundaries) translate to higher investment burdens for associated stakeholders, with focal point on end-users in scenario 'all-electric', 'hybrid' and 'efficiency', and on local entrepreneurs in scenario 'MT heat A' and 'MT heat B'. Scenario 'all-electric' is the most energy-independent scenario with only 1.5 TJ external electricity required, closely followed by scenario 'LT heat' with 1.8 TJ of external electricity required.

The analysis has indicated some weaknesses in the data and the sensitivities that result from this data uncertainty. Little consensus in the existing data was found for the costs of major renewable heating technologies, in particular heat pumps and district heating. Concerning insulation, the costs of extensive renovation (energy label A and A+) is highly uncertain and data from on past renovations of various housing types is lacking. Limited information is available on the future costs of technologies as well, which impacts both the preference of one scenario over another, but effects the feasibility of technologies even more. Considering the large spread in results and identified sensitivities, it is essential to gather better data on the costs of renewable heating technologies.

The model results need to be further explored and decided on in stakeholder dialogue, as the data is meant to form input for a participatory process with stakeholders that are involved in different levels of the system. The optimal solution is eventually determined by the stakeholders in dialogue, and depends on which KPI or combination of KPIs is valued most by each stakeholder. The model outcomes presented in this paper support that dialogue. The integration of the modeling with the planning process needs to be further explored and is therefore an area of future research. One of the main challenges in this integration is how and when the techno-economic model data is brought into the social process with stakeholders. Further, the eventual modeling procedure could be combined with optimization techniques. Although the scenario approach is assumed to fit best with stakeholder processes, multi-objective optimization models could help identify promising scenarios and further refine scenarios that are selected during the stakeholder process.

The study has focussed on techno-economic KPIs so far, but with the same methodology it is possible to include non-technical indicators and other effects in the analysis as well. Comfort improvements, noise pollution, nuisance during construction and space use are, among other things, aspects that are often part of the discussion with stakeholders and are relevant to be weighed in. The same applies to the property value of dwellings, which was not included in the analysis, but which may become a relevant factor in stakeholders' considerations concerning sustainable energy measures. Further work is required to develop methods to map and quantify these aspects.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Data availability

The data and equations are further explained as 'model documentation', available as Supplementary Material

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2023.100045.

Appendix A: data

Tables A1–A5

Appendix B: relevant equations

Table B1

Appendix C: model output

The model produces three main output tables for economic, energetic/technical and environmental performance in Excel: (1) an overview of outputs per KPI, including carbon emissions and mitigation costs (environmental analysis), (2) an energy balance with all demands, supplies and losses of the system (energy analysis) and (3) an overview of all the costs components per stakeholder (economic analysis).

An overview of the outputs per KPI is illustrated in Fig. 14. The chosen KPIs consist of three indicators on system level - total yearly system costs, emission savings and mitigation costs - and three indicators on end-user level – total yearly end-user costs, end-user investments, and payback period.

Fig. 15 shows the output table for the energetic analysis. The energy balance shows how the original (current) energy demand is supplied in the scenario. The contribution of demand reduction (insulation), efficiency, sustainable (local) production and external production can be evaluated. The 'efficiency gains' refer to any gains and losses due to conversion anywhere in the system, such as the efficiency gain from heat pumps or the heat loss over district heating pipes.

Fig. 16. shows the output table for the economic analysis, showing the costs and benefits for eight different stakeholders. The investment costs per stakeholder group not only depend on which level (house or neighbourhood) the measures are implemented, but also on the in- or exclusion of taxes (energy tax, ODE, VAT) and subsidies, including SDE++ [74] and ISDE [75,76]:

- The *system costs* represent the total costs including investments, O&M costs and fuel costs related to the proposed solution excluding taxes and subsidies.
- *Government costs* cover the income of the government through energy taxes through energy tariffs and VAT on consumer purchases and the expenditures in subsidies.
- *End-user costs* and *real estate owner costs*, include investments, O&M costs and fuel costs, including taxes and subsidies.
- *Tenant costs* only include fuel costs, including taxes and subsidies.
- *Grid operator costs* include the investment costs of all adaptations in the grids for gas and electricity.
- The *local investor costs* include the investment costs of all technologies on district level, as well as district heating grids, including subsidies.

The proposed structure creates a clear overview of which costs are attributed to whom, and makes hidden costs, such as subsidies, visible so that system choices can be evaluated inclusively.

Appendix D: scenarios longlist

Table D1

References

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