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Local energy planning in the built environment: An analysis of model characteristics

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ABSTRACT

Energy planning in the built environment increasingly takes place in local settings. Suitable planning models should therefore be able to capture local dynamics, such as stakeholder behaviour, resource availability and building characteristics. In relation to the key challenges of energy transition in the built environment, building efficiency and renewable heating, little attention has been paid to the model characteristics needed to address these challenges. This paper analyses the characteristics of available models from the scientific community and the professional practice. Secondly, the paper reviews modelling approaches for integrating social factors within techno-economic models, as many local dynamics have a non-technical nature. Based on the gaps identified in the analysis, an analytical framework is proposed for local energy planning models for the built environment. Building characteristics, social context factors, temporal dynamics and spatial characteristics have been identified as key building blocks for a new modelling approach. To be able to deal with the socio-technical context, an integrated, socio-technical approach is suggested. This model collaboration, consisting of model calculations and empirical and participatory methods, will be capable of better supporting decision-making in a local, multi-stakeholder context.

1. Introduction

The building sector accounts for almost 40% of final energy consumption in the EU, 80% of which is accounted for by heat demand [1]. Transformation of the sector is thus essential for achieving ambitious climate targets. Efficiency measures and renewable heat will play a key role in this transformation [1]. Many decisions concerning the transformation of the building sector are taken in local settings, such as the adoption of efficiency measures and end-use equipment, and the construction of district heating networks. Thus, action at the municipal level is needed to accomplish policy objectives on the national and European level [2]. The importance of local implementation of policies is recognized by the EU. This is demonstrated in initiatives such as the Covenant of Mayors, which brings together local governments committed to implementing EU policy. Hence, municipalities play a strategic role in energy planning processes and the design of future energy systems [3,4]. Clearer direction and support at the national level, specifically guidelines, access to information and planning instruments, are necessary to support energy planning at the local level [4]. In particular, there is a need for developing simple modelling tools and decision support systems for energy planning at the municipal level [4–6], with simple reference to approaches that demand minimum experience and technical knowledge to be used by decision-makers [5,6].

To develop adequate models and tools, the specific characteristics of local energy systems must be analysed in detail and incorporated in the modelling exercise [2]. Whereas national energy planning has a strong focus on policy development, local energy planning is mainly used for policy implementation, which requires a more detailed modelling approach. It is important to consider the local context in order to find solutions that make optimal use of the physical characteristics of the area. It requires the consideration of building characteristics, resource potential, available infrastructure, et cetera. Previous reviews have paid attention to local scale models, including district scale models [6], optimization models at municipal scale [7], integrated community energy system models [8,9], community planning models [10] and urban energy models [11,12]. However, the key challenges that the built environment faces - building efficiency and renewable heating - were not specifically addressed nor did these reviews pay specific attention the representation of the local context.

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Abbreviations

EU	European Union
NIMBY	Not In My Back Yard
SAS	Story and Simulation
CIB	Cross-impact balance
STET	Socio-technical energy transition
ETM	Energy Transition Model
ICQ	Information-Choice questionnaire
KPI	Key performance indicators

Modelling local energy systems calls for a detailed representation of the techno-economic system which is placed in its social context. The importance of the social context has been widely acknowledged by energy modellers. Non-technical factors highly influence the success of renewable energy projects: 'Much of the existing models highly focus on technical and economic aspects, whereas issues such as political will, public acceptance, behaviour and the difficulty to change it stand in the way of technology deployment' [13]. Although those issues are particularly relevant on the local scale (such as the NIMBY phenomenon), few data and models are available for the non-technical variables or relations [11]. The various socio-economic factors are generally not included in macro (centralized) energy planning [14]. Existing energy scenario models are criticised for their limited treatment of socio-political dynamics, the co-evolving nature of society and technology, and a lack of depiction of specific actors that bring about systemic change [15]. To be able to support local decision-making, local models should provide the information needed by stakeholders. By including social factors, the possibility of finding solutions that can count on stakeholders' support will be increased. An overview of current approaches may be the starting point for designing new modelling approaches which better include these non-technical factors.

The aim of this review is to assess currently available models and tools in order to explore the characteristics of adequate local models. Energy planning on the local scale, whether it be in a city, a village, a district or a neighbourhood, has a different focus than national energy planning and requires different properties than traditional (macro-economic) energy models can offer. This review will provide an analysis of the model characteristics needed for application in the built environment on the local scale. By assessing a wide variety of models and modelling approaches, from different disciplines and from both science and practice, we aim to map the state-of-the art modelling techniques. This overview will help select the best approaches for current modelling exercises as well as indicate areas of future development.

2. Review methodology

2.1. Conceptual framework

The focus of this review is on energy planning models for the built environment that are applicable to the local scale. Compared to macro-scale energy models, local models have a specific challenge in considering the heterogeneity of the local context. There are two aspects of the local context that are further assessed in this paper: 1) physical characteristics (i.e. buildings, physical (urban) space, energy resource potential) and 2) social characteristics (i.e. inhabitants, local stakeholders). Corresponding these two aspects, the review will have the following focus:

A. Techno-economic detail: Local energy systems in the built environment can be conceptualized as systems consisting of a combination of building efficiency, renewable supply, infrastructure and storage. To support decision-making on the local level, the level of detail should be sufficient to assess options for replacing building installations, efficiency measures, (seasonal) storage of renewable heat, renewable generation potential bounded by resource constraints and adjustments to the local infrastructure. Hence, physical and technical measures should be included at a disaggregated level, which is also stated by Li et al. [15]. This review explores the level of system representation in existing models.
B. Social and institutional context: As non-technical factors, such as markets, institutions and consumer behaviour, affect the way technical systems are designed and operated, a wider view is needed that accounts for the local context [11]. Social characteristics could be included in a modelling tool itself, for instance in an agent-based model. Alternatively, a broader conception of a model could be considered, such as that of an integrated process of model calculations and tools to acquire social data and support stakeholder dialogue. A prime criterion for local planning models is that it supports decision-making in a multi-stakeholder context by considering social and human factors. A broad spectrum of approaches for integrating social factors is assessed in this review.

2.2. Review method

To conduct the review, different types of data were used, dividing the review in three stages. In the first stage, the Scopus database was searched for examples of models or modelling studies that were applied to the built environment on a local scale. The key words used consisted of a combination of the term 'energy model' or 'energy scenario', or 'energy planning', and the term 'local' or 'regional' or 'municipal' or 'district' or 'community' and the term 'renewable' or 'distributed'. The search yielded 1083 results. Additionally, we searched recent volumes (2015–2018) of a number of relevant journals[1] to obtain more specific results, after which another 39 papers were added for further review. Next, we filtered the results based on the following criteria: 1) published journal article or review 2) English language papers, 3) papers that describe integrated system modelling (specific models such as building energy demand, storage systems, district heating, electricity microgrids, etc. were excluded) and 4) attention for the representation of the local context (papers that focused mainly on (mathematical) model functioning were excluded). The reference lists of the relevant articles were scanned for additional studies (snowballing). We then grouped the most common approaches and selected commonly applied models. The selected models were further analysed using a set of evaluation criteria (section 2.3).

Secondly, we looked at models used in the professional practice for the energy transition in the built environment, taken the Dutch context as a case study. More practical models and studies are hardly presented in scientific papers, which is why grey literature was searched. Expert interviews were conducted to gain additional information on these models and check assumptions. One expert was interviewed for each model, with a total of five interviews. The experts all worked for the company or institution that developed the model (see Table 4) and were involved in the model development as a business manager or as a technical expert. We then compared those models with the results from the analysis of models described in the scientific literature, by applying the same evaluation criteria.

Thirdly, we searched the Scopus database for methodologies for the integration between social and techno-economic components in energy models, which is not sufficiently covered by reviewing established models. Key words used consisted of a combination of 'integrated' or

[1] Relevant Journals that were considered are: Energy and Buildings, Renewable and Sustainable Energy Reviews, Environmental Modelling & Software, Applied Energy, Energy, Energy Research & Social Science, Sustainable Energy Planning and Management, International Journal of Sustainable Energy.

'holistic' or 'socio-technical' or 'socio-economic' or 'hybrid', which seem the most common terms for models that combine technical and social components, and 'energy model' or 'energy scenario' and 'social' or 'qualitative'. The 112 results of this third search were then filtered based on the selection criteria 1) published journal article or review 2) English language papers and 3) to extent to which a distinctive scenario technique or modelling approach is described. Additional papers were found through the snowballing method (identifying relevant literature by using the reference lists of papers found in the database search). The selected papers were then grouped by their methodology as described in section 5.

2.3. Evaluation criteria for local models

Evaluation criteria to classify energy models have been provided by Refs. [16–19]. We applied a selection of these criteria for the analysis as indicated in Table 1. These are however general evaluation criteria to classify many different types of models. To support a more detailed analysis of model specifications for integrated models tailored to the built environment on district or neighbourhood scale, we have defined an additional set of evaluation criteria. This additional list contains criteria that are more specific to the application within this scope, looking more closely at the characteristics of buildings, physical context surrounding buildings, social context and usability of the model by practitioners. An initial list of criteria was established based on the authors' expert knowledge. After a few iterations of the model review using this list, the initial list was complemented with model specifications found in the reviewed models. Each time a model showed specific strengths in relation to modelling on a local scale or to the built environment, it was added to the list of evaluation criteria and applied on the other models. The final list reflects the strongest characteristics of the reviewed models. The final list for comparing and distinguishing local models consists of the following evaluation criteria:

- **Energy potential:** The possible technology options depend on the energy potential of the area. On the local scale, differences in resource availability can become very large. Therefore, local models should contain the characteristics of the area to identify the potential of energy resources, including available space (solar roofs, solar thermal), subsurface conditions (heat and cold storage, geothermal energy, sewage), available ambient heat (residual heat, surface water) and biomass potential. This can also include cross-sectoral characteristics such as the vicinity of industry and agriculture for exchanges of energy flows;
- **Energy demand:** Local energy models require more detailed demand data than the aggregated demand data provided by national databases. Local models should make use of sufficiently detailed, disaggregated demand patterns. In addition, not only a representation of the current situation is required, but also assumptions or projections of how energy demand develops over time as a result of post-insulation, mutations in the building stock, etc.;
- **End-user characteristics:** Age of residents, socio-economic status, financial capacity, norms and values, etc. determine the adoption of technologies and thus the implementation success of the system. Including these characteristics would give a better estimation of which technology options would be likely to be adopted by end-users, and therefore improve the use of local models for planning purposes;
- **Infrastructure and storage:** Renewable energy systems require adaptations to the existing infrastructure: existing electricity grids may need reinforcement; gas infrastructure may need to be removed or adapted to new gases and heat infrastructure may need to be built. Depending on local circumstances, congestion and imbalances could be dealt with at the local scale or in conjunction with the wider energy system. Local models should therefore be able to include current state of infrastructure and map the effects on infrastructure with sufficient detail;
- **System costs and benefits:** Traditional macro models often present total system costs in order to come up with optimal system design with maximum system performance at minimum costs. For the local scale it is equally important to differentiate between costs and benefits for different stakeholder groups, individual business cases per technology and societal costs and benefits. Such a model supports multi-stakeholder decision-making by showing consequences for different stakeholder groups. Cost parameters such as technology learning curves and energy price development are equally important in local models as they are in macro models to be able to explore the future in detail and present accurate results;
- **Energy saving measures:** The technology options that are possible in a certain situation highly depend on building characteristics. Vice versa, the technology options determine the required adaptation of buildings. Models that do not include building characteristics may give sub-optimal or non-realistic modelling outcomes;
- **System boundaries:** Local energy systems often have clear geographical boundaries, but also the technical boundaries of the system need to be clear. Production units can be placed inside or outside the geographical boundaries, and energy and fuels can be imported and exported between systems. System reliability in a renewable energy system may be overcome internally by storage, conversion or demand response or externally by grid connection to the broader energy system. The model only gives reliable results if it is explicit about the system boundaries;
- **Output:** Local models have a purpose in the implementation of national targets and should therefore be coherent with national and regional renewable energy targets. Usually this involves at least CO_2 emissions. To support decision-making and stakeholder dialogue the costs and benefits per stakeholder and for the system as a whole should be included.;
- **Interface:** Because of the application of the models in practice, the interface and 'ease of use' should be considered. Models with a web-based interface are more easily accessible for practitioners without training and easily used as communication tool. Models that are (partly) operated by a programming language or have very large (hidden) datafiles, are less easily applied in a multi-stakeholder planning process;
- **Flexibility of measures:** Variations in system components may vary widely on a small-scale level. Additionally, innovative energy systems may contain components that are not included in standardized

Table 1
Evaluation criteria for the classification of energy models.

CRITERIA	Purpose of the model	Methodology	Spatial resolution	Sectoral coverage	Time horizon	Temporal resolution	Data availability	Model availability
CATEGORIES INCLUDED	Description of specific purpose	Simulation Scenario Operation optimization Investment optimization	Global National Regional Local/ community Single-project/ building	Electricity Gas Heat Transport Industry	Years	Yearly Monthly Weekly Hourly Minutely	Internal database External database External data required	Commercial Proprietary Open source

models. The extent to which technologies and measures can be added to the model increases the flexibility of its use. In relation to the larger context, the flexibility is increased with the extent to which a model can be linked with models or components that represent the wider energy system. Even if the model only includes the most common technological options, a flexible model will allow a detailed analysis and comparison of options for integrated systems.

2.4. Review structure

The paper is structured as follows. Section 3 discusses which models are currently used for local energy planning and what their limitations and challenges are by applying the evaluation criteria presented in section 2.3. In section 4, we focus on the gap between academic practices around local models and the professional practice. Models from the professional practice are evaluated similarly to the established models in section 3. In section 5, we focus on the integration of social factors with techno-economic energy models by assessing different integration methods. Section 6 builds on the previous review sections and further explores the key characteristics of local models. Finally, an analytical framework is presented to support future developments on local energy planning. Fig. 1 illustrates the review structure, showing that the review of both techno-economic models and methods to integrate these models with social factors, lead to model specifications for dedicated local energy models for the built environment (with building characteristics, social characteristics, spatial characteristics and temporal characteristics as key building blocks).

3. Review of available energy planning models on local scale

3.1. Use of established models for local energy planning

Various authors have listed models and modelling tools that have been used for local energy planning, on municipal, community, urban, district and neighbourhood scale. Previous reviews that cover the scope of local energy modelling have been provided by Refs. [6,7,9,10,12,13,16,20,21]. We have summarized the findings from these reviews related to the applicability of modelling tools to the local scale level and have provided a detailed analysis of modelling parameters of 8 common models for the local scale, using the evaluation criteria defined in Table 1 and section 2.3 (see Tables 2 and 3).

Various authors report a distinction between general models that have been applied on the local scale and models with a specific local focus. Pfeifer et al. [13] has reviewed models that are applied in studies of sustainable energy islands. Their review shows that 10 out of the 17 reviewed island case studies use common modelling tools such as EnergyPLAN, HOMER and H2RES. The other studies used specific or tailor-made models. From this review, EnergyPlan is finally selected for performing a case study, for being an established model that covers all necessary sectors and has an add-on for analysing integration of local

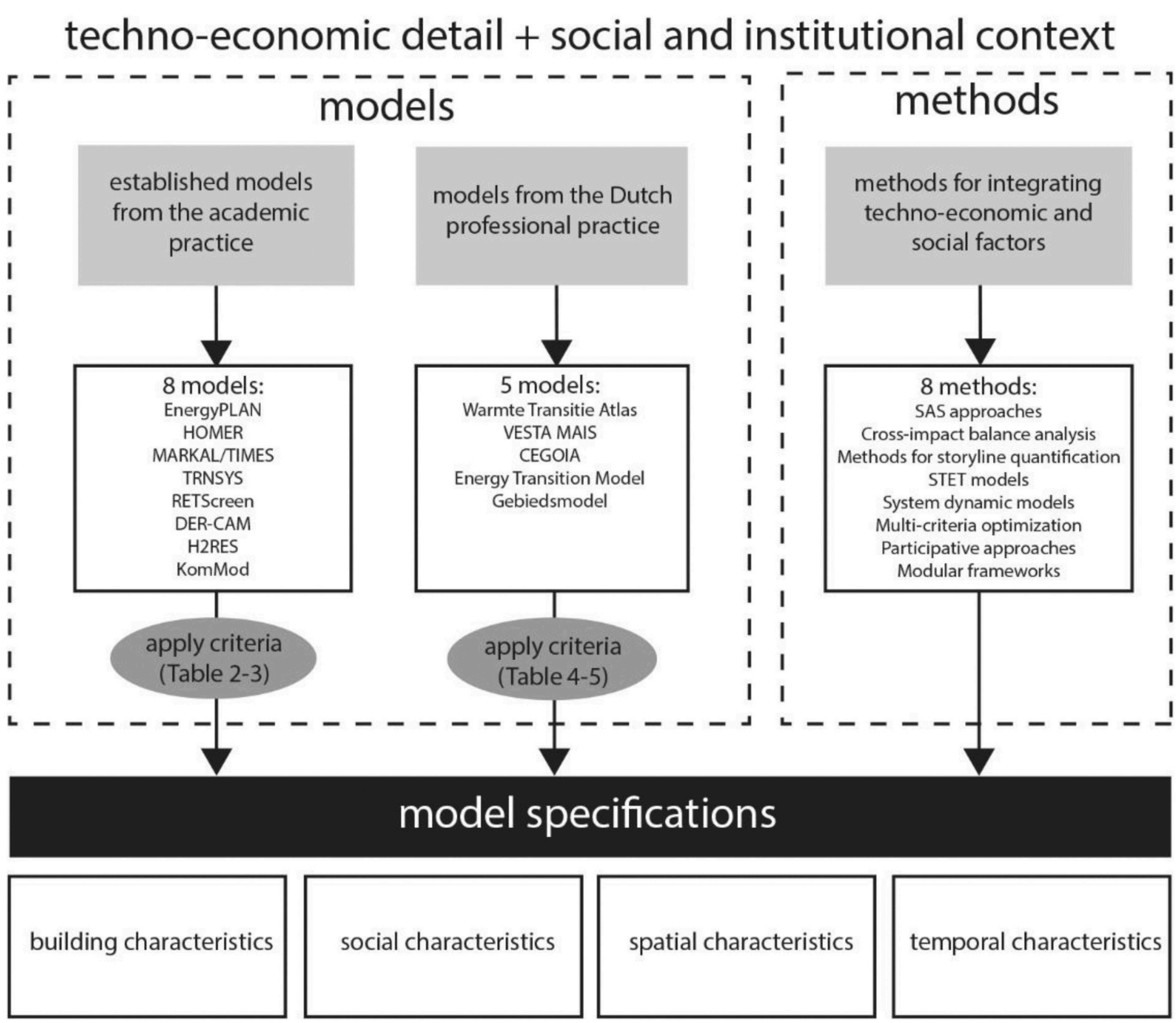


Fig. 1. Review structure.

Table 2
Characterization of energy models used for local energy planning.

	Purpose of the model	Methodology	Spatial resolution	Sectoral coverage	Time horizon	Temporal resolution	Data availability	Model availability	Developer
EnergyPLAN	Analyse energy, environmental and economic impact of various energy strategies, with emphasis on synergies between the whole energy system [10,22]	Simulation, scenario, operation optimization [16,18],	National Regional [22] Local/community [13]	Electricity, heat, transport, industry [16, 22]	1 year [16,22]	Hourly [10,16,18, 20,22]	Internal databases: input data, costs, distribution data [23] External data: Energy demand, renewable sources, station capacities, costs, regulation strategies [16,20, 22]	Open source [10,16,18]	Aalborg univ., Denmark
HOMER	Micropower design tool that simulates and optimizes grid-connected or off-grid systems [9, 16,24],	Primarily simulation, partly operation optimization and investment optimization [9, 16,20,25]	Local/community [9,16]	Focus on electricity, also includes heat [6,16]	1 year [16]	Minutely [16]	Internal database: technical components, grids, resources (fuels), loads; External data: climate data, financial parameters, etc. [24]	Commercial [20] Free trial	National Renewable Energy Laboratory, U.S.
MARKAL/ TIMES	Energy-economic tools for national energy systems with focus on interplay between macro-economies and energy use [16, 26]	Scenario, equilibrium, investment optimization (mixed integer linear programming) [9]	Global National Regional Local/community [16]	Full-sector (commercial and residential heat & electricity, transport industry) [9, 16,26]	Max 50 years [16]	Max. hourly (user-defined) [9]	Internal databases External data: Load curves, technology costs, technical characteristics, etc. [26,27]	Commercial [9,16]	IEA-ETSAP. International
TRNSYS	Modular structured model for community energy systems [16]	Simulation, scenario, partly operation optimization, investment optimization [16,25]	Local/community Single project/ building [16]	Focus on heat, also includes electricity [6, 16]	Multiple years [16]	Seconds-1 hour [16]	Internal databases: component library [28]	Commercial [16] Free demo	Univ. of Wisconsin Maddison [16]
RETScreen	Financial evaluation of renewable energy projects on building scale	Scenario, investment optimization (mixed-integer linear programming) [9]	Local/community Single project/ building [9,20]	Building level heat & electricity [16]	Max 50 years [16]	Monthly [9,16,18]	Internal database: products, costs, climate, hydrology, projects database, benchmark, energy resource maps. External data: Fuels, schedules, equipment, end-use, technology costs [20,29]	Commercial (professional mode) with open source viewer mode [29]	RETScreen International
DER-CAM	Minimize the total annual costs or CO_2 emissions of energy supply with DER in buildings and microgrid systems [25,30]	Operation optimization, investment optimization (mixed integer linear programming) [25]	Local/community Single project/ building [7,9]	Electricity, heat, transport [7]	1 year [25]	Minutely-hourly	Internal database: load, solar, tariff databases [30]	Open source [9]	LBNL [9]
H2RES	Simulate the integration of renewable sources and hydrogen in the energy systems of islands or	Simulation, scenario, operation optimization [9, 16]	Local/community (islands) [9,16]	Focus on electricity, also includes heat, partly transport [16, 32]	No limit [16]	Hourly [9, 16]	External data: Aggregated demand data [33]	Proprietary [16]	Instituto Superior Técnico/ Univ. of Zagreb

(continued on next page)

Table 2 (*continued*)

	Purpose of the model	Methodology	Spatial resolution	Sectoral coverage	Time horizon	Temporal resolution	Data availability	Model availability	Developer
	other isolated locations [31]								
KomMod	Structural analysis and optimization of the municipal energy system [34]	Optimization (linear programming) [34]	Regional Local/community (divided in zones, subzones and building types) [34]	Electricity, heat, gas, transport [34]	1 year [7]	15 min/ hourly [7]	Internal database: building types External data: Supply technologies, electricity & process heat demand, financial parameters, infrastructures, building refurbishment [34]	Proprietary	Fraunhofer ISE, Germany [20]

and national systems. Allegrini et al. [6] provided a review of 20 modelling tools for district scale energy systems. Among the reviewed models is one cluster of well-known models such as TRNSYS and HOMER, and one cluster of models with a specific urban emphasis, including CitySim, SynCity, Epic-hub and EnerGIS. They conclude that there exist many detailed, operational models at the component level on the district scale whereas models applicable to the planning stage are being a challenge.

One of the main characteristics of models included in the reviews, is that they are built for optimization analysis. Optimization algorithms are especially applied for smaller scale systems and have gained much attention in research in recent years [5,18]. Optimization analysis is considered necessary at the local level by some authors (e.g. Refs. [9, 20]). Mendes et al. [9], who reviewed 6 models for integrated community energy systems (HOMER, DER-CAM, EAM, MARKAL/TIMES, RETScreen, H2RES) point out that most of the models, apart from H2RES, appear to be useful for optimization analysis on the local scale due to the optimization algorithms and built-in flexibility. Scheller & Bruckner [7] have reviewed optimization-based models on the municipal level, and point out that those models are limited at this scale. Tozzi & Jo [20] have discussed the differences of simulation and optimization models, by making a distinction between renewable energy models, multi-level tools (e.g. RETScreen) and regional level tools (e.g. EnergyPLAN). They conclude that the applicability of renewable energy models with a focus on districts (e.g. HOMER), is high for integrated projects on a small scale, in comparison to the other two types of models. In their view, the district scale requires in-depth analysis with a focus on optimization of 'individual' projects (e.g. microgrid) rather than entire systems.

Whereas some authors specifically use established energy models, other authors claim those models are ill-suited for local scale energy planning. Connolly et al. [16] for instance have assessed the time scale that established models are operated on and have identified shortcomings in this area. They consider it necessary for local renewable energy planning that models are operated on small (hourly) time steps to assess system reliability as well as on long-time ranges for scenario analysis. From a detailed review of 37 modelling tools at various scale levels, from analysing single building systems to national energy systems, they identify two tools that are operated on both time scales and are therefore suitable for the local or community scale (TRNSYS and HOMER). Huang et al. [10] looked at the methodological focus of available models. They stress that the emphasis of traditional models is on supply-demand balance rather than demand driven optimization which they consider essential for integrated community energy systems. Based on a survey of methods and tools for community energy planning, they concluded that traditional energy planning tools, such as LEAP and MARKAL, are not suitable for the planning and analysis of community scale energy systems. Another shortcoming of current models is reported by Mendes et al. in a review of 6 available models for community scale energy systems [9]. They conclude that 'social aspects are not considered in any of the surveyed tools, both short-term and long-term' [9]. Similarly, Scheller & Bruckner [7] state that integrated models require the inclusion of individual actor decision-making. Their review shows that actor activities are underrepresented in current models.

The reviews show that there are few suitable models available for modelling renewable energy systems on the local scale. Also Mendes et al. [9] conclude that integrated multi-energy models for the local (community) scale are rare. The application of currently available models at this scale level is likewise limited, especially at the community (urban) scale and the scale of individual villages, clusters of villages, blocks or districts in the rural context [10,21].

3.2. *Selected findings*

Differences between models exist by the granularity with which the various aspects are addressed. The biggest gaps are found in an equal and detailed representation of the heat and electricity sector, representation of end-users and retrofitting potential of the building stock. The first issue with the use of established models for the built environment at local scale is the unequal inclusion of energy sectors. A valid analysis for an integrated system requires the consideration of both heat and electricity at a sufficient level of detail. Some models put an emphasis on one energy sector, whereas general purpose models, including EnergyPLAN and MARKAL/TIMES, do treat all sectors with the same degree of detail, but don't treat the individual components with a level of detail that is tailored to the local scale. In general, local energy models tend to have a stronger emphasis on electricity systems. Models that are specifically designed for the community scale, are done so with a specific goal in mind which is reflected in the included parameters and level of detail. HOMER for instance was developed for microgrid applications and focusses on electrical energy, and H2RES was developed for islanded systems with hydrogen integration and therefore allows a more detailed analysis of the electrical system than it does for heat and transport.

Furthermore, the analysis confirms an underrepresentation of end-user characteristics. Concerning the level of techno-economic detail we found most gaps in the representation energy-savings measures. General-purpose models lack a sufficient level of detail on buildings aspects. Energy savings measures are only treated with an annual improvement rate. HOMER, TRNSYS, RETScreen DER-CAM and KomMod do include energy savings measures. There is however a difference in the extent to which it is included. On a local scale, it is desirable to be able to apply specific energy saving measures to each building type rather than uniformly applying measures to the entire building stock,

Table 3
Parameters included in selected models used for local energy planning.

	Energy potential	Energy demand	End-user characteristics	Infrastructure and storage	System costs and benefits	Energy saving measures	System boundaries	Model output	Interface	Flexibility of measures
EnergyPLAN	Partly, available renewable production is input value [10,23]	Total demand and demand profile for each sector [23]	Not included	Electricity, gas, district heating/ cooling [22] Pumped hydro, battery storage, hydrogen storage, Compressed Air Energy Storage, thermal storage, seasonal storage, gas storage [23]	Investment costs, fuel costs, operation costs [17]. Manually add infrastructure costs (other than heat) and building efficiency costs [23]	Not included. Possible to include manually as in [35]	Operated without electricity balancing or in island mode [23], MultiNode add-on tool for integration analysis between national and local plans [35]	Energy balances, and resulting annual production, fuel consumption, import/exports of electricity and total annual system costs [10,16,22,23]	Graphical user interface, export options with result screen, print, graphs, and export option to excel [23]	Possibility to include add-on modules (incl. MultiNode)
HOMER	Partly, includes local climate data (solar radiation, wind speed, water speed, ambient temperature, stream flow, biomass) [10,24]	Hourly thermal electrical and hydrogen load profiles, differentiates between residential, commercial, industry and community for two peak months a year	Not included	Infra included with advanced grid add-on module, including grid extension [24] Storage: Flywheels, customizable batteries, flow batteries, hydrogen [24]	Investment and operational costs, net present cost (output)	Includes efficiency measures [24]	Both off-grid and grid-connected systems [24]	Feasible configurations, energy balances, net present cost [24]	Graphical user interface, displays tabular and graphical output [24]	Possibility to include add-on modules (components, load, sources) [24] and module packs (incl. Advanced On-Grid Package)
MARKAL/ TIMES	Partly, resource availability can be added as a constraint in the objective function [27]	Aggregated sector specific data and differentiates between multi-family, single family urban and single family rural houses	Considers household income [27] Behavioural aspects can be incorporated as constraints in the objective function [27]	Infrastructure not specifically modelled. Storage: night-day storage, pumped hydro, storage plants [17]	Total yearly costs including: investments, operation & maintenance, imports & exports, fuel costs, welfare losses and taxes and subsidies [17]	Annual efficiency improvement in existing dwelling stock due to demolishment and other improvements independent of energy savings [36]	Includes import and export of energy and materials beyond system boundaries	Energy system configurations, energy flows, energy commodity prices, GHG emissions, capacities of technologies energy costs marginal emissions abatement costs	User interface in VEDA or ANSWER [9]	Through add-on modules and/or objective function
TRNSYS	Partly, includes weather data [37]	Detailed user behaviour, building energy system [6]	Not included	Detailed thermal model, simplified electrical model, detailed thermal storage [6]	System costs are analysed external to TRNSYS16 in a spreadsheet tool [16]	Building efficiency can be added to the building component [38]	Not included	Monthly and yearly summaries of building energy load [25]	Graphical user interface [39]	Possibility to add or modify components [40] Possibility to include add-ons
RETScreen	Yes, includes location climate data and uses Energy Resource Maps [10,29]	Energy use fuel consumption, benchmark data or manual; Specific demand data for archetypes	Not included	Simplified thermal networks, Simplified thermal storage [6] Limited electrical storage, only batteries [9]	All costs, base-case compared to proposed case [16]	Includes energy efficiency measures for various types of buildings [29]	Central grid or isolated grid option [41]	Annual energy production or energy savings, financial viability & risks, emission reductions	Graphical user interface linked to Excel spreadsheet [9]	Unavailability for further expansion and adaptation [8]
DER-CAM	Partly, includes weather data [30]	Load database - end-use hourly load profiles for 3 design days per month [30]	Customer adoption model [42]	Includes grid constraints, heat losses; storage: stationary storage, electric vehicles, heat storage, cooling storage [25]	Total annual cost of energy supply: operation and maintenance costs, fuel costs, costs related to utility imports [42]	Building refurbishment measures [7]	Includes sales to the grid [42]	Optimal selection of DER and storage combination, hourly operating schedule and resulting costs, fuel consumption and CO_2 [25]	Graphical user interface [30]	Modification of the objective function to multi-objective [30]

(*continued on next page*)

Table 3 (*continued*)

	Energy potential	Energy demand	End-user characteristics	Infrastructure and storage	System costs and benefits	Energy saving measures	System boundaries	Model output	Interface	Flexibility of measures
H2RES	Partly, model uses local climate data (wind velocity, solar radiation, and precipitation) [31,32], includes Resources potential by category, high-med-low [33]	Total hourly electrical load profile as input data, also includes heat and hydrogen load [43–45]	Not included	Grid stability analysis on hourly basis included [45] Storage: pumped hydro, batteries, hydrogen, heat [31]	Investment costs, operation & maintenance costs; calculates electricity price [45]	Not included	Stand-alone systems [31] grid connection with mainland as back up, export and import of electricity from mainland grid possible [45]	Share of renewables (technical evaluation), cost of electricity (economic evaluation), CO2 emissions (environmental evaluation) [45]	Graphical user interface	Some technical, economic, security of supply, social and environmental parameters could be included as optimization constraints [45]
KomMod	Partly, includes location specific climate data	Disaggregated demand data (60-15 min basis), based on standard load profiles [34]	Split up of costs between stakeholder groups (including end-users) [34]	Includes network extensions; storage: heat storage, battery storage, electric storage [34]	Total system costs, including: yearly fixed costs, yearly variable costs, one-time costs	Yes, building refurbishment per building type, expressed as refurbishment rate (%) [34,46]	Model allows import/export between different spatial levels + within a level [34]	(Cost) Optimal configuration & operation, land requirements, optimal heat supply & refurbishment rate, emissions [34] Split up of costs between stakeholder groups [34]	Graphical user interface	Modular structure, component models can easily be replaced [34]

because the possible measures and associated costs can vary largely between different building types and frequent building types may also vary largely between sites. Only RETScreen was found able to consider individual measures. We also identified gaps in the representation of infrastructure. Since the transition in the built environment requires changes to the infrastructure, both heat, gas and electricity grids may be infected. Only KomMod clearly includes the full range of infrastructure and includes grid extensions.

4. Local energy models in practice

4.1. Local energy planning and the professional practice

Collaborations between universities and other knowledge institutions and planning authorities are quite common for national and regional (EU) energy planning. Concerning local energy planning, collaborations between local authorities and knowledge institutions have taken place across Europe on the small scale and in an experimental way. One such example is the Scottish 'Energy efficient Scotland' program [47], where the Scottish government, University of Edinburgh and a number of pilot local authorities work together to develop Local Heat and Energy Efficiency Strategies, including modelling tools.

However, the overall review process of models in the Dutch context has shown that local energy planning does not make much use of available models from the scientific community. The nature of the models that were found suitable for including in this review, indicates that local planning authorities seem to find their way to consultants and advisory bodies more easily than to the scientific community and the models and tools they can provide. Hence, a gap can be identified between the scientific community and the professional practice, when it comes to energy planning on a local scale.

To analyse the differences between planning models provided by the scientific community and those used in the professional practice in more detail, we take the Dutch situation as a case study. In policy for the transition of the built environment in the Netherlands, an approach was chosen in which.

local governments have received increasing responsibility in energy planning processes. Models developed by the professional practice currently support local governments in this challenge.

We selected five tools that have been applied by municipalities and other local stakeholders in local energy planning processes and have analysed its model characteristics. The selected models have a focus on the built environment (as single-sector or multi-sector model) and are suitable for modelling on neighbourhood scale. Tables 4 and 5 give an overview of the characteristics of the selected models and Fig. 2 shows the extent to which each model satisfies the criteria for local models in a radar chart. The data of Tables 3 and 5 have been translated to a value between 0 and 5 as input for the scales in the charts. If a criterion for a certain model has been evaluated as missing, it was assigned a score of 0 in the radar chart, if the model included only part of the aspects mentioned in the criteria or lacked detail, a score between 1 and 4 was assigned depending on the quality and if the model included all aspects in a high degree of detail, a score of 5 was assigned.

4.2. Selected findings

The models show a large variety in the amount, nature and level of detail of parameters that are included. One of the main differences with the available models from the scientific community is that basically all of the models are simulation, not optimization models. Most models are designed to explore different technology options for an area and include the most common technologies, with relatively aggregated and static data. Four out of five models are operated on a low temporal resolution (yearly time steps). Some of the models only allow a limited number of technology options to be assessed, others include some flexibility towards adding more measures. There are generally two categories of

Table 4
Overview of energy models used for local energy planning in the Dutch context.

	Purpose of the model	Methodology	Spatial resolution	Sectoral coverage	Time horizon	Temporal resolution	Data availability	Model availability	Developer
Warmte Transitie Atlas (Over Morgen)	GIS based model that calculates the lowest societal costs per neighbourhood and identifies promising buildings/neighbourhoods	Simulation	Regional Local/community	Residential and commercial heat, partly electricity	1 year	1 year	Internal databases: technology costs, demand, etc. External database: building data	Proprietary	[48] overmorgen.nl
VESTA MAIS (PBL)	Calculates energy use, costs and CO_2-emissions for the building stock as input for policy development	Simulation	National Regional Local/community	Residential and commercial heat, partly electricity, greenhouse horticulture	Max. 30 years (until 2050)	1 year	Internal databases: Technical characteristics, technology costs, etc. External databases: building data, building energy demand External data: local specific data	Open source	[49,50] pbl.nl
CEGOIA (CE Delft)	Excel based model that calculates integrated costs of heating supply in the built environment	Simulation Partly investment optimization	National Regional Local/community	Residential and commercial heat, partly electricity	Multiple years	1 year	Internal databases: Technical characteristics, costs External databases: building data, building efficiencies	Proprietary	[51] ce.nl
Energy Transition Model (Quintel Intelligence)	Model calculates CO_2 emissions and costs as a result of user defined model input	Simulation	National Regional Local/community	Residential and commercial heat and electricity, transport, agriculture	Max. 30 years (until 2050)	1 h/15 min	Internal databases: building efficiency, technology costs, technical characteristics External data: yearly energy demand per sector	Open source	[52] energytransitionmodel.com
Gebiedsmodel (Dcision/Alliander)	Model calculates economics, environment (CO2), infrastructure, employment as a result of user defined model input	Simulation	Regional Local/community	Residential and commercial heat and electricity, industry, transport, agriculture	1 year	1 year	Internal databases: technical characteristics, technology costs, etc. External data: local characteristics technical characteristics, technology costs	Proprietary	[53] netbeheernederland.nl

models: one that has a focus on heat specifically, and one that allows a wider systems analysis. The policy focus on decarbonization of the heat supply in the Dutch context has led to a focus on heat planning, with a limited integration between heat and electricity. Vice versa, models that have been developed for wider systems analysis include a limited number of heating options. Either way, a systems analysis with sufficient level of detail is challenging with these models.

A difference was found in the amount of input data that is required. One group of models requires manual input of demand data (e.g. ETM) and another group of models are linked to a GIS database and/or other databases and load input data of the area of study (e.g. Vesta). The inclusion of data on the energy potentials in the area of study are dealt with quite differently among the models. Excluding an accurate estimation of resource potential may lead to unrealistic outcomes. In some models it is possible to supply 100% of all energy demand with solar PV although the area needed exceeds the available space of the location. As a consequence, the use of the model requires additional analyses and subsequently manual adaptation of the parameters to obtain realistic results.

End-user characteristics are hardly or not at all included in any of the models, whereas several models do include some form of stakeholder differentiation. Those models calculate for instance the business case or financial result per stakeholder group, including end-users. This corresponds with its main purpose of providing a first analysis that should feed the discussion with stakeholders. However, as input for integrated decision-making, these models are likely to be too limiting in their scope.

Table 5
Parameters included in selected regional energy models.

	Energy potential	Energy demand	End-user characteristics	Infrastructure	System costs and benefits	Energy saving measures	System boundaries	Model output	Interface	Flexibility of measures
Warmte Transitie Atlas	Not included	Yearly aggregated demand data based on historic energy use	Not included	District heating: Key number per connection, includes investments in grid reinforcements included in all-electric option Storage: not included	Total investment costs, operation & maintenance costs, infrastructure costs, differentiates costs in natural replacement and standard	Includes two retrofit options for buildings, differentiates between collective and individual approach	Not included	Total (yearly) societal costs	Web application	Limited
VESTA	Yes, technical potential (rooftop PV, waste heat, geothermal, seasonal storage)	Key data per building type + year + household size Demand development based on housing stock prognoses + degree days	Option to include technology acceptance indicators in the future	District heating: track + differentiation between high and low temperature, includes costs for grid expansion and removal Storage: not included	Total yearly system costs, including investment costs, operation & maintenance costs, infrastructure costs, end-user costs, includes learning curves technologies (min-max) and projection of energy prices (high-low)	Indexed efficiency per housing type and year of construction	Not included	CO_2 Energy use National costs Societal cost-benefit-analyses per stakeholder group	No user interface	Standard list + editor
CEGOIA	Includes potential local heat sources.	Yearly aggregated energy demand data based on historic energy use	Includes average income per neighbourhood to determine investment space	Includes district heating costs: connection costs (key number per connection), substations, distribution grid; grid reinforcement costs (€/kW depending on insulation level and technology) Storage: not included	Total yearly system costs, including investment costs, operation & maintenance costs, infrastructure costs, end-user costs, includes learning curves technologies and projection of energy prices	Savings and associated costs based on energy label steps	Not included	Total yearly costs, costs end-users	Web application, Microsoft excel	Limited
Energy Transition Model	Energy potential is an input variable.	Aggregated energy demand for 1 base year is input variable. Model uses hourly patterns for balance analysis	Not included	District heating costs: key number per connection or per capacity + operation & maintenance costs Electricity grid: balance analysis, grid reinforcement costs Storage: includes batteries, vehicle-to-grid (V2G), hydrogen, power-to-heat, pumped hydro	Total yearly system costs, including investment costs, operation & maintenance costs Allows dynamic prices of electricity Includes learning rates (manual)	User defined percentage of efficiency improvement differentiated by 5 housing types	Includes import/ export of electricity	CO_2 Investment costs Energy use Energy import Percentage renewable Security of supply	Web application	Limited - quantification of measures through sliders
Gebiedsmodel	Availability of several heat sources (yes/no checklist)	Fixed average yearly uses per end-use	Not included	Investments in grid reinforcements, grid capacity: high and low voltages lines, high and low temp. heat Storage: includes batteries	Total yearly system costs, including investment costs, operation & maintenance costs Includes price developments	Insulation is included as percentage of efficiency improvement + efficiency measures	Includes import/ export of electricity	Financial analysis (costs & benefits) CO_2 Infrastructure effects Employment effects	Microsoft Excel	Selection from list, measures could be added by the user

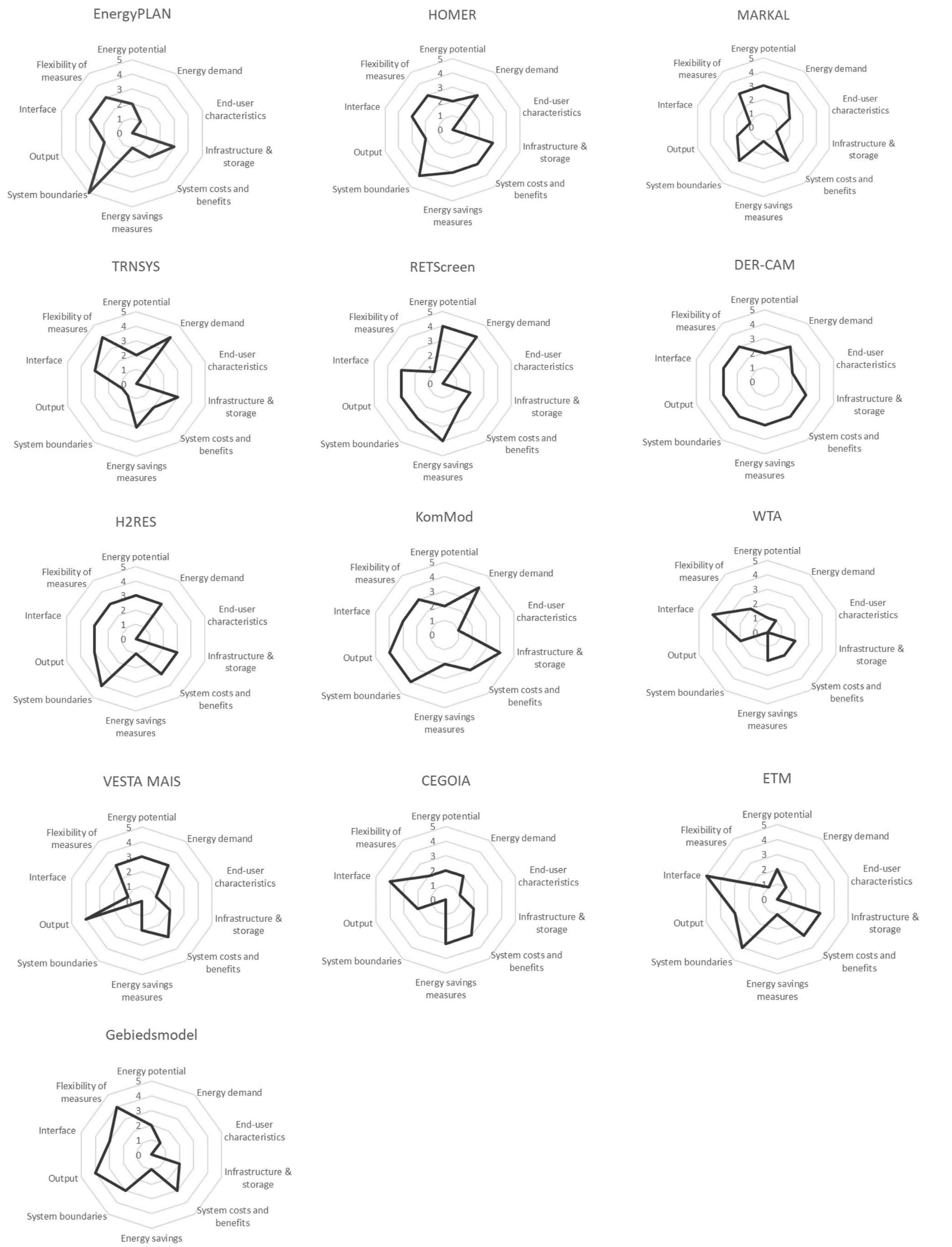


Fig. 2. Radar charts indicating how well each reviewed model satisfies the evaluation criteria for local models in the built environment as defined in section 2.3 on a six-point scale.

5. Review of methods to integrate social factors in techno-economic energy models

The inclusion of human and social factors improves the quality of energy models, making them more robust and better suited for policy purposes and decision-making [54–56]. Up until now, social factors have generally been considered to be non-numerical, qualitative input that is difficult to quantify and incorporate in techno-economic models. The difficulty of integrating these kinds of data has been a methodological search in the field of energy modelling. This section outlines the most common approaches to include social factors into models as well as some promising new integration methods.

Fig. 3 provides a summary of the reviewed methods for integrating social factors in techno-economic models. The methods can be categorized over two axes: the horizontal axe showing the extent to which social and technical aspects are integrated into one model versus the combination of several tools to cover all aspects and the vertical axe showing the extent to which models are capable of including a specific social context (i.e. stakeholders) versus more general social aspects. The figure also shows methods for qualitative data gathering that were mentioned in the reviewed integration methods.

5.1. SAS approaches

Integrated scenario methodologies (i.e. Story and Simulation (SAS)) have become state of the art in developing explorative scenarios of socio-environmental and socio-technical change [57]. Storylines or context scenarios have gained importance as they provide a coherent context for modelling assumptions and confront the modelling parameters with realistic assumptions on developments in the embedding society [55,56,58]. Most examples of integrated methods in energy research concern the use of storylines and developments of the method have been reported in the recent literature. Three types of approaches to the use of qualitative storylines have been defined by Geels et al. [59] and by McDowall [60], who differentiate between different levels of integration between storyline and energy model:

- The use of storylines as tools for identifying and differentiating the values of key parameters for modelling exercises;
- The use of storylines for a detailed quantification of narrative scenarios to ensure they are technically feasible and consistent;
- The use of storylines in dialogue with the modelling exercise. A more intensive, iterative process where the energy model and storylines are confronted with each other in different phases throughout the modelling process (see Refs. [54,59–61]).

An advantage of the method is that it also becomes possible to represent key issues that are widely recognised by stakeholders to be important but are not necessarily translated into measurable parameters. These issues may however guide decisions, but potentially remain unexamined tacit assumptions in existing models [43].

Although the third variant of the method can be seen as an attempt to increase the robustness of scenarios by better integrating quantitative and qualitative parameters, the method is still subject to criticism. SAS approaches are based on an intuitive logics style, meaning that there is no theoretical foundation but subjective assessment underlying the construction of scenarios [62,63]. Criticism on the use of storylines includes the reliance on expert opinion, lack of scientifically soundness or objectivity and lack of a systematic way of constructing the storylines [56,62,64]. Traceability and consistency are defined by Kosow [62] as

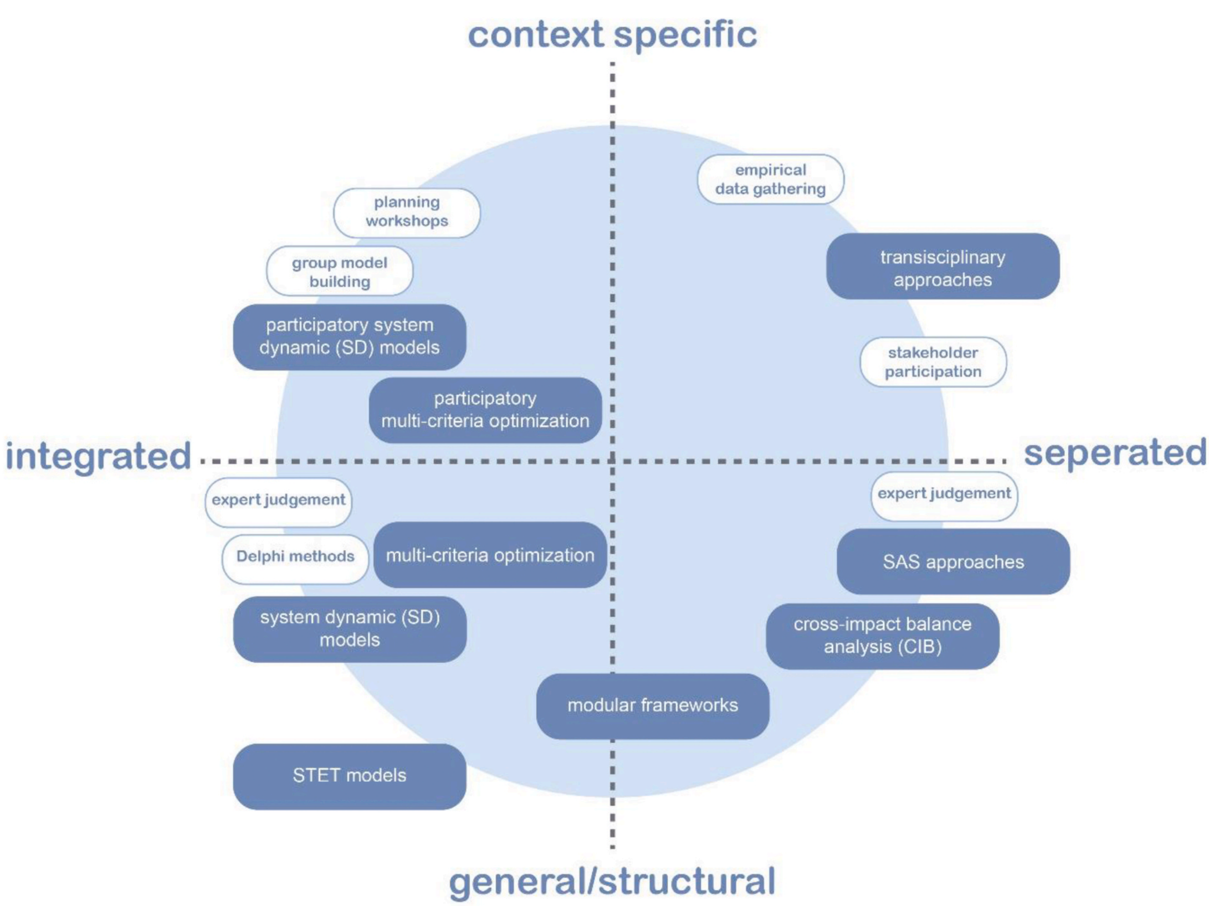


Fig. 3. Summarizing figure of methods for integrating social factors in techno-economic models (blue boxes) and qualitative data gathering methods (white boxes).

the main criteria to assess the quality of integrated scenarios. In a case study applying these assessment criteria on two cases, Kosow found that empirical evidence on traceability and consistency needs was especially low.

5.2. Cross impact balance analysis

Cross-impact analysis, originally introduced in 1968 by Gordon & Hayward [65] and further developed into cross-impact balance (CIB) analysis by Weimer-Jehle et al. [64], provides a more systemic way of constructing storylines. In CIB analysis, the influence of interdependencies between context developments is assessed in order to create consistent storylines [66]. The underlying idea is that impacts cannot be seen separately, and the correlation between the scenario factors (so-called 'descriptors') should be assessed by varying these factors simultaneously. The internal consistency of possible configurations is assessed through the construction of an impact matrix. After the identification of the most important scenario factors (such as fuel prices, energy policies and willingness to invest), an impact matrix can be constructed. The interrelationship between factors is evaluated through expert judgement. The resulting numbers in the cells of the impact matrix represent the nature of the interrelationships, ranging for instance from −3 for a strong negative relationship to +3 for a strong positive relationship. A scenario is considered consistent when the chosen assumptions are consistent with the balance of all impacting factors [67]. The identification of consistent scenarios requires the checking of many combinations and is therefore carried out by computer calculations.

A problem with the CIB method is that the number of variations to check may become extremely high in detailed stories with many factors. Validating the internal consistency would then become unmanageable with traditional CIB. To address this problem Schweizer et al. [68] introduced a modification to CIB, which they call 'linked CIB' that divides one large impact matrix into several smaller matrices to allow multi-scale and multi-sectoral scenario analyses. Linked CIB is a mathematical approach for assessing interrelationships in a computationally feasible way by exploring smaller partitions of the matrix for consistent combinations. Vögele et al. [66] introduce an approach called 'Multi-level Cross-Impact' which also allows complex analyses on different scale levels (global, national and sectoral). Separate cross-impact matrices are constructed for each scale which are adjacently linked to create consistent storylines.

Although the CIB methodology combines a quantitative approach with a more explicit appraisal and a deeper analysis of societal assumptions [56], CIB analysis still struggles to really merge the qualitative and the quantitative knowledge and suffers from many of the weaknesses of other SAS approaches, in which the translation of qualitative into quantitative knowledge, remains one of the weakest links in these procedures [69].

5.3. Other methods for storyline quantification

The main issue with the translation of qualitative into quantitative knowledge is that the diverse parameters included in the storylines cannot fully be translated one-on-one into modelling assumptions of existing models. In response to this issue, Trutnevyte et al. [57] propose an approach that links detailed storylines with multiple, cross-scale models, which have different spatial, temporal and disciplinary foci. Translation of detailed storylines into model assumptions results in a narrower representation of the system. The use of multiple models, that each have their own strengths, allows a broader spectrum of insights than one single model. The concept of 'the landscape of models' is introduced for mapping the key field of expertise of models. However, they conclude that the translation procedure is one of the weaknesses of the study and a 'unified framework for the translation of storylines into modelling assumptions', would need to be defined.

Robertson et al. [70] builds on the work of Trutnevyte et al. [57] and presents a more formal approach to storyline quantification. The methodology is based on an iterative procedure with an interdisciplinary team of researchers leading to scenario factors that are more accurate, consistent and robust. The method depends on expert opinion for identifying which assumptions are modelled. The method does not show how different dynamics in the storyline lead to a descriptor.

5.4. STET models

Another issue with SAS approaches is that narratives are not able to deal with complex variables [57]. Neither are techno-economic models able to include transition dynamics in the modelling [60]. In reality, the structure of the system itself evolves and rules guiding development co-evolve with technologies, behaviours and business strategies [71]. Formal quantitative models are unable to adequately represent the dynamics of socio-technical change [60]. Scenario storylines do provide a way to make assumptions and views on socio-technical change explicit, but scenarios are primarily used to induce learning by exploring possible futures, rather than giving an accurate representation of which dynamics are likely [72,73].

Socio-technical energy transition (STET) models provide a more advanced method for further integrating qualitative factors – including transition dynamics - in the energy modelling, by bringing energy modelling and socio-technical transitions theory together. Li et al. [15] name the requirements for fully integrated models that capture the dynamics of socio-technical energy transitions, being:

A. Techno-economic detail
B. Explicit actor heterogeneity
C. Transition pathway dynamics

Li et al. conclude in their review that the field of STET models is small but emerging. This is supported by McDowall [60], who states that 'models that include transition dynamics, informed by evolutionary or co-evolutionary thinking are developing, but in their infancy'. The models that do come close to the definition of what a STET model should be, use dynamic modelling or agent-based modelling and thus form a quite different type of model than the aforementioned SAS methods. Some of the reviewed STET models were linked frameworks, which indicates that model collaborations may be a promising future development for models that cover the three STET model domains.

5.5. System dynamic models

System dynamic modelling is often applied to understand behaviour of complex systems. They do not primarily serve as a decision support tool directly, but create opportunities to identify knowledge gaps and to develop models that can be used as decision support tools [74]. The approach differs from techno-economic models in the sense that system dynamic models consider feedback, time delays and non-linear behaviour. Dynamics between various elements of systems, including social drivers of system change, can be assessed, which makes it a suitable method for complex, interdisciplinary and large-scale systems. It is therefore a useful method to explore scenarios based on different policy interventions [74] and to assess costs of policies in relation to their effects [75].

There are multiple examples from the field of energy. Xavier et al. [75] for instance describe a system dynamics model applied to the Minas Gerais area in Brazil. The methodology was chosen primarily due to the capabilities to develop a causal descriptive model, that is capable of identifying and quantifying the feedbacks across the economy, society and environment. The model quantitatively addresses the social, economic and environmental impacts of selected policy interventions. Moalemmi [76] describe a modelling approach based on system dynamics which they call "dual narrative modelling approach". In this approach, the narratives inform the developments of the model structure. Vice versa, model simulations can inform narratives by clarifying the complexities, causal relations and non-linear dynamics and side-effects of transition dynamics.

System dynamic models can easily be combined with participatory methods. Xue et al. [77] describe an online modelling tool for the urban circular economy and state that dynamic models are relevant for participatory policy-making by creating insight in the complexity of problems for the involved stakeholders. Eker et al. [74] describe a participatory system dynamics modelling approach to capture the complexity of the interactions between housing, energy and wellbeing in an integrated manner. The system dynamics approach is combined with a participatory method: stakeholders are directly involved in the model development process, which they call ‘group model building’. The expert knowledge gained from stakeholder workshops serves as input for the model. Similarly, Rees et al. [78] develop a combined approach for the transport sector with a Delphi analysis, where a panel of international experts provided qualitative material for developing a system dynamics model. The resulting causal map proved to be useful in identifying the drivers and barriers to change in the transport system.

5.6. Multi-criteria optimization

Local energy models in the rural context are mainly developed for economically weak regions, where local energy planning is used as a means to address environmental issues (e.g. resource extraction, pollution) and socio-economic goals (e.g. job creation, social acceptance) in a region simultaneously, as variations in socioeconomic and ecological factors of a region are not easily resolved by macro energy planning [79]. These diverse goals are reflected in the applied methodologies. Multi-objective optimization and multiple linear programming are common methodologies in microlevel energy planning in rural areas, including resource constraints, reliability and socio-economic factors.

A number of examples of such methodologies can be found in India and other Asian regions. Deshmuk et al. [79] for instance describe an optimization model for micro-scale energy planning in rural India that finds the best resource mix to create minimum cost, maximum system efficiency and optimum resource allocation. Among the eight optimization objectives are also non-technical factors: ‘maximum reliability’, ‘maximum social acceptance’ and ‘maximum employment generation’. Similarly, Chandrashekar [80] describe a multi-objective programming method applied in the Phewatal watershed in Nepal. Among the 6 optimization objectives, categorized as economic objectives, equity objectives and environmental objectives, are ‘increased employment’ and ‘reduced pollution’. Hiremath et al. [81] describe a goal programming tool for the Tumkur district in India, also including ‘maximizing employment generation’ and ‘maximization of reliability’ among the objectives. Hiremath et al. [21] mention various other examples of multi-objective programming models in the Indian (rural) context.

In the European context, similar examples can be found of rural energy planning using multi-objective programming approaches. Beccali, Cellura & Mistretta [82] for instance describe a multicriteria decision-making method which was applied to the island of Sardinia, Italy. Attention is paid to the socio-economic status and history of the island, using criteria such as ‘labour impact’, ‘land requirements’ and ‘consistence of the installation and maintenance requirements with local technical know-how’. Kyriakarakos et al. [5] describe a fuzzy cognitive maps decision support system for renewables local planning that also use multiple evaluation parameters, including legal and regulative (e.g. license maturity status), social context (e.g. community acceptance) and environmental categories (e.g. land use). The choice of parameters again shows the inclusion of local characteristics concerning socio-economic and spatial requirements.

5.7. Participatory approaches

A separate category among local energy models is related to the use of participatory methods in the modelling exercise. Energy planning on the local scale involves many different stakeholders in the decision-making process that each have their own interests and perspectives. The different stakeholders, their motivations and the interactions between them affect the design and implementation of local energy systems. This is a quite different approach than the aforementioned models, as there is not a model that provides the ‘best’ solution or set of solutions, but local stakeholders assess scenarios that are generated by a fairly simple model.

There has been no systematic approach on the interactions between consumers, grid operators, prosumers, and utilities and the effect of different technical, economic and regulatory grid operation models [83]. Attempts to better include stakeholders in the local energy planning process, have led to the development of participatory planning procedures. These methods generally focus on the collection of qualitative data to construct storylines (see Ref. [58]) or on the identification of stakeholder values for performing multi-criteria analyses (see Refs. [84–86]). These methods are however not typically combined with a techno-economic model.

The combination of a quantitative scenario analysis with a participative multi-criteria analysis has been studied by Kowalski et al. [87], who have applied the approach in a case study of local communities in Austria. Local stakeholders were involved in the scenario development process and the selection of criteria and weightings for the assessment of scenarios was derived from the stakeholders through workshops and interviews. Similarly, Heaslip & Fahy [88] describe a transdisciplinary method for community energy planning with HOMER where context and place specific, energy related empirical evidence was collected through social scientific research methods and used to inform the quantitative analysis. Transdisciplinary approaches aim at a more in-depth analysis of qualitative aspects. Planning workshops, focus groups and interviews with community members were used for data collection.

5.8. Modular frameworks

Integrating transition dynamics highly increases the complexity of models. With this complexity, resulting from the need to include multitudinous interactions, models become untransparent and are therefore criticized as unsuitable for policy analysis [89]. Although appropriate methods do not yet exist in abundance, suggestions in the recent literature [15,89,90] indicate modular frameworks that integrate different modelling techniques, that are either soft or hard linked.

Wiese et al. [90] propose such an approach to interdisciplinary modelling: an open source energy modelling framework based on a modular structure, open data and a generic concept of energy system representation. Because of its underlying generic basis in combination with a flexible programming language, it facilitates the modelling process for complex and changing systems such as highly integrated, renewable-energy-based systems. The concept allows the integration with other modelling techniques, i.e. approaches that suit interdisciplinary modelling, including agent-based models. Although Wiese describes the functioning of an existing framework with these properties, the model does not function as described just yet.

In line with [48], Pfenniger et al. [89] question the appropriateness of current large models and propose modular frameworks that have a wide range of tools and methods available to select from to answer specific questions. In their view, a modular framework would be able to address key challenges to modelling 21rst century energy systems, with higher resolution of time and space being a particular concern. In relation to the local scale, where also the integration of many different qualitative and quantitative elements is essential, a modular approach seems the most plausible. None of the existing methods assessed so far has been able to render and facilitate the complexity and dynamics of energy transition on the local scale. What is needed to tackle the issue in a comprehensive way, is a combination of interconnected methods [91].

6. Synthesis and research prospect

Based on the foregoing reviews, we have identified the main gaps in current modelling approaches. We have found that the level of detail of established models is often inadequate for the local scale. Especially the inclusion of building characteristics, with a specific focus on retrofitting potential and equipment potential, can be identified as an important shortcoming in many models. The lack of level of detail also becomes visible in the low temporal resolution that many of the reviewed models are operated on. It should be further explored how temporal dynamics should be included in a local model to allow the assessment of i.e. fluctuating renewables and storage options as well as transition dynamics. Similarly, spatial characteristics, in particular the inclusion of resource potential, is essential in a local (urban) context and feasible methods for including spatial characteristics should be found. Concerning the social context, little attention has been paid in current models to the integration of techno-economic components with social factors.

These gaps lead to the identification of four key areas of model development: building characteristics, social context factors, temporal dynamics and spatial characteristics. We have made a first attempt to further explore the main buildings blocks for a local energy model for energy planning in the built environment based on the key areas. The following sections will elaborate on these building blocks by selecting the best approaches from the reviewed models and indicating where future development is needed.

Fig. 4 presents an analytical framework with these building blocks that covers the key dimensions of such a model. The figure shows the identified building blocks that are highly relevant for the local scale, but which are underrepresented in current energy models, as well as the state-of-the-art methods and techniques for integrating those components with techno-economic modelling.

approaches. Based on the literature review, we have identified the data that can be made use of to further define and construct these components. As indicated by the dotted lines, the integration of some building blocks is less well represented in current approaches than others and those components in particular indicate a need for further research. The research agenda for local scale models should prioritize the inclusion of stakeholder behaviour, integration of different time and spatial scales, and typologies with more detailed building characteristics.

6.1. Key building blocks

6.1.1. Building characteristics

Most of the reviewed models use aggregated data on building energy demand. Sectoral data without any differentiation between different building types is the most common way to include energy demand. For retrofitting potential, some models do differentiate for two or more building types (e.g. Markal, ETM, RETScreen). However, the heterogeneity of the building stock is not well addressed in most models. It is important to consider building specific data in order to make realistic assumptions about the potential of technologies and to be able to inform stakeholders, including individual home-owners. We therefore explored some options to better represent the heterogeneity of the building stock.

At a higher spatial resolution, disaggregated data becomes more important to construct detailed demand profiles. According to Moghadam et al. [92], two main approaches can be distinguished for how current energy models deal with the issue of demand modelling: 1) Deterministic, engineering based approaches that allow detailed demand simulation on building level using micro-climatic data, and 2) Statistical approaches that use aggregated demand patterns for the whole stock based on historic demand data obtained from national databases. Engineering approaches are accurate, but are time-consuming and require many detailed data. Statistical approaches on the other hand are much less accurate and little detailed, at least on building level, but are rather easy to generate and often provide sufficient input for energy planning purposes on larger scales such as districts and neighbourhoods.

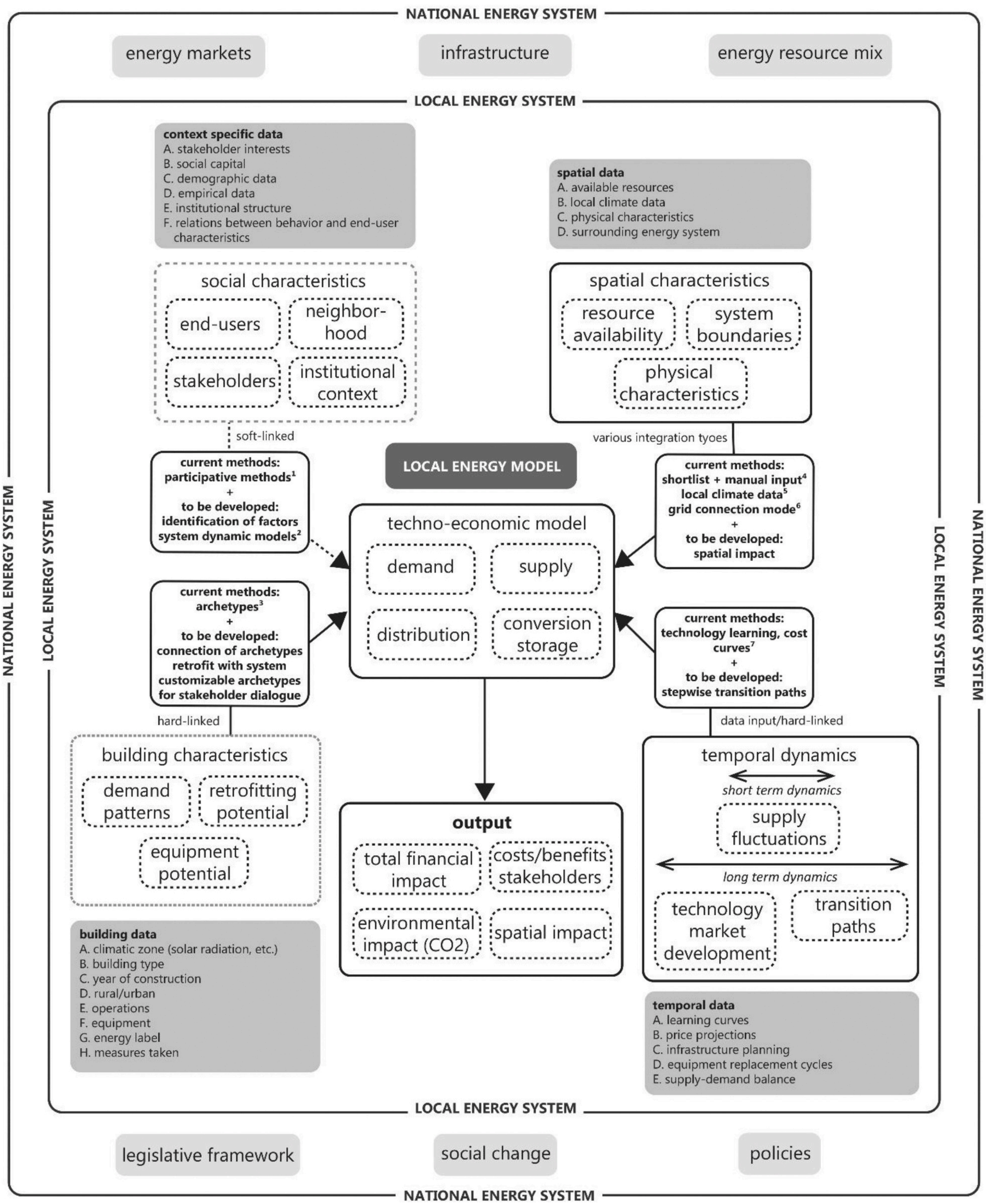
Statistical data however, is often only available at an aggregated level on a yearly basis for larger shares of the building stock. The inclusion of building characteristics allows a more accurate generation of demand patterns based on disaggregated data. This is needed for the analysis of energy systems with high shares of fluctuating renewables. It also allows the consideration of energy saving measures, which is only possible at building scale [93]. The evaluation at building scale at the same time supports decision-making for different stakeholders (decision-makers, buildings owners, citizens and other stakeholders) by showing differences between building types, related strategies and associated costs and benefits [94]. Building characteristics are now often excluded from general energy models and demand data are aggregated for the buildings sector instead.

Including all individual buildings in the model is too extensive for analysis on district or neighbourhood scale. The method therefore requires simplification of the building stock. The use of archetypes or reference buildings as representatives of the building stock is a common simplification methodology for energy savings analysis [95]. The method is not standard procedure in typical renewable energy modelling. From the reviewed models, only RETScreen and KomMod use building typologies. In RETScreen the archetypes provide a reference for the analysis of a single building or cluster of buildings and allow the application of various retrofit measures, whereas KomMod is able to construct several clusters of a building type but only allows a retrofit rate per building type. Archetypes should represent the heterogeneity of the building stock, by choosing the right level of spatial resolution, in which the building, the neighbourhood and the broader context are sufficiently represented. Hence, the definition of archetypes is a compromise between feasibility and building stock representativeness [93].

Common parameters for categorization of the building stock are climatic zone, construction period and building type [96]. In addition, the difference between rural and urban context has been applied by Refs. [95,97]. To identify appropriate retrofitting opportunities, current installations should also be included. Only some authors [93,98] mention the inclusion of 'operations' and 'systems (equipment)' as additional parameters. Data gathering may become an issue for some of those parameters as privacy sensitive information on socio-economic and physical characteristics is required. In general, data availability and data uncertainty easily become an issue in complex systems modelling at municipal scale, as reported by Refs. [7,11]. Monteiro et al. [99] conclude that data on operation and systems, which are related to the occupants' behaviour and preference settings, is especially incomplete at buildings level. The use of archetypes can help fill the data gap. Once the archetypes are properly defined with complete information for a set of parameters, it becomes possible to include detailed data in the scenario analysis for a large number of buildings without having to go through a time-consuming data gathering process each time [96]. Further development of building archetypes should involve the relation of retrofit levels with building equipment and the local energy system. By choosing a higher retrofit level, it becomes for instance possible to lower the temperature of a district heating system.

6.1.2. Social context factors

Existing techno-economic models are insufficiently capable of incorporating (heterogenous) stakeholder behaviour and other social aspects [15,100]. In the reviewed models and methodologies, it often even remains unclear what exactly is meant by the term 'social'. Although the inclusion of context specific, non-technical data is



[1] Examples participatory modelling approaches are provided by Kowalski et al (2009), Heaslip & Fahy (2018) en Eker et al (2018); [2] Examples of systems dynamic models that include social context are given by Xavier et al (2013), Eker et al (2018); [3] RETScreen is an established model that uses building archetypes; [4] Some models include resource potential as a manual input, examples inlude Gebiedsmodel. Resource potential is not commonly included in larger, established models; [5] Established models often include a dataset or manual entry with local climate data. Examples include: RETScreen and H2RES. [6] Some models represent the isolated system in connection with the larger energy system. Examples include EnergyPLAN with the MultiNode add-on tool. Other models include only import and export options from/to the central grid, such as DER-CAM, H2RES and ETM. [7] Established macro models generally include technology learning and price developments (i.e. MARKAL). Some other models also include some temporal dynamics (i.e. CEGOIA). Other models make price developments etc. optional.

Fig. 4. Analytical framework for integrated local renewable energy system models.

considered to be important for scenario analysis, we observe a lack of understanding of which social factors should be included to adequately represent the social context, and how they should be mapped and measured accordingly. Multi-criteria optimization (see Refs. [79–82]) is one of the few methods that is specific about what social factors are included as criteria and provides a method to weigh non-technical factors such as social acceptance in the quantitative analysis in a transparent and consistent way. The reliability of the outcome of the scenario exercise however depends on expert opinion as the values are not (necessarily) determined by context specific data. Participatory approaches (see Refs. [87,88]) do use context and place specific data, but are still relying on stakeholder judgement. The method is therefore better connected to the area of study, but is lacking validity and reproducibility [58]. Thus, a methodology must be found in which the use of context specific, real world data through social scientific methods is incorporated in the modelling process while balancing feasibility and practicality on the one hand and objectivity, consistency and robustness on the other.

To develop better methods for including the social context, the relevant social context factors should be better understood. System dynamic models (see Refs. [74–76,78]) can help understand which social factors are of influence on the planning and realization of future energy systems. It allows a broader analysis of the system: Eker [74] for instance found in their study on energy efficient housing that improving communal spaces had positive effects on both energy efficiency adoption and wellbeing. In a system dynamic model, the energy system is represented as a complex system that consists of a range of actors and technologies that interact through physical and social networks [100]. These interactions can be studied in order to understand the behaviour of a system itself, the relations with its environment and the evolvement of the system over time [100]. Elements that could be considered to better represent social dynamics in the energy system include stakeholder values and behaviour, demographic characteristics, social capital, institutional structures and the interactions between them.

However, complexity science is not well understood by practitioners in the energy domain [100]. In other fields, neighbourhoods have been considered as interlinked systems in which there is a relation between social and physical characteristics. Statistical studies in the field of health care for instance have shown relations between social capital and mental and physical health (e.g. Refs. [101,102]). In ecology, relations between urban forestry and demographic characteristics such as type of housing, homeownership and income have been studied by Steenberg [103]. By knowing the effect of social drivers, practitioners can predict outcomes and strategize policies and decision-making [103]. The same could be applied in the domain of energy to better support decision-making.

To get a better idea of which social factors we could consider to represent the social context, we looked at which factors are considered as relevant social characteristics in three different fields: the energy domain, sociology and behavioural psychology. The identified social factors are summarised in Table 6. From the field of energy, we found that energy research makes little use of available knowledge on relations between social characteristics and energy behaviour. As Kalkbrenner & Roosen [104] mentions, the issue in the energy domain is merely the lacking of quantitative research on the participation of citizens where 'little is known about citizens' attitudes toward local energy and their willingness to engage in community-based renewable energy projects'. It is relevant to include this type of knowledge because insight in the attitudes, beliefs and intentions that lead to certain behaviours can be helpful in predicting behaviour [105]. Previous research has provided insights in behavioural aspects such as social acceptance of distributed energy systems on neighbourhood scale [106], socio-economic factors of technology adoption [107], key determinants of climate adaptive behaviour [108], determinants of energy investment behaviour [109], amongst others, and can be used to enrich the energy modelling parameters. General insights can be refined by context-specific data

Table 6
Summary of social factors where a relation was found with sustainable behaviour.

Construct	Source
Income	[104,107,113,116]
Homeownership	[103]
Household age and composition	[107]
Attitude/environmental concern	[104,105,117]
Environmental knowledge	[108,117]
Locus of control/outcome efficacy	[108,117]
Perceived behavioural control/self-efficacy	[105,108]
Subjective norm	[104,105,108]
Intention	[105]
Responsibility	[108,117]
Trust	[104,112,113]
Memberships in associations/organizations	[112–114,118]
Social network/friend-kin-ties	[112,113,118]
Reciprocated exchange	[112,113,118]
Place (neighbourhood) attachment	[108,112,113,116]
Social-physical infrastructure	[74,118]
Community identity	[104]
Stakeholder network	[100]
Institutional structures/Institutional trust	[108]

through the use of surveys as integrated part of the modelling procedure as shown by Refs. [88,110,111]. Heaslip and Fahy [88] for instance, build scenarios based on qualitative data gathered through interviews, surveys and focus groups.

From the field of sociology, research is being done on neighbourhoods and social cohesion. It gives some tangible indications on which social factors are worthwhile to consider and contains various studies where those factors are quantified and their interlinkages mapped. The main area of attention is the quality of neighbourhoods and how poor neighbourhoods can be improved by stronger social ties. The starting point in this area of literature is the idea that strong social interactions between people leads to less social problems, a better chance of collective action towards solving problems and potentially more wealth and well-being [112,113]. Social cohesion is presented as the most prominent aspect of the quality of neighbourhoods, although there are different views among scholars on which subcategories it consists and how it can be measured. Neighbourhood attachment, social network, membership in organizations, reciprocated exchange and trust seem to be the most common aspects of cohesion, which is confirmed by several studies, some of them referring to social capital rather than social cohesion [104,113–116].

The field of behavioural psychology gives more insight in the individual factors that lead to behavioural change. The theory of planned behaviour is based on four constructs: attitude, subjective norm, perceived behavioural control and intention [105]. There is also literature available that used similar constructs, but then applied to environmental issues. In Fielding et al. [117] for instance, these constructs are applied in a study on environmental behaviour among young Australians. They used the constructs: environmental knowledge and concern, responsibility and locus of control, and attitudes (pro--environmental intentions and behaviour). We see some aspects here that are specifically relevant for environmental issues compared to general behaviour. Table 1 presents an overview of social factors are worth considering in future community energy research based on the aforementioned literature.

In conclusion, methods for adequately representing the social context have not yet been demonstrated and for developing better methods it is necessary to 1) create more insight into the factors that influence the implementation success of local transitions, 2) define these social context factors by empirical research and 3) develop methods to measure those factors to be able to use them in energy models. Qualitative data gathering methods such as surveys and focus groups are expected to play an important role.

6.1.3. Temporal dynamics

In the review we found that both a high temporal resolution is needed for local scale, integrated models as well as long-time ranges and that only a vast minority of models deals with both time scales. A high temporal resolution is needed to model high shares of fluctuating renewables in the system. On a local scale, a high temporal resolution is required to detect surpluses and shortfalls that occur locally in the system. Operated with small time intervals, the model allows the analysis of storages in the system versus the import and export of energy to the wider energy system to solve imbalances. Especially models with a strong focus on off-grid operations are strong in this type of analysis, including HOMER and H2RES.

To be able to study the transformation of the buildings sector, we also need to consider large time-frames, as socio-technical transitions typically unfold over long time periods as a result of processes of technology diffusion and social change [100]. Demand for instance may change over time as a result of improvements in building performance and changes in lifestyle. These possible changes represent significant uncertainties that should be dealt with adequately in the modelling. Therefore, we agree with Li et al. [15] that the time horizon of the modelling study should be sufficiently long enough to capture the dynamics associated with the socio-technical transitions in the (local) energy system.

However, a long-time horizon in itself it is not enough of a criterium. The transition paths and the dynamics of the elements at hand within the time horizon should be included as well to be able to develop successful energy planning strategies. According to the Multi-level perspective theory on socio-technical transitions, systems don't radically change from one state to another, but change is rather incremental as the current system is characterized by lock-in and path-dependence [119]. Based on historic energy transitions it can be concluded that most energy transitions have been, and will likely continue to be, path dependent rather than revolutionary [120]. Path-dependence results in change only taking place when it is aligned with changes in other parts of the systems simultaneously.

In current models, the development of costs and performance of energy technologies is generally incorporated through learning curves and cost projections. In particular macro models such as MARKAL are strong examples. However, typical transition elements, related to the acceptance of technologies and the social change associated with technology innovation, are not well represented. Existing models do not sufficiently take into account that energy systems change structurally over time, e.g. with changing populations, lifestyles, technologies and costs [100].

Considering the gradual change of the system, we need to incorporate in the models what is realistic in what timeframe and which changes can take place in which order. Decision-making behaviour is strongly related to changes in the system. Along the way, decision-making changes as a result of the implementation of new policies and regulation, introduction of new technologies, community development, etc. Some of these changes are uncertain and unpredictable, but others are known or can be predicted. Those events can be incorporated in the planning strategy. Natural replacement of installations and equipment for instance, could be an important driver for technology adoption by end-users. The same is true for infrastructure replacement, which is associated with longer time periods and therefore is a driver for lock-in. When not sufficiently taken into account in the planning strategy, existing lock-ins could be maintained and new ones could be created which may lead to inefficient system design (for instance when a district heating system is designed for high temperature while insulation levels are expected to be increased at a later period of time).

In conclusion, the challenge of temporal dynamics in modelling local energy systems lies in the large variation in time scales that should be analysed, from very small to very large time horizons. Especially the construction of realistic transition paths over time are of particular concern for further model development.

6.1.4. Spatial characteristics

Spatial characteristics determine the potential of various measures and – if mapped with sufficient detail - indicate how to make optimal use of the physical characteristics of a certain site. Based on the physical characteristics, trade-offs need to be made between which measures are possible and desirable to realize locally, and where connection with the wider energy system is needed. The reviewed models from the professional practice are generally better at including location specific (spatial) data whereas established models are rather limited in the inclusion of spatial characteristics. We found little examples of models that include resource constraints to determine energy potential. Concerning the inclusion of system boundaries, we found that most models represent the local system in relation to the wider energy system to some extent. Based on these results we will now further explore three key components of spatial characteristics: 1) resource potential, 2) physical characteristics and 3) system boundaries i.e. the integration of the local system with the wider energy system.

Resource planning becomes especially relevant for local energy modelling, as resource constraints primarily become visible at a local scale. Energy sources can vary dramatically from one place to another [3], and therefore the specific local circumstances concerning resource constraints need to be taken into account. Adequately integrated, models can give a more exact estimation of the role that might be played by energy technologies in the future energy system [121]. This eventually leads to more realistic pathways. Most of the reviewed models include local climate data for determining resource potential. Some models have a more elaborated way of including resource constraints: RETScreen holds links to worldwide resource maps and H2RES requires resource potential categories (high-medium-low) as input value. Some of the reviewed models from the professional practice include some level of resource constraints, thereby linking the model with information holding GIS maps. Thus, modelers can make use of national explorations of resource availability, complemented by local data gathering.

Physical characteristics of a neighbourhood, such as the historical character of buildings, shape and orientation of roofs and the available space in and around buildings, should be mapped to determine how to make optimal use of a site's characteristics. Subsequently, it is important that a local model shows what the spatial impact of measures is. This will be an important input for the dialogue with stakeholders, whose living environment will be affected by measures such as infrastructure expansion, heat buffers, energy retrofitting of buildings, etc.

System boundaries refer to the integration between the renewable system to be developed and the wider, conventional system, which merely takes places at the connection between both systems (see also [13]). In many systems, part of required energy will be generated outside the geographical boundaries and system balance will be maintained using the wider energy system. Renewable energy systems with high shares of intermittent renewables are subject to imbalances between supply and demand that can be dealt with by storage or by exchange with the wider energy system. This affects the share of renewables and carbon reduction that is realized within the system, as well as the spatial impact on the local scale. System boundaries and the relation with the larger system is therefore an important theme in local renewable energy planning. Most established energy models include import and export of energy flows over the system boundaries. EnergyPLAN has an add-on tool (MultiNode) specifically for this purpose, and therefore supports a more advanced analysis than most other models. The integration between local systems and the surrounding national energy system is further studied by Refs. [35,122].

6.2. Towards an integrated, socio-technical modelling approach

Next to a further development of the aforementioned building blocks (sections 6.1.1-6.1.4), the research agenda for a modelling procedure for local models should include the role of the model in the planning process. To be able to cover all necessary aspects, a modelling procedure should be considered as an integrated part of the planning process. This involves a broader conception of the modelling procedure than current approaches centred around techno-economic modelling. In order to cover the 'very large dimensions related to sustainable planning', there is a need to combine different methods and tools [123]. The spectrum of methods and tools may consist of 'high-level qualitative frameworks for analysing systems change in combination with more quantitative detailed models' as proposed by Bale, Varga & Foxon [100]. In line with the trends described in the literature, an integrated approach is modular in nature and consists of different modelling elements that are interlinked. Connolly et al. [14] underline the need for a modular package of models and state that 'a flexible toolbox is believed to be the most suited methodology for adjustments to local circumstances'.

This understanding of the role of the model in the planning process does not correspond with current practices. The technical modelling, decision-making process and finally communication and social acceptance building, are now separated phases in the planning process with little connection between them. Decision-making will be strengthened when stakeholders are better involved in the planning process. Also for having the necessary practical relevance and effectiveness, the involvement of all relevant stakeholders in the planning process will be important [4]. According to Neves et al. [124], local actors should be involved in the planning process to ensure transparency and legitimacy of the process and better chances of actual implementation. The planning process should therefore offer opportunities of engaging stakeholders by establishing a shared framework between them [123]. This involves bringing together both experts and non-experts from different fields. The approach is therefore transdisciplinary in nature.

Section 6.1.2 has provided an overview of relevant social factors that can be used to map the social context, which interact and are meant to be embedded in different stages of an approach. To be able to engage stakeholders, and in particular the inhabitants, the first step of such an approach is to understand the social characteristics of the neighbourhood. As it is important for collective action to involve everyone, the social factors can best be mapped quantitatively in a survey so that a representative view of the neighbourhood can be obtained. The outcomes of such a survey provide a first direction of model scenarios, by giving insight in three important areas: 1) the potential for a collective solution (such as district heating) based on the level of social cohesion, 2) the likeliness for individual action based on individual factors and 3) specific barriers towards energy transition such as underlying (social) problems. At the same time, the outcomes provide insight in the different social groups that can provide essential insight for participative activities.

The second step of the approach is to gain insight in the technical preferences of inhabitants which will provide a starting point for scenario selection. Uninformed opinions can be unstable and people tend to change their views and behaviour after new information is provided [125,126]. To get a good sense of technical preferences, it is necessary to present essential information at the beginning of the process before measuring attitudes. This can for instance been done with an Information-Choice Questionnaire (ICQ). Results from such a study can be linked with a model and feed the scenario selection process by comparing the different scenario outcomes with sensitivities presented in the ICQ outcomes. This comparison is possible by investigating the same key performance indicators (KPI's) in the ICQ as are provided by the model.

The third step involves the understanding of the broader context of the neighbourhood by expanding the analysis to the involved stakeholders and institutional structures relevant to the project. The type of stakeholders that are involved and the role they take on influence the dynamic between inhabitants and their attitudes and behaviour towards the project, and therefore it is important to map this context. Stakeholder analysis and social network analysis could be helpful in this step.

The final step of the approach is stakeholder dialogue based on model scenarios. Local energy models have an important function in stimulating the dialogue between stakeholders by making consequences of different system choices visible. Insights from practice show that local scale models primarily function as a tool that supports stakeholder dialogue and development of a shared vision, which also explains their nature as simulation rather than optimization models. In a later stage of the planning process, models should support informed decision-making based on a more detailed analysis as well. The output of the model should therefore provide the information that is needed to support the stakeholders in their decision-making process, which means that adequate KPI's should be chosen. This includes at least an overview of the costs and benefits per stakeholder group, a financial and environmental evaluation of the system as well as more social consequences of system choices such as inconveniences during construction, noise pollution and spatial impact. Further research is needed to identify the required output of the model for the participative process involving stakeholders. This process is preferably iterative in nature, similar to SAS approaches: the model provides input whereas participants give scenario input until consensus is reached. Planning workshops can be organized to that end based on insights in how such a session could be set up from the fields design research, action research and similar (see e.g. Refs. [127–130]).

7. Concluding remarks

There is a need for developing simple, but effective energy planning tools that support municipalities and other local stakeholders in their growing responsibilities to implement ambitious national renewable energy policies in the built environment. Local energy planning requires suitable models that have characteristics that are specific for the local scale and have a strong relation to the use in the professional practice, where decision-making takes place in a multi-stakeholder, interdisciplinary setting.

Based on a review of state-of-the-art energy models and methodologies, we identified the main gaps in current modelling approaches. The biggest gaps were found in the representation of end-users, equal and detailed representation of the heat and electricity sector and retrofitting potential of the building stock. Further modelling developments should focus on more detailed modelling of building characteristics, focussed on energy retrofitting potential, and on renewable heating technologies, which are key challenges for the energy transition in the built environment.

An important limitation in current practices is the lack of an integrated systems approach, bringing together techno-economic and social aspects with sufficient level of detail. The local system should be considered in relation to the social context and the context of the wider energy system. To be able to model a diverse socio-technical context, a combination of interconnected methods is needed. This model collaboration will support the energy planning process as a whole. A more holistic conception of a planning model, consisting of model calculations in combination with empirical and participatory methods, better supports the decision-making process with stakeholders.

To develop this modelling framework, special attention should be paid to the inclusion of stakeholder behaviour and other social context factors, in which more insight is needed for developing better integration methods. This paper has sketched an outline of an integrated modelling framework, and has shown which combination of tools could be used and in what way they can be connected. Additionally, more insight is needed in the nature and granularity of the output that the model should generate to effectively support the participative process with stakeholders. To better understand the decision-making process in a multi-stakeholder context, the interactions between actors and the system should be identified and described, as well as the integration of those interactions within energy models and planning processes.

Declaration of competing interest

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

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