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A review of multi-energy system planning and optimization tools for sustainable urban development

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***Abstract*—Implementing renewable energy resources to enable sustainable development of cities, requires a more flexible and resilient energy system than currently present. Integrating multiple energy carriers and services allow more efficient implementation of these renewables. Although most research efforts so far have focused on the electricity grid, multi-energy systems attract ever more attention. Over the last decades, a wide variety of energy tools has been developed; potentially providing a solid basis to build upon. This paper reviewed those tools specifically able to model multi-energy systems and applicable to a city scale. 13 (of 72 total) are able to and were further analyzed. Challenging is to incorporate short- and long-term dynamics of an energy system. Although some tools combine planning and operational methods, none are able to model solutions that are practically feasible from a grid perspective. Future research aims to integrate the tools reviewed here with power system simulation models.**

***Index Terms*—energy modeling, multi-energy systems, smart cities, sustainable development**

I. INTRODUCTION

As of July 2007 more than half of the world's population lives in urban areas [1]. In developed countries, already more than 70% (Europe) and 80% (North-America) of the population is counted as urban dweller. This continuous urbanization means the sustainability challenges the world is facing are increasingly concentrated in cities. Currently, cities already use about 75% of all resources and emit around 70% of all greenhouse gases [2]. Simultaneously, they will experience the most impact of climate change. As the World Bank states [3]: "*Food distribution, energy provision, water supply, waste removal, information technology and susceptibility to pandemics are all the Achilles heels of cities.*" Therefore, the urgency and the incentive for cities to work on sustainable development are high.

One of the main sustainable development issues for a city is securing a clean, reliable and affordable energy supply. Integrating electricity generated from renewables into the energy mix using Smart Grid concepts is one option. However, the energy demands of a city are only partially fulfilled through electricity: in Europe in 2010 about a third of final energy use was electricity [4]. Hence, expanding the concept of a Smart Grid beyond electricity is gaining interest; especially when discussing sustainable urban development (or in popular terms: Smart Cities). This expanded concept is called a multi-energy system (MES) or smart energy system (SES) [5]; to emphasize the multi-carrier aspect, the former term will be used. Besides electricity, a MES takes into account all relevant energy carriers (e.g. natural gas, diesel, hot water) and services (e.g. heating, cooling, transportation). Consequently, it creates more degrees of freedom when optimizing energy solutions. As such, it could increase the efficiency of the entire system. As stated in [6]: "*MES can feature better technical, economic and environmental performance relative to "classical" independent or separate energy systems and at both the operational and the planning stage, and this is now being recognized by a wealth of research being performed on related topics*." For example, an energy system with a high wind power penetration leading to volatile prices could be balanced by Combined Heat and Power installations (CHP). Or, the peak wind production could be shaved by using it to charge an electric vehicle, to produce hydrogen through a fuel cell or to heat buildings with storage capacities (intrinsic due to thermal inertia or extrinsic using Phase Change Materials).

In short, viewing the energy problem at a city and multi-energy perspective is befitting and creates increased degrees of freedom, allowing for increased efficiency improvements in planning and operation towards sustainable urban energy systems. However, it also significantly increases the complexity of the system, making it difficult to model. Over the last decades, a multitude of energy tools has been created; potentially providing a solid basis for MES modeling. Current methodologies that reviewed the use of these tools in energy system planning and operation, do not explicitly regard a MES approach at a city scale [6],[7],[8] and [9]. This paper aims to fill that gap by further analyzing these tools and providing a review of those specifically able to model MES and applicable to a city scale. The paper begins by further defining terminology and outlining corresponding challenges. Section III describes the review methodology. Then, each tool will be reviewed and the results are shortly described in IV and displayed using Table I and II. Finally some conclusions are drawn and future research is described. Research gaps are identified as well as opportunities for ways to fill those gaps by integrating the modeling methods reviewed.

I. TERMINOLOGY AND CHALLENGES

Different interpretations of the terms *sustainable urban development* and *MES* are conceivable. How these terms are interpreted in this paper, is clarified in this paragraph. In addition, some challenges with regard to these definitions are outlined.

A. Sustainable urban development

The above-mentioned term technically consists of two parts: *sustainable development* and *urban.* The first has many definitions of which the most generic is employed: *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs*"[11]. In addition, the Triple Bottom Line [12] is taken into account, which defines a measure of sustainability that includes financial, social and environmental performance measures. A challenge here lies in the multiple ways to quantify these three performance measures; while one stakeholder might prioritize societal impact, another might prioritize CO_2 emissions.

Another challenge is determining the scale of a city; to decide on what falls within the urban context. The larger the scale, the more degrees of freedom, but also the higher modeling complexity. On the other hand, if the boundaries are too limited, some energy solutions might not be considered, potentially leading to inefficiencies. For the purpose of this study, the authors decided to adhere to the 'geographic-plus' definition [10]. This definition includes everything within the administrative boundaries of a city including easily traceable upstream flows: an electricity generating plant on the outskirts of a city is included, imported electricity is not. However, electricity imports might be relevant when modeling a MES city from its current situation to a certain future. In that respect, exceptions are applied when relevant for modeling objectives.

Although it creates increased complexity, the scale of a city could allow for economic application of more technologies and systems. An important issue to overcome when moving to a renewables economy is energy balancing. One solution is demand side management, which changes demand profiles to fit supply profiles more closely. But it also helps if the demand profiles are complementary to begin with. For example, a set of households does not nearly provide as much variety as an entire city, which includes industrial and commercial demand profiles. This could also reduce required storage capacity.

The entire term 'sustainable urban development' corresponds to a more popular one used in the last few years: Smart Cities. As [13] states: "*A smart city (…) is a healthy, energy-efficient city that uses renewable energy sources as much as possible and is a pioneer in the deployment of advanced smart technologies";* a definition fitting this research.

B. Multi-energy system (MES)

A single definition of a MES has not yet been made, which provides a challenge altogether in finding common terminology, system boundaries, etc. Technically, moving beyond electricity means just that: including other energy sectors. The most comprehensive description uses four perspectives [6]: spatial, multi-service, multi-resource (i.e. 'fuel') and network perspective. In this research, the first perspective is specifically focused on cities. As such, the subsequent three perspectives depend on the modeled city. In general, this means as many energy services (e.g. lighting, heating, cooling, transportation, etc.) and as many energy resources (e.g. natural gas, oil, coal, solar, wind, biomass, etc.) as logical. Consequently, corresponding networks are taken into account. The network perspective is mentioned separately to emphasize the importance of energy networks to facilitate multi-energy solutions and truly minimize system cost while maximizing environmental performance [14].

II. METHODOLOGY

Using the review papers mentioned in Section I [5-8] and an extensive collection at [15], all candidate energy tools were established. This included a total of 72 tools; a handful of which were not or no longer available like *deeco*, EADER and EMINENT. These tools were first filtered on their applicability to the problem of sustainable urban development, which reduced the number of applicable tools to thirteen. Those were analysed along the characteristics described in paragraphs B and C, using the latest available on-line and scientific publications about their methods and models.

A. Selection filters

To begin with, the tools were filtered on their applicability to a city scale. Although that sounds evident, tools applying a slightly larger or smaller scale might also be useful for a city. For example, modeling a national energy system could be used to test whether the city abides by national limitations; results of modeling a smaller scale could be used to aggregate into the actual scale of a city. In other words, the scale of an international model is too large and a single-plant model is too small (unless its interaction with a region is modeled, as in COMPOSE [25]).

Secondly, the tools were tested on their ability to handle MES. The most important requirement to determine this was the multi-service perspective. Spatial coverage was already determined; multiple resources occurred in all tools and filtering with a network perspective turned out to be too restrictive.

Finally, to tackle the complexity of modeling a multi-energy city, it is very important to build upon existing work and to provide a building block for future research. Hence, the tools were filtered further on their availability and ability to incorporate new aspects. They qualified if they were either freely available, had a free academic license or if they were open source.

After these filters, thirteen tools were left. These are all analysed as explained in the remainder of this section.

B. Modeling approaches

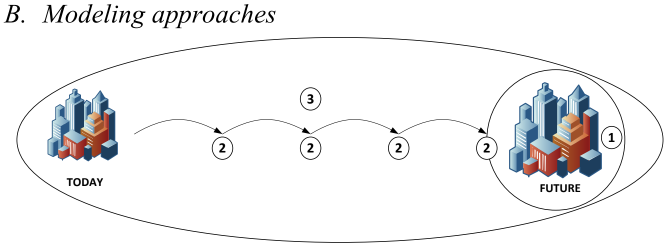

Figure 1. Schematic of MES modeling approaches: (1) Scenario, (2) Operational, (3) Planning

Applying a MES to enable cities to instigate sustainable development can be subdivided into three phases and corresponding modeling approaches (as depicted in Figure 1). First, a model can be used to determine a (range of) future scenario(s). Then, some models calculate the operational feasibility of such scenarios; potentially providing feedback to adjust the scenarios. Afterwards, one can simulate how to arrive at this desired scenario using a planning model. Again, a feedback loop could be applied using operational models to check whether each planning step creates a feasible system.

Note that some tools clearly apply one modeling phase, but there are also tools or so-called aggregation concepts that can be used in more or even all phases. One example specific to MES is the energy hub model [16]. This modeling approach starts with future greenfield scenarios in mind. Next, the aggregation concept is used for planning as well as operational optimization [17].

1) Scenario models

Most research in smart grids and other forms of sustainable development starts with a desired future situation. Often this situation is defined by several goals, usually measured with regards to a base year:

- A reduction of greenhouse gas emissions;
- A percentage of renewable energy consumption;
- An increase in energy efficiency[1].

Other goals might be more qualitative like having a secure energy supply or ensuring high standards of living; both of which might also be quantified. Translating these goals to a certain high-level (technical) scenario – how much and which type of demand/supply/storage is required – is exactly what scenario modeling implies.

2) Operational models

After defining the scenario, it is important to determine whether this scenario is operationally sound. Often this is closely coupled (or simply incorporated with) the scenario models. While the full energy balance of one year might be met, and while the cost estimations might fit, it cannot be said if this is the case for every moment in time when it comes to meeting all economic, social, regulatory and especially technical constraints (e.g. storage and load flexibility). Usually a full year is simulated with small enough time steps to account for all different seasons and corresponding demand and supply profiles (e.g. 15 minutes), which is especially relevant when integrating intermittent renewables. Operational models can be used to fully optimize the future scenario or to check the feasibility of each planning step towards this future.

3) (Long-term) Planning models

Once a future scenario has been fully tested, the next question is how to get there. In planning models, one accounts for long-term evolution of many of parameters like fossil fuel availability, technology prices and even renewable resources [19]. The time steps used in planning models are larger, since the time horizon is also much larger; usually one to five years to model 30-50 years into the future.

C. General and technical characteristics

Besides the general filters and the modeling approaches, there are several other relevant general and more technical characteristics. These are described below and the results are displayed in Table I.

1) Scale – the main focus is the city scale, but national and community/island scales could also be useful;

2) Availability & room for innovation –technologies currently at lab-stage might become serious innovations in coming years (e.g. biobased energy applications). As such, it is good to know whether the tool allows room for innovations, i.e. is it open source? Simultaneously, in order to make it useful for all academia and to ensure future work is in fact possible: is it freely available?

3) Modeling approach – can the tools determine scenarios, optimize their operation and plan towards them?

4) Objective – what is the optimization objective, if any?

5) Time steps & scales – when checking the operational feasibility of future scenarios, small time steps (15 mins. – 1 hour) to model a full year could account for all constraints. In contrast, planning models use larger time steps of 1-5 years and larger time horizons (up to 50 years) to model from today towards a certain future.

6) Evaluation criteria – the goal of this research is to facilitate sustainable urban development. Whether a certain solution is in fact sustainable, depends on a balance between *people, planet* and *profit*. Hence, it is important to account for these type of criteria; either by applying constraints as model input or by showing them in the results, as model output.

a) Social – social criteria could refer to a wide range of things. For example, legislation or regulations as input and health effects as output (note that local air pollution is environmental, but also has health effects).

b) Environmental – inputs could take the shape of emission constraints to embody environmental ambitions; outputs could show the final environmental impact.

c) Economical - similarly, there might be economic ambitions or constraints; knowing whether a model can incorporate economic inputs and outputs is relevant.

7) User friendliness – how easily can the tool be handled; what Graphical User Interface (GUI) is used, if any?

8) Training requirements – how much training time is needed to be able to use the tool as intended?

D. Energy characteristics

The tools need to be both realistic and as generic as possible; to ensure they resemble a city as close as possible and to be applicable to many different cities. As such, besides the initial MES filters and the other general and technical characteristics there are quite a number of additional characteristics related to the modeled energy system on which the tools were tested. The results can be found in Table II.

1) Energy resources– one of the main characteristics of a MES is that it incorporates multiple resources. This characteristic defines which ones are incorporated in the tools.

2) Energy services – corresponding to the multi-service perspective it is important to determine which services are modeled. Only electricity and heat? Or does the tooll include cooling, transport or even chemical energy [20]?

3) Demand sector – multiple services can be delivered to multiple sectors, each with different demand profiles and

[1] These examples correspond to the current energy goals the EU set for its Member States, for 2020, known as the “20-20-20-targets”[18].

attributes. Special attention is given to the inclusion of electric transportation, given their usage profiles and storage potential;

4) *Thermal generation* – which forms of thermal electricity and/or heat generation are incorporated?

5) *Renewable generation* – which forms of renewable electricity and/or heat generation are incorporated?

6) *Conversion and storage* – which forms of energy conversion and storage are considered?

7) *Energy costs* – which relevant costs are incorporated? Is there a static of a dynamic fuel price? If new technologies are implemented, besides the capital investment, are there variable Operation & Maintenance (O&M) costs?

8) *Greenfield or brownfield* – some tools are used to model new cities, starting from a greenfield. Existing cities are considered in this paper, hence the brownfield situation is more relevant; although a greenfield might provide relevant insights or inspiration for future possibilities.

III. RESULTS

Using the abovementioned characteristics, all thirteen tools were analysed to determine their applicability to a city sized MES. Those results can be found in Tables I and II. A short description of each tool is provided below.

Balmorel [21]

The original Balmorel project was funded by the Danish Energy Research Program and several other research institutes. The tool has been developed, maintained and distributed under open source ideals since 2000. Balmorel is a very detailed and advanced modeling tool [22]. Given its open source character, a lot of upgrades have been made over the years, for example to incorporate hydrogen as energy carrier [23],[24].

COMPOSE [25]

COMPOSE (Compare Options for Sustainable Energy) is the most recent tool of this selection: it was created in 2008 at the Aalborg University (Denmark) [26]. It is very flexible and has been used to calculate the intermittency friendliness of an energy system [27] and so-called quad-generation [28]. Worth noting is that COMPOSE can import of projects from energyPRO (commercial tool modeling co/trigeneration plants), export and import hourly distributions to and from EnergyPLAN and import climate data for localization of distributions from RETScreen.

DER-CAM [29]

The Distributed Energy Resources Customer Adoption Model (DER-CAM) has been under development at the Lawrence Berkeley National Laboratory (USA) since 2000 [30]. Currently, there are two versions: Investment & Planning and Operations. Both are continuously expanded, for example to incorporate zero-net-energy-buildings and uncertainty in electric vehicle driving schedules [31], [32].

EnergyPLAN [33]

EnergyPLAN has been developed and expanded since 1999 at the Aalborg University (Denmark). It is one of the most versatile tools in this selection, incorporating nearly all relevant parameters for operational and planning analyses. It even includes electricity grid stabilization measures, but these are all at a one-hour time step, which is too large to fully account for power balance and network constraints. Sources: [34], [35], [36]

ENPEP-BALANCE [37]

ENPEP-BALANCE is part of the ENPEP (Energy and Power Evaluation Program) family of models; developed at the Argonne National Laboratory (USA) in 1990. Many countries have used it to create initial greenhouse gas mitigation assessments for their interaction with the UNFCCC [38], [39].

TABLE I. SMART CITY MODELING – GENERAL & TECHNICAL CHARACTERISTICS

Energy tool	Scale	Availability/ innovation	Modeling approaches[a]	Objective	Time step & scale	Evaluation criteria[b]	User-friendliness	Training requirements
Balmorel	All	Both*	Oper, Plan	Min. cost	1 hour-5 years; 1-50 years	EN-in, EN-out, EC-in, EC-out	Low; GAMS & dedicated GUI	1 week
COMPOSE	SP, Loc	Free (incl CPLEX)	Oper	Min. operational cost	1 hour; unlimited years	EN-out, EC-in, EC-out	High; Excel GUI	3 days
DER-CAM	SP, Loc	Free for academics*; o.s. option	All	Min. cost/CO_2	5&15 min, 1 yr; 1 wk, many yrs	SO-in, EN-in, EN-out, EC-in, EC-out	Medium: dedicated GUI	N/A
EnergyPLAN	Loc, Reg, Nat	Free	Oper, Plan	Optimize economics/technologies	1 hour; 1 year	All	High; dedicated GUI	Few days – month
ENPEP-BALANCE	Loc, Reg, Nat Int	Both	Scen, a bit Plan	Find supply/demand equilibrium	1 year; up to 75 years	SO-out, EN-in, EN-out EC-in, EC-out,	Medium, dedicated GUI	1-2 weeks
eTransport	All	Free for academics	Oper, Plan	Min. cost	1 hour, 1 year; days,1-30 years	EN-in, EN-out, EC-in, EC-out	High; Visio 2007 GUI	N/A
HOMER	Loc, Isl	14-day free trial	A bit Scen, mainly Oper	Min. NPC	1 hour; 1 year	EN-out EC-in, EC-out	High; dedicated GUI	1 day
LEAP	Reg, Nat, Int, Glo	Free for academics	Scen, Plan	Accounting, min. cost	1 year; 20-50 years	SO-out, EN-in, EN-out, EC-in, EC-out	High; dedicated GUI	3-4 days
RETScreen	SP, Loc, Isl	Free	A bit Scen, mainly Plan	Min. cost	1 month, 1 year; many years	optional EN-in, EC-in, EC-out	High; Excel GUI	Several hours
SIVAEL	SP, Loc, Reg, Nat	Free	Oper	Min. variable costs	1 hour; 1 day - 1 year	SO-in, EN-in, EC-in, EC-out	Low; combi. Fortran, SQL	1-2 weeks
STREAM	Nat, Int	Both	Scen, a bit Oper	Manual min. cost/CO_2	5 years; 30 years[#]	EN-in, EN-out, EC-in, EC-out	High; Excel GUI	Several hours
TIMES	Loc, Nat, Reg, Int, Glo	Free source code*, open source	Scen, Plan	Min. cost	1 hour, 1 year; 20-100 years	All	Low; VEDA & ANSWER GUI[##]	Several months
TRNSYS	SP, Loc, Isl	Educational license; open source	Oper	Energy performance/min. cost**	0.01 s – 1 hour; many years	EN-in, EN-out	Medium; dedicated GUI	1 day

*GAMS license required **using GENOPT via TRNOPT module; [#]manually adjustable & duration curve model runs 1 yr with 1 hr time steps;; [##]commercial GUIs: VEDA (support.kanors-emr.org), ANSWER (www.noblesoft.com.au); a. Scen = scenario, Oper = operational, Plan = planning; b. EC-in/out, EN-in/out, SO-in/out = economic, environmental and social input/output;

TABLE II. SMART CITY MODELING – ENERGY CHARACTERISTICS

Energy tool	Energy resources[a]	Energy services[b]	Demand sectors[c]	Thermal generation[d]	Renewable generation[e]	Conversion/storage[f]	Economic parameters[g]	Green/ Brownfield
Balmorel	F, R, N, W	El, Ht, eTr, neTr	Res, Tr, Im, Ex	All	BP, HyP, PV, Wi	PHES, CAES, HS, HP, H2Pr, H2St, CCS	FP, CC, v-O&M, CT, SQ	Brown
COMPOSE	F, R, W	El, Ht, Co, neTr	Im, Ex	All	All	BES, HS, CS, HP	FP, CC, O&M, CT	Both
DER-CAM	F, R, W	El, Ht,Co, eTr, neTr	Res, Com, Oth, Im, Ex	CHP	GeP, BP, PV, ST	BES, HS, FC, AR	FP, CC, O&M, CT	Both
Ener-gyPLAN	F, R, N, W	All	Ind, Tr, Im, Ex	All	All	BES, PHES, HS, HP, H2S, CCS	All	Both
ENPEP-BALANCE	F, R, N, W	All	all	All	all but CSP, Ti, Wa	N/A	v-FP, CT, SQ	Brown
eTransport	F, N, R, W	El, Ht, Co,	'dwellings', Im, Ex	CP, GaP, CHP	BP, PV, Wi, ST	storage module, HS, HyP, HyS, AC/DC, AR, CCS	FP, CC, O&M	Both
HOMER	F, R	El, Ht, Co	Not specified	CHP, 'micro-turbines'	BP, small HyP, PV, Wi, ST	BES, FC, H2P, H2S, AC/DC	v-FP, CC, O&M	Brown
LEAP	F, N, R, W	El, Ht, Co, neTr, Ch	all	All	All	All	All	Brown
RETScreen	F, R, W	El, Ht, Co	Res, Com, Ter, Ind, Oth	GaP, GCC, CHP	All	BES, FC	CC, O&M, CT	Both
SIVAEL	F, R	El, Ht	Im, Ex	CP, GaP, CHP	Wi	PHES, BES, HS, HP	v-O&M, SQ***	TBD
STREAM	F, N, R, W	El, Ht, Co, neTr	All	All	All but Ti	PHES	FP, CC, O&M, CT	Brown
TIMES	F, N, R, W	All	All	All	All	PHES, BES, CAES, HS, HP, HyP, FC, CCS	FP, CC, O&M, CT	Both
TRNSYS	F, R, W	El, Ht, Co	Res, Com, Ind	CP, GaP, CHP	BP, GeP, PV, Wi, ST	BES, HS, CS, HP, AR, FC, H2P*, H2S*	none**	Both

*registered TRNSYS users can add HYDROGEMS; a tool to simulate integrated hydrogen energy systems; **can only model a cost function in GENOPT via TRNOPT module; ***SO_2, NO_x, CO_2 quota; indirectly economic; a. F = fossil, N = nuclear, R = renewables, W = waste, b. El = electricity, DH = district heating, Ht = heating, Co = cooling, eTr = electric transportation, neTr = non-electric transportation, Ch = chemical energy; c. Res = residential, Com = commercial, Ind = industrial, Ter = tertiary (e.g. office buildings), Tr = transportation, Oth = other (e.g. schools, hopsitals, data centers), Im = import, Ex = export; d. CP = Coal-fired power plant, GP = gas-fired power plant, CHP = combined heat and power plant, NP = nuclear power plant; e. BP = biomass power plant, HyP = hydro power plant, ST = solar thermal, PV = photovoltaics, GP = geothermal power plant, Wi = wind power, Wa = wave power, Ti = tidal power; f. PHES = pumped-hydroelectric energy storage, BES = battery energy storage, CAES = compressed air energy storage, HS = heat storage, CS = cold storage, HP = heat pump, AR = absorption refrigerator (or other chiller), H2Pr = hydrogen production, H2St = hydrogen storage, FC = fuel cells, CCS = carbon capture and storage, AC/DC = AC/DC converter; g. v/f-FP = varying or fixed fuel prices (unspecified if without prefix), CC = capital costs, v/f-O&M = variable and/or fixed operational and maintenance costs (unspecified if without prefix), CT = carbon taxes, SQ = subsidies or quotas.

eTransport [37][40]
The development of eTransport has been funded by the Research Council of Norway and 11 Norwegian energy companies since 2001 [41]. Typical of eTransport is that it does not just calculate how much of which resources to use, but also where and when to invest (i.e. taking into account topology and geographic distance of multiple energy infrastructures). In addition, it optimizes diurnal operation as well as the expansion plan of an energy system. eTransport was recently expanded to incorporate biomass supply chains [42].

HOMER [43]
In 1992 the National Renewable Energy Agency (USA) released the first version of HOMER (Hybrid Optimization of Multiple Energy Resources) [44]. A very useful, and relatively unique [9] feature of HOMER is its ability to perform sensitivity analyses on hourly data sets such as the primary electric load or renewable resources. It has been used for many off-grid energy system analyses [45], [46].

LEAP [47]
LEAP (Long-range Energy Alternatives Planning System) was originally created in 1980 for the Beijer Institute's Kenya Fuelwood Project [48]. Since the founding of the Stockholm Environment Institute in 1989, its US Center has further developed and supported LEAP. Using input data from the Intergovernmental Panel on Climate Change, the US Department of Energy and the International Energy Agency, LEAP integrates bottom-up and top-down approaches to track the entire energy supply chain in all sectors of an economy; ranging from city to global scales [49],[50],[51].

RETScreen [52]
The first version of RETScreen was released in 1998 and has been developed ever since by Natural Resources Canada. It can be used to analyze various types of renewable energy and energy-efficient technologies (RETs); always comparing a base versus a proposed case. Since it is Excel-based, it is very intuitive and has been widely adopted [53]; for example to assess building-integrated PV and other residential energy systems [54], [55]

SIVAEL [56]
SIVAEL (SImulating heating ("VArme") and ELectricity)) has been developed since the late 80s by the former Danish electric utility Elsam (currently Energinet.dk) [57] and is still updated today; for example to incorporate wind forecast errors. Energinet.dk used its unit commitment/load dispatching tool for many different studies, including its yearly Environmental Report [58], [59].

STREAM [60]
Development on STREAM (Sustainable Technology Research and Energy Analysis Model) started in 2004 for the "Future Danish Energy System" project, carried out by the Danish Board of Technology [60]. It is a simple, but powerful Excel-based tool; combining three sequential spreadsheets (i.e. duration curve, energy savings and total energy model) to model future energy scenarios [62], [63].

TIMES(/MARKAL) [64]
As of 2008, the TIMES model is the official successor of the MARKAL model; and thus the main focus of this paper. Both tools were developed by the International Energy Agency's Energy Technology Systems Analysis Programme (ETSAP);

MARKAL since 1980 and TIMES since 2000. The tools have been used for a large variety of energy analyses: examples include application of nuclear fusion, renewables and hydrogen [65], [66], [67].

TRNSYS [68]
TRNSYS is the oldest tool of this selection; it has been commercially available since 1975. Currently it is maintained by an international collaboration from the University of Wisconsin (USA), the Centre Scientifique et Technique du Bâtiment (France) and TRANSSOLAR Energietechnik (Germany). As becomes evident from these organizations, TRNSYS contains an extensive selection of building, solar and building integrated solar (BIPV) components and has been widely used to model such systems [69], [70], [71].

IV. Conclusions

In this paper a group of tools was identified which could be used for modeling MES in the scenario building, operational or planning phases that enable sustainable urban development. These tools were further reviewed on general, technical and energy-specific characteristics.

Several challenges arise when modeling MES in a "smart city" context: (1) to find the balance between the necessary level of detail to incorporate critical technical constraints (e.g. power balance of the electricity network, nonlinearity of the model of a gas network [6]) and computability of the model; (2) to incorporate short-term dynamics of renewable resources as well as long-term evolution of fossil fuels, technology prices [72] and even renewable resources and (3) to deal with the lack of heuristics, terminology, and system boundaries for MES.

The analyzed tools vary significantly in level of detail and potential application area; from extensive scenario builders, to detailed operational optimization models to planning-focused models. However, none of them overcome all the above mentioned challenges. Although some tools do combine the optimization of both operational and planning phases; either automatically like eTransport, DER-CAM and Balmorel, or manually like EnergyPLAN; none of them incorporate proper modeling of the power system. Either because too large a time step is used (eTransport, Balmorel and EnergyPLAN), or because the electricity grid is not modeled at all (DER-CAM).

One way to solve this is by combining different tools. In the past, several studies have applied a combination of the tools described [63], [72] and [73]. However, the lowest time step used was one hour in all studies; again too large to properly incorporate short-term dynamics of renewable resources and the electricity grid. Without this, it remains possible to envision scenarios and plan towards them at a high level, but for a city to be able to truly incorporate a scenario into its long-term plans, it is essential to know whether that scenario and the planning steps necessary to reach it are practically feasible from a grid perspective as well.

To truly help cities in making proper decisions towards sustainable future energy scenarios, more extensive tools (or combinations of tools) are required. Future work to complement this review aims to combine the tools surveyed here with accurate power system simulation tools, e.g. [74], [75], [76].

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