Assessment of tools for urban energy planning

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In recent years, studies and policies have encouraged the diffusion of distributed energy supply tech-nologies and large integration of renewable sources. This increases the need for new professionals in energy planning. Several computational tools for energy planning have been developed as described in the technical literature. However, energy planners of urban/district areas engaged in the transition to-wards smart systems related to buildings energy services require well-documented tools to evaluate the combination of available energy sources by proper conversion technologies. With this, after a scientific review, we selected 17 tools targeted on an urban/districts scale that can evaluate several energy ser-vices, sources and/or technologies, and provided with detailed and easily accessible documentation. These tools were classified based on their defined features: analysis type, operation spatial scale, outputs time scale, energy service, and licence. Among them, 6 user-friendly tools were identified (energyPRO, HOMER, iHOGA, EnergyPLAN, SIREN, WebOpt) that can provide hourly energy calculations and can be considered as viable for widespread use. Specifically, the general information, functionalities, structure, graphic user interface, required input data, and outputs were described. Therefore, the energy planners are guided towards choosing the most suitable tool based on their skills, aims, and data availability for a specific application.

Keywords:
Planning of energy systems for building stocks
Smart energy systems
Urban/district energy models
Energy planning tools
User-friendly urban energy planning tools

1. Introduction

To reduce energy and environmental impacts attributed to urban building stocks, research and policies encourage the diffusion of distributed energy supply technologies, large integration of renewable energy sources (RES), improvement of district heating (DH) through RES integration [1] and low-exergy networks [2], installation of storages [3], and demand-side management strategies [4]. The transition towards smart energy systems has implications on several aspects, which should be properly addressed [5]. In addition, it implies higher complexity with the need for reliable tools to assist the optimisation of related design and operation. Technical literature emphasises that existing tools are featured with heterogeneous characteristics. For instance, Connolly et al. [6] assessed 37 tools for largely renewable integrated energy systems by providing useful information to guide decision makers. These tools are classified as *simulation* to simulate the operation of a given energy system, *scenario* to combine a series of years into a long-term scenario, *equilibrium* to explain the behaviour of the supply, demand, and prices in the entire or partial economy of several markets, *operation optimisation* to optimise the operation of a given energy system, *investment optimisation* to optimise the investments in an energy system, *top-down* when using macroeconomic data, and *bottom-up* when analysing specific energy technologies. Sinha and Chandel [7] assessed 19 tools for hybrid electric energy system planning and, according to Ref. [8], classified them as *pre-feasibility* for rough components sizing and comprehensive financial aspects analysis, *sizing* for determining the optimal component size and providing detailed information on energy flows, *simulation* for determining systems behaviour based on detailed component assessment, and *open architecture research* for allowing users to edit the algorithm and components' interaction. Markovic et al. [9] classified 13 tools according to different planning phases: *geography models* for the assessment of resources' spatial location, distribution and morphology of the built environment, *energy models* for the construction of consumer demand curves prior to distributed generation (DG) scenarios, and *evaluation models* for the assessment of energy-related aspects. Tozzi and Ho [10] classified 12 tools by their scale of application: *multi-scale* (for utility-scale projects), *district scale,* and *regional scale*. Manfren et al. [11]

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Published Journal Article available at: https://doi.org/10.1016/j.energy.2019.04.054

provided a comprehensive review on distributed generation systems and also classified 14 models according to their design phase (*preliminary, pre-processing, design, post-processing,* and *impact assessment*) and main function (*accounting simulation, optimisation, externalities and environmental impact calculation, databases,* and *advanced local energy planning*).

From previous review studies, a large number of tools are established as suitable for energy planning at different scales with heterogeneous characteristics (e.g., performed analysis objective, required data level of detail, user skills, etc.).

As a development of this field of research, this study aims to guide energy planners engaged in the transition of urban/district areas towards smart energy systems and focuses on the need for matching energy profiles of buildings with flexible and diverse sources and technologies.

In this framework, 17 tools targeted the urban/district scale to evaluate several energy services and/or sources and conversion technologies with detailed and open documentation have been described and classified based on their most useful features.

In addition, 6 detailed tools with at least an hourly-based time resolution and a user-friendly graphic interface is focused on. These tools carried out a good level of usability by energy planners.

Therefore, this survey contributes in choosing the suitable tool according to the aims and skills of the energy planners and the available datasets.

2. Methodology

After collecting information on different tools from previous review studies and online research, 17 tools that can assess energy systems at an urban and/or district scale building sector with diverse energy services/conversion systems and a detailed and easily accessible documentation were selected for this review study (Fig. 1).

The selected tools have been classified according to their output's time resolution (over-hourly based or sub/hourly based outputs), ease of use (advanced models mainly targeted on academic researchers or models with user-friendly interface), and type of licence (subject to payment or not) (Fig. 2). In the following sections, we outlined 3 tools that report *over-hourly output data* of energy demand-supply that can be adopted at the early stages of urban energy planning and among hourly (or sub-hourly) based output tools, 8 *advanced models* and 6 *user-friendly tools* either with a *commercial* or a *free licence*. The 6 user-friendly tools are described by their general information on the developer affiliation and licence access type, including the modules and/or subsections, required inputs, and provided outputs. The required energy data to accomplish an energy system assessment as well as the required economic and environment data have been investigated in detail.

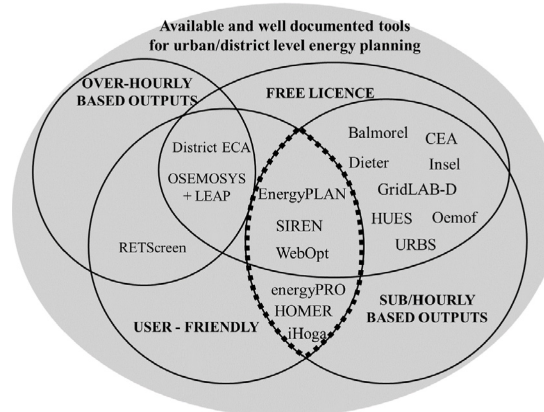

Fig. 2. Scheme of the method adopted for the classification of the 17 tools.

2.1. Tools with over-hourly based outputs

District ECA was developed by the Fraunhofer Institute for Building Physics with the IEA-ECBCS Annex 51 partners to support the decision makers in the first stage of planning energy-efficient districts to quickly evaluate the effects of both the supply and demand side strategies. The software is freely downloadable through preliminary registration [12] and comprises a set of tools with miscellaneous scopes [13]. The main core is a convenient tool (i.e.,

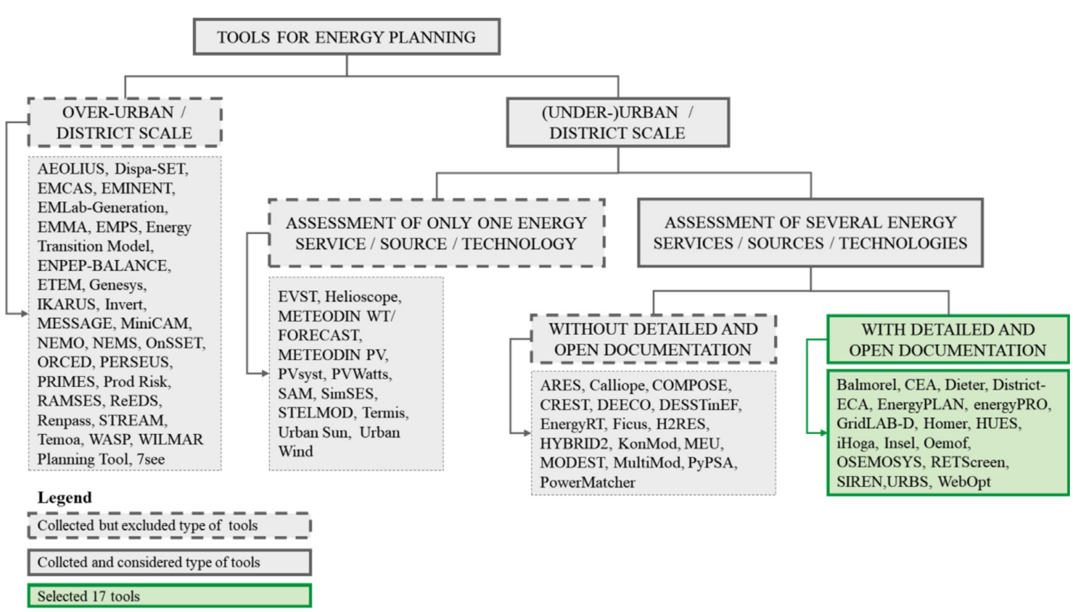

Fig. 1. Scheme of the method adopted for the selection of the 17 tools.

Energy Assessment of Districts) for accomplishing a monthly-based assessment of energy balance and related emissions of a district. Main limitations are: each single building of the district has to be modelled, the library includes technologies mainly referred to space heating and weather data as well as typical technological solutions are related to IEA-ECBCS Annex 51 participating countries [14].

OSeMOSYS (Open Source Energy Modelling System) is an open-source modelling tool for long-term energy assessment and planning [15] downloadable at [16]. Its most common graphic user interface (GUI) is the commercial software LEAP maintained at the Stockholm Environment Institute [17] and referred to as a decision support software, which enables users to have extensive data management and reporting and assessment of medium/long-term scenarios, including changes in energy use, related emissions, and resources deployment for any economic sector. Most of its calculations occur on an annual time-step, with an unlimited time horizon. As examples of its applications, assessments of different energy policies implications have been conducted from an energy and environmental perspective until 2035 for Tehran city in Ref. [18], from also an economic perspective for Taiwan until 2030 in Ref. [19], and for the Nigerian system until 2040 in Ref. [20]. Since it is a general-purpose tool, the required input data widely depend on the case study (e.g., top-down, bottom-up, economic, social data, etc.). Concerning energy related data, the annual demand and production values by the sector and fuel are required. Additionally, systems and energy costs, systems efficiencies and capacities, energy profiles, emission factors, interest, and inflation rates can be indicated.

RETScreen was developed at the Natural Resources Canada as a clean energy management software system [21]. Currently, it consists of an Excel-based and a Windows-based software package. With this, it is possible to model any scale systems and develop different scenarios (energy efficiency measures on buildings envelope and systems, various electricity and thermal energy supply plants, RES integration, etc.). According to its manuals [22,23], its required information includes general data and settings on calculation, climatic location, type of project, sector, and system features, such as capacity, delivered energy, and efficiency. Additionally, the CO_2 emissions per fuel and financial data (e.g., inflation rate, life-time, debt ratio range, initial costs, incentive, grants, annual oper-ation, maintenance, and fuel costs) can also be added.

2.2. Advanced models with hourly or sub-hourly based outputs

Balmorel supports users in modelling, analysis, and cost-optimisation of an energy system with emphasis on electricity and combined heat and power (CHP) [24]. It allows assessment under regional to national energy systems, it develops either long-term or short-term scenarios and accounts for hourly variations of energy fluxes. It is a freely downloadable open-source model. However, it is formulated in the GAMS[1] language, which requires commercial license.

CEA (City Energy Analyst) was developed at ETH Zurich, it is a free open-source GIS-integrated software and is conceived as an urban building simulation platform for the design of low-carbon and high-efficiency cities [25]. Until now, this software has been used for academic and real case studies for the characterisation of energy consumption of urban districts [26] and related energy production optimisation [27]. Among the constituting modules, a library of prototyped buildings, which is mainly based on Swiss context with data on envelope and installed systems characteristics based on hourly profiles calculated by the tool, is included. The modules under development include multi-objective optimisation, library of energy supply technologies, sensitivity analysis, and RES assessment.

Dieter (Dispatch and Investment Evaluation Tool with Endogenous Renewables) has been developed to study the role of power storage and other flexibility options related to high RES penetration [28]. The model determines cost-minimising combinations of power generation, demand side management, and storage capacities with their respective dispatch. As an open source model, it can be freely used and modified by users, although a paid license for GAMS is required to run it.

GridLAB-D was developed by the Pacific Northwest National Laboratory as a free open source agent-based tool that can be integrated with other modules to expand its capabilities [29]. It is conceived to model power systems and affect overlying systems (e.g., distribution automation technologies, peak-shaving strategies, new rate structures offer, and DG energy technologies, such as on-site generation, building CHP, and storages).

HUES (Holistic Urban Energy Simulation) Platform is an open source platform of resources to support distributed energy system design and control [30]. It includes a set of models for simulation and optimisation of building and district energy systems, databases of aggregated yearly heat demand and photovoltaic (PV) potential in Switzerland, and technical and economic properties of distributed systems. Its codes are freely accessible and editable; however, they must be run on commercial MATLAB[2] and Aimms[3] models.

INSEL (Integrated Simulation Environment Language) has been developed at the Faculty of Physics of Oldenburg University as a block diagram simulation system for programming applications with RES integration [31].

Oemof is a modular tool for energy system modelling and optimisation [32]. It is based on the open source Python[4] programming language and additionally, uses PostgreSQL[5] and PostGIS[6] for data processing.

Urbs is an open source and free model for multi-commodity energy systems modelling and cost-optimisation focusing on storages [33]. The energy demand and intermittent energy supply are modelled through time series datasets, energy supply and greenhouse gases (GHG) emissions are defined with both annual and time step values and can be limited to investigate the effect of policies, and storages are defined by the charging/discharging efficiency, capacity, investment, and fixed and variable costs.

2.3. User-friendly commercial tools with hourly or sub-hourly based outputs

The tool energyPRO, was developed by the Danish company EMD International A/S [34] to accomplish techno-economic analysis and optimisation of energy projects with a combined supply of electricity and thermal energy from multiple different energy-producing units [35]. It is typically used for analysing scenarios including district heating (DH), CHP, and combined cooling, heat, and power (CCHP), but can also be used for projects including geothermal energy, solar collectors, PV, wind farms, hydro pumping stations, and storages. In Ref. [1], energyPRO has been used in investigating the long-term improvement on existing district heating networks in Helsinki region and Warsaw by integrating

[1] https://www.gams.com/.

[2] https://it.mathworks.com/products/matlab.html.

[3] https://aimms.com/.

[4] https://www.python.org/.

[5] https://www.postgresql.org/.

[6] https://postgis.net/.

biomass, geothermal energy, waste heat, and heat storages from energy, economic, and environmental points of view. In Ref. [36], the most cost-effective size of gas engine CHP and thermal storage in the UK system has been investigated. In Ref. [37], energy scenarios to meet the heating and electricity demands in Pécs City, Hungary have been investigated from the energy, environmental, and economic points of view.

The user should select the type of assessment among *Design* for emphasis on energy conversion and operation payments for annual calculations, *Finance* for multi-year investment analysis, *Account* for a more detailed economic assessment, and *Operation* for optimisation of daily operation. The user can provide information on external conditions by adding data, i.e., loads and energy prices, as time series. It is possible to assess regional level scenarios by defining more interconnected distributed production sites.[7] When describing the energy exchange among possible sites, the required information includes the start and end site, transmission direction, energy service (heat, process heat, and cooling), and transmission capacity and loss which can be defined by functions or time series. Fuels' calorific values with related unit measure and eventually, the maximum useable fuel storage and offered fuel to production units per each month can be indicated. An unlimited number of demands per service (heat, process heat, electricity, and cooling) can be defined. In the tool library, arbitrary profiles as well as profiles from national German standards of electric and thermal energy are included. Otherwise, it is possible to specify user data both as an annual or time series (i.e., hourly or sub-hourly based) amounts, both as fixed or dependent on weather data (i.e., average ambient temperatures) values, and variable throughout the years by adding a defined fixed or variable index to specify the time series development over the years. Regarding the energy supply, the included units are heat rejection, CHP, electric boiler, absorption/electric chiller, heat pump (HP), flat plate/evacuated tubs solar collector, PV, wind farms, and storages. The required data depending on the technology are the capacity, production, fuel, power curve, inlet and outlet temperatures, operation dependence on another unit, charging/discharging power, hydro pumping storage reservoirs height difference, dimensions, technical features, etc. The operation strategy, except for the user-defined one, is driven by the net present cost (NPC) minimisation through an assigned priority level to the production units. The emissions of CO_2, NOx, and SO_2 per unit mass can also be defined. It is possible to define an electricity market by choosing between a fixed tariff and a spot market.

HOMER has been developed at the U.S. National Renewable Energy Laboratory to assist the design of micropower systems and to facilitate comparison of power generation technologies across a wide range of applications [38]. Hitherto, several studies on district energy optimisation adopted HOMER.

In Ref. [39], a set of RES-based systems to meet the electric and heat energy demand of rural and urban small communities along Ireland were investigated. In Ref. [40], the cost-optimal RES-based microgrid for Waterloo City, Canada was inspected. In Ref. [41], the authors explored a set of grid-connected PV systems with different tracking systems from a techno-economic perspective. In Ref. [42], the HOMER tool was used to validate the developed model for urban district energy optimisation.

HOMER can perform three assessments [43]: *simulation* to model the micropower system behaviour on an hourly basis and determine the techno-economic feasibility over its life, *optimisation* to simulate different system configurations in search of the one that satisfies the technical constraints at minimum NPC, and *sensitivity analysis* to evaluate the impact of changes in input parameters on the optimisation results, even from a long-term perspective. First, the climatic zone of the context under study must be specified to determine the RES availability. Then, four types of energy load are considered: the primary load (electric demand), deferrable load (electric demand that can be met any time within a time interval e.g., water pumps, icemakers, and battery-charging stations), thermal load, and hydrogen load. The primary, thermal, and hydrogen loads must be featured by indicating the average daily energy and power values, peak power, and daily hourly schedule. The profiles can be modified either by introducing weekly/monthly variations or by adding a percentage of disturbance to randomly change the curve. The tool includes default arbitrary hourly profiles, which are equal per energy service but different per end-use sector and have been used for lacking data such as in slightly electrified rural areas [40]; otherwise, it is suggested to use external datasets mainly referring to a US context, or if possible, by importing the hourly data of the user. There is a wide library of supply/conversion/storage units; else, they can be created by the user. Generally, the required information includes the system capacity, plant lifetime, unit costs of investment, replacement, and operation and management with related frequency, if the electricity current is alternating or direct. Fuels can be defined based on the library or based on its type, unit price, calorific value, and GHG emissions. For modelling RES-based systems, other data regarding the supply system efficiencies, technical characteristics, and average monthly availability of resources are required. After modelling the energy system, the user has to define the settings of the system assessment and optimisation. Regarding the economical parameters, the nominal discount rate, expected inflation rate, project lifetime, system fixed capital, operation and maintenance (O&M) costs, capacity shortage penalty, and currency are required. To define the optimisation constraints, the maximum annual capacity shortage, minimum RES fraction, and operative reserve as a percentage of the load or RES output are required. Possible economic penalties and annual limits of GHG emissions production can be set. The main outputs in tabular and graphic form are the total and annual cash flows per component either per NPC or per annualised costs, electricity production and consumption details per component and load types, annual emitted pollutants, possible ranking of developed scenarios according to NPC, and sensitivity analysis.

iHOGA (Improved Hybrid Optimisation by Genetic Algorithm), developed at the University of Zaragoza, is a software for the simulation and optimisation of hybrid stand-alone systems of electric power generation based on RES [44]. An educational version is free to download [45]; however, it lacks several functionalities and its computer-related requirements (i.e., internet connection and Windows version) widely limit its use. Therefore, it was not accounted for in this review. As an example, the tool has been used in optimising stand-alone hybrid systems located in Zaragoza (Spain) [46] and Kalonge (Congo) [47]. The expected load consumption of alternating/direct electricity and hydrogen and/or water has to be defined by either adopting monthly average values or selecting default profiles, which eventually applies a percentage of random variation. The included profiles are from literature and stand-alone system case studies; otherwise, the time-step based profiles of the user can be adopted by importing the files with rows of data referring to the hourly power, hydrogen mass flow rate, and water volume flow rate. It is possible to indicate data on solar irradiation, wind, and hydrogen either as average monthly values from NASA or as own time-step-based files. The simulation time step between a minute and an hour and the time horizon must be chosen. For the whole system life, the user has to choose between a mono-objective (based on net present value minimisation) and a

[7] A production site is defined as the location that contains the demands, energy units, and storages, which can exchange energy with other sites.

multi-objective optimisation (based on minimisation of net present value, equivalent CO_2 emissions, or unmet energy load); else, more advanced alternatives can be defined. Regarding the financial data, the nominal interest rate, expected annual inflation rate, system lifetime/assessment period, currency, installation costs, and variable initial cost, as both fixed cost and percentage to initial cost must be indicated. The total cost of different solutions and CO_2 emissions are graphically represented.

2.4. User-friendly freeware tools with hourly or sub-hourly based outputs

EnergyPLAN is a deterministic software developed at the Department of Development and Planning at Aalborg University [48] to assist the design of national energy planning strategies based on technical and economic analyses. It is downloadable through preliminary registration [49]. Moreover, it has been used in several scientific studies. For instance, it was used to investigate the optimal RES penetration into the national electricity production mix in UK [50] and Italy [51] as well as, in largely RES-based cross-sector scenarios, including low-temperature DH for the Danish cities of Frederikshavn [52] and Aalborg [53].

Two alternative analyses can be performed: *technical simulation* to balance either thermal or electric energy fluxes and *market-economic simulation* to assess system feasibility based on annual costs. In the electricity, heating, cooling, industrial and fuel, transport, and water subsections, related consumptions can be modelled. For all of them, the required input data are the total annual energy requirements and related hourly distributions. The hourly distribution is the energy consumption profile for a leap year, where each value is normalised to the maximum hourly value. In the library, the energy demand distributions are included at a town level, usually from utility companies for some investigated contexts, and at a national level from energy balance or STRATEGO project [54]. Additionally, the heating and cooling efficiency of the production units must be specified. The contribution from solar thermal energy by entering the capacity of the heat storage in days of average heat demand, the share of consumers with solar thermal collectors, and the related total annual production and hourly dis-tribution can also be modelled. The option of deferring a share of the electricity consumption is also included. The supply side is separately modelled with reference to energy service (i.e., sub-sections heat and electricity, electricity only, heat only, thermal plant fuel distribution, and waste, liquid, and gas fuels) and plants with the required annual production and/or capacity, operation efficiencies, and hourly production distribution. For more than one DH demand, the data must be reported for each defined group. Moreover, the carbon dioxide content per kilogram of fuel can be inserted. For performing a market-economic analysis, the interest rate, and for each plant unit, the investment cost, lifetime, and fixed operation and maintenance costs percentage share are required for the software to calculate the annual cost. In the subsection 'Additional', as suggested in the manual, other costs can be indicated such as that referring to building retrofitting. The hourly energy balances, annual/monthly fuel consumptions, CO_2 emissions, and system costs are provided as the outputs, which can be exported in an Excel sheet, and charts of the hourly fluxes can be plotted.

The SIREN (SEN Integrated Renewable Energy Network) Modelling Toolkit is developed by the Australian non-profit organisation called Sustainable Energy Now and is currently freely distributed as a beta version [55]. Its goal is to calculate energy generation for renewable energy power stations and to develop electricity in long-term scenarios. Specifically, it aims to determine optimal locations to access RES, minimise grid connection costs, and meet the varying grid demand, while achieving the best efficiency, cost effectiveness, and energy security. The entire software is made of a geo-referenced tool (SIREN), an energy calculation tool (SAM Power Models) provided by the National Renewable Energy Laboratory, and Excel worksheets for energy system optimisation (Power Balance tool). The project area can be defined based on the coordinates and related imported satellite image. The satellite maps are used to visualise, locate, and model both the existing electricity network and new RES plants. Aside from that in Australia territory with available default data, the hourly weather, electricity load data, and existing geo-referenced electric network layout must be imported. The possible supply technologies are biomass, PV (fixed, tracking, or rooftop), geothermal, solar thermal, wind, hydro, and wave. The required data are the location, power capacity, area, capital, operation and maintenance costs, hourly power production, and for wind farm and PV, the type, rotor diameter, number of turbines and panels, and orientation. The connecting lines regarding the type, cost, and maximum carrying capacity must be specified. Using the SAM Power Models, the hourly electricity balance is reported and exported to the Power Balance tool, which quantifies and cost-optimises various amounts of storage and generation technologies to completely balance the system. Finally, the CO_2 emissions can be calculated as outputs.

WebOpt, which stands for Distributed Energy Resources Web Optimisation Service, is an academic online version accessible through preliminary registration [56] of the Distributed Energy Resources Customer Adoption Model (DER-CAM) software developed at the Berkeley Lab [57]. Compared to the DER-CAM software [58], the browser-based version is limited and is less adopted in existing studies for cost optimisation [59] and evaluation of renewables integration [60] in CHP-based systems. It is a fairly complete tool to assess an integrated energy system; hence, we decided to assess it. WebOpt allows modelling and optimisation of energy scenarios under the criteria of the economic costs and/or carbon dioxide emissions. Three alternative optimisation strategies can be accomplished: cost minimisation, CO_2 emissions minimisation, or multi-objective analysis, which is CO_2 minimisation with cost constraint, which is required to fix the maximum allowable energy cost of buying electricity from the grid. The hourly energy loads for electricity, electric cooling, electric refrigeration, space heating, water heating, and/or natural gas should be im-ported as normalised profiles (distributions) to 1 GWh. They can be inserted using a one-building default profile suggested for the first analysis, or copying and pasting in each cell with a user-defined data, or selecting a profile from the ASHRAE U.S. climate Regions. If user-defined load data are entered, a monthly average hourly value, typical hourly-based weekly profile differing if possible, be-tween working and weekend days, and peak are required. Specif-ically, the cooling and refrigeration loads are always expressed in terms of the consumed electricity of an electric chiller with a co-efficient of performance of 4.5. It is possible to model in detail the costs of electricity and natural gas, by indicating differences of cost on a seasonal/monthly basis, fixed and variable costs, and different time of use. The system investment, O&M costs, lifetime and maintenance period, efficiencies, and capacity must be defined. Moreover, if possible, the percentage of schedulable load, solar radiation daily profile, and carbon dioxide emissions per energy unit can be established. In information regarding the total annual costs, payback time, and installed plants capacities, the detailed hourly energy profile is provided as simulation results.

3. Results

The main features surveyed of the preliminarily selected 17 tools are summarised in Table 1. The type of analysis is distinguished as *simulation* to model the operation of a given energy system on the

Table 1
Main features of surveyed 17 tools.

Tool	Type of Analysis	Optimal Spatial Scale	Time Scale of Outputs		Energy Service	Licence
			Time Horizon	Time-step		
Balmorel	CostOpt	Nation/Area	N Years	Hourly	EH	Free –O.S.
CEA	Sim	City/District	1 Year	Hourly	EHC	Free - O.S.
Dieter	CostOpt	Power Grid	N Years	Hourly	E	Free- O.S.
District ECA	Sim	District	1 Year	Monthly	EH	Free
EnergyPLAN	Sim	Nation/Region	1 Year (leap)	Hourly	EHCTI	Free
energyPRO	CostOpt	Region/District	N Years	Sub-Hourly	EHC	Comm.
GridLAB-D	Opt	Power Grid	N Years	Sub- Hourly	E	Free - O.S.
HOMER	CostOpt	District	1 Year	Hourly	EH	Comm.
HUES	Opt	District/Building	N Years	Hourly	EHC	Free - O.S.
INSEL	Sim	Any	Any	Any	EH	Free - O.S.
iHOGA	MultiOpt	Power Grid	1 Year	Sub- Hourly	E	Comm.
Oemof	Opt	Any	N Years	Hourly	EHCT	Free - O.S.
OSeMOSYS	CostOpt	Nation/City	N Years	Daily	EHCT	Free.
RETScreen	Sim	Any	1 Year	Monthly	EH	Free
SIREN	CostOpt	Power Grid	N Years	Hourly	E	Free –O.S.
URBS	CostOpt	City	N Years	Hourly	E	Free - O.S.
WebOpt	MultiOpt	District	N Years	Hourly	EHCT	Free

Legend - Sim: energy system simulation; Opt: energy system optimisation; CostOpt: cost constrained energy system optimisation; MultiOpt: multi-criteria energy system optimisation; E: electricity; H: space heating; C: space cooling; HC: thermal; T: transports.
I: industry; Comm.: commercial; Free: freeware; O.S.: opensource

supply and demand sides and *optimisation* to select a better system operation/configuration based on one or more criteria (e.g., costs, pollution emissions, etc.). We indicated the optimal spatial scale, i.e., the one for which they were conceived, according to the existing documentation even with viable applications on other scales. For instance, EnergyPLAN with optimal national or regional application has been used by developers at an urban level [52,53]. Regarding the time scale of both the calculations and provided outputs, two types of information are reported: the time horizon for distinguishing between short-term or long-term tools modelling, and the time resolution. Other specifications are regarding the energy service and licence type.

A more detailed investigation focused on 6 user-friendly tools is summarised in Table 2. These tools have been selected because of their user-friendliness and ability to assess energy balance with at least an hourly resolution (iHOGA and energyPRO can run with time-steps until 1 min). In addition, we noted the easy usage of Homer, EnergyPLAN, and WebOpt. However, the online use of WebOpt is featured with its slowness and limited basic functions (e.g., copy and paste and lack of shortcuts).

Generally, their usage is easier due to good support platforms, including video-tutorials, lists of related publications, user manuals, and guides on the required data resources. The tools, energyPRO, Homer, and EnergyPLAN, benefit from the mostly complete training material. The internationality of such tools has also been assessed based on their languages and currencies. For instance, energyPRO and HOMER include languages and currencies from several countries. As an additional value, the integration of spatial representation, such as georeferenced satellite maps in SIREN or network graphical representation in energyPRO and iHOGA, could allow spatially analysis on the energy fluxes, optimal location of RES plants, estimation of distributed network losses, etc. Modelling and comparison of more than one scenario at time is only possible with Homer, SIREN, and WebOpt. Regarding default loads, all tools foresee the possibility of importing their own time series for specific case studies, which is also the most suggested option; otherwise, default profiles are either arbitrary or constrained to specific contexts. We also distinguished between the demand profiles expressed as ‘distributions’ and ‘loads’. ‘Distributions’ refer to profiles with hourly values in percentage of the maximum value. Conversely, ‘loads’ are energy hourly absolute values that constitute to the profile. HOMER, iHOGA, and SIREN are more suitable for assessing the electricity supply/demand. In HOMER, modelling the thermal energy depends on preliminary modelling of the electric energy. However, it can consider up to two thermal loads and some heating supply components, with no plant

Table 2
Main features of surveyed 6 user-friendly tools with (sub-) hourly based outputs.

	Energy PLAN	energy PRO	HOMER	iHOGA	SIREN	WebOpt
Outputs time resolution	hourly	sub-hourly	hourly	sub-hourly	hourly	hourly
Easy to use	yes	yes	yes	yes	yes	yes (slow)
Good support platform	yes	yes	yes	yes	no	yes
Free licence	yes	no	no	no (full)	yes	yes (limited)
Language/Currency[a]	EU-DK	many	many	EU	US	US
Simultaneous scenarios	no	no	yes	no	yes	yes
Spatial representation	no	yes	no	yes	yes	no
Energy demand profiles type[b] and source	Distributions • user-defined • case-studies	Loads • user-defined • arbitrary • standards from Germany	Loads • user-defined • arbitrary from US	Loads • user-defined • literature • case-studies	Loads • user-defined • from Australia	Distributions • user-defined • from US
Several energy services	yes	yes	≈	no	no	yes

[a] EU refers to English language and Euro currency, DK to Denmark language and currency; US to English language and Dollar currency.
[b] Distributions refer to profiles made of hourly values in percentage of the maximum value; Loads refer to profiles made of hourly absolute values.

Table 3
Default energy supply technologies by tool and building energy services.

Energy service	Energy supply technology	EnergyPLAN	energyPRO	HOMER	iHOGA	SIREN	WebOpt
ELECTRICITY	Power plant/grid	x		x		x	
	CHP/CCHP	x	x			x	x
	Hydroelectric	x		x	x	x	
	PV	x	x	x	x	x	x
	Wind turbine	x	x	x	x	x	
	Biomasses	x				x	
	Electric Storage	x	x	x	x	x	x
	Others	x		x	x		
HEATING	District heating	x	x				x
	Boiler	x	x	x			
	HP	x	x				x
	Solar thermal	x	x				x
	Heat storage	x	x				x
	Others	x		x			
COOLING	District cooling	x					
	HP/chiller	x	x				x

specifically included for space cooling. In contrast, other tools can model more energy services, which allow assessment of the integration and its flexibility in urban energy systems. The energy services that can be modelled are listed in Table 3 with reference to the supply technologies provided in the six tools libraries.

4. Conclusions

To support decision makers in urban energy planning, several tools are currently available, as documented by the technical literature. Previous studies have concluded that tools able to model several energy services and to evaluate the economic and environmental implications of energy strategies should be preferred. However, the choice of the tool strictly depends on the specific project goals, data availability, and skills of the energy planners. This contribution origins in this framework, bringing a useful classification of the 17 tools suitable for energy evaluations at an urban/district level as requested by new energy planning applications.

To be more direct and effective, synoptic practical tables are reported to summarise the selected tools' most important features.

To model interactions among variable energy fluxes and to evaluate the effects of several energy supply units it is essential adopting tools with at least hourly-based outputs hence a deeper selection has been accomplished in the present research.

Six tools with user-friendly graphic interface and therefore, a good level of usability by energy planners, have been evaluated in detail.

These tools can be used in different applications of energy planning with the foresight of importing proper data for the considered case study or adapting embedded default energy profiles for a specific application to avoid incorrect estimations during the energy analysis.

We hope that this contribution can support and guide effective energy planning experiences at an urban/district level for the evolution of current energy systems. We believe that the presented results can promote the widespread use of these tools. Consequently, suggestions for their improvement in the future can be derived by the analysis of several expected applications.

Acknowledgements

The authors thank the Annex 75 "Cost-effective Building Renovation at District Level Combining Energy Efficiency & Renewables" working group of the International Energy Agency – Energy in Buildings and Communities - for the motivation to develop the present research.

NOMENCLATURE

CHP	combined heat and power
CCHP	combined cooling, heat and power
DC	district cooling (network)
DG	distributed generation
DH	district heating (network)
GHG	greenhouse gas (emissions)
GUI	graphic user interface
HP	heat pump
NPC	net present cost
O&M	operation and management (costs)
PV	photovoltaic
RES	energy from renewable sources

References

[1] Hast A, Syri S, Lekavičius V, Galinis A. District heating in cities as a part of low-carbon energy system. Energy 2018;152:627–39.

[2] Prasanna A, Dorer V, Vetterli N. Optimisation of a district energy system with a low temperature network. Energy 2017;137:632–48.

[3] Weiss T, Zach K, Schulz D. Energy storage needs in interconnected systems using the example of Germany and Austria. Journal of Sustainable Development of Energy, Water and Environment Systems 2014;2(No. 3):296–308.

[4] Kayo G, Suzuki N. On-site energy management by integrating campus buildings and optimizing local energy systems, case study of the campus in Finland. Journal of Sustainable Development of Energy, Water and Environment Systems 2016;4(4):347–59.

[5] Kozioł J, Mendecka B. Evaluation of economic, energy-environmental and sociological effects of substituting non-renewable energy with renewable energy sources. Journal of Sustainable Development of Energy, Water and Environment Systems 2015;3(4):333–43.

[6] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82.

[7] Sinha S, Chandel SS. Review of software tools for hybrid renewable energy systems. Renew Sustain Energy Rev 2014;32:192–205.

[8] Turcotte D, Ross M, Sheriff F. Photovoltaic hybrid system sizing and simulation tools: status and needs. In: PV horizon: Workshop on photovoltaic hybrid systems; 2001. p. 1–10.

[9] Markovic D, Cvetkovic D, Masic B. Survey of software tools for energy efficiency in a community. Renew Sustain Energy Rev 2011;15:4897–903.

[10] Tozzi P, Jo JH. A comparative analysis of renewable energy simulation tools: performance simulation model vs. system optimization. Renew Sustain Energy Rev 2017;80:390–8.

[11] Manfren M, Caputo P, Costa G. Paradigm shift in urban energy systems through distributed generation: methods and models. Appl Energy 2011;88:1032–48.

[12] http://www.district-eca.com/index.php?lang=en.

[13] Fraunhofer Institute for Building Physics IBP. Manual district energy concept adviser. 2013.

[14] Weber J, Ecker-Brinkmann A, Budde E, Wössner S, Erhorn-Kluttig H. Technical

manual - district energy concept adviser. Fraunhofer Institute for Building Physics; 2014.
[15] Howells M, Rogner H, Strachan N, Heaps C, Huntington H, Kypreos S, Hughes A, Silveira S. OSeMOSYS: the open source energy modeling system. An introduction to its ethos, structure and development. Energy Policy 2011;39: 5850–70.
[16] http://www.osemosys.org/.
[17] https://www.energycommunity.org/default.asp?action=home.
[18] Pedram N, Mohammad H, Abtin A, Mojtaba N, Elnaz K. Environmental assessment of energy production from landfill gas plants by using Long-range Energy Alternative Planning (LEAP) and IPCC methane estimation methods: a case study of Tehran. Sustainable Energy Technologies and Assessments 2016;16:33–42.
[19] Huang Y, Bor YJ, Peng C. The long-term forecast of Taiwan's energy supply and demand: LEAP model application. Energy Policy 2011;39:6790–803.
[20] Nnaemeka VE, Chinenye CE, Girish PM, Adaeze SAE. Energy policy for low carbon development in Nigeria: a LEAP model application. Renew Sustain Energy Rev 2017;68:247–61.
[21] http://www.nrcan.gc.ca/energy/software-tools/7465.
[22] Minister of Natural Resources Canada. *RETScreen software online user manual*, 1997-2005. http://publications.gc.ca/site/eng/search/search.html?st=1&ssti=&e=0&f=0&adoof=0&ast=user+manual+&cnst=&hpp=10&psi=1&rq.ssp=-5.
[23] Rene EG, Paul WS, Russell JD. RETScreen plus software tutorial. 2014.
[24] http://balmorel.com/.
[25] https://cityenergyanalyst.com/.
[26] Fonseca JA, Schlueter A. Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts. Appl Energy 2015;142:247–65.
[27] Fonseca JA, Nguyen T, Schlueter A, Marechal F. City Energy Analyst (CEA): integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. Energy Build 2016;113:202–26.
[28] http://www.diw.de/de/diw_01.c.508843.de/forschung_beratung/nachhaltigkeit/umwelt/verkehr/energie/modelle/dieter/dieter.html.
[29] http://www.gridlabd.org.
[30] https://hues.empa.ch/index.php/HUES_Platform.
[31] http://www.insel.eu/en/what-is-insel.html.
[32] https://oemof.org/.
[33] https://urbs.readthedocs.io/en/latest/index.html.
[34] www.emd.dk.
[35] EMD international A/S, user's guide – energyPRO. 2017.
[36] Fragaki A, Andersen AN, Toke D. Exploration of economical sizing of gas engine and thermal store for combined heat and power plants in the UK. Energy 2008;33:1659–70.
[37] Kiss VM. Modelling the energy system of Pécs. The first step towards a sustainable city. Energy 2015;80:373–87.
[38] HOMER energy, HOMERPro version 3.7 - user manual. 2016. Boulder, USA.
[39] Goodbody C, Walsh E, McDonnell K, Owende P. Regional integration of renewable energy systems in Ireland – the role of hybrid energy systems for small communities. Electrical Power and Energy Systems 2013;44:713–20.
[40] Hafez O, Bhattacharya K. Optimal planning and design of a renewable energy based supply system for micro-grids. Renew Energy 2012;45:7–15.
[41] Al Garni HZ, Awasthi A, Ramli MAM. Optimal design and analysis of grid-connected photovoltaic under different tracking systems using HOMER. Energy Convers Manag 2018;155:42–57.
[42] Best RE, Flager F, Lepech MD. Modeling and optimization of building mix and energy supply technology for urban districts. Appl Energy 2015;159:161–77.
[43] Lambert T, Gilman P, Lilienthal P. Micropower system modeling with HOMER. *Integration of alternative sources of energy*. 2006. p. 379–418.
[44] Dufo-López R. iHOGA Version 2.4 User's manual. Spain: University of Zaragoza; 2017.
[45] https://ihoga-software.com/.
[46] Bernal-Agustín JL, Dufo-López R. Efficient design of hybrid renewable energy systems using evolutionary algorithms. Energy Convers Manag 2009;50: 479–89.
[47] Dufo-López R, Pérez-Cebollada E, Bernal-Agustín JL, Martínez-Ruiz I. Optimisation of energy supply at off-grid healthcare facilities using Monte Carlo simulation. Energy Convers Manag 2016;113:321–30.
[48] Lund H. EnergyPLAN. Advanced energy systems analysis computer model. Documentation Version 2017;13.
[49] http://www.energyplan.eu/.
[50] Anh N, Bhattacharyya S. Integration of wind power into the British system in 2020. Energy 2011;36:5975–83.
[51] Franco A, Salza P. Strategies for optimal penetration of intermittent renewables in complex energy systems based on techno- operational objectives. Renew Energy 2011;36:743–53.
[52] Østergaard P, Lund H. A renewable energy system in Frederikshan using low-temperature geothermal energy for district heating. Appl Energy 2011;88: 479–87.
[53] Østergaard P, Mathiesen B, Moller B, Lund H. A renewable energy scenario for Aalborg Municipality based on low- temperature geothermal heat, wind power and biomass. Energy 2010;35:4892–901.
[54] Connolly D, Hansen K, Drysdale D. STRATEGO creating national energy models for 2010 and 2050 work package 2 - background report 1. 2015.
[55] http://www.sen.asn.au/modelling_overview.
[56] https://building-microgrid.lbl.gov/projects/distributed-energy-resources-web.
[57] Stadler M, Marnay C, Cardoso G, Donadee J, Siddiqui A, Wang S, Feng W, Lai J, Bhattacharya P, Mégel O, Groissböck M, Yu-Ko C. WebOpt user manual, DER Web optimization service (WebOpt). Lawrence Berkeley National Laboratory (LBNL); 2013. p. 1–32.
[58] Ghatikar G, Mashayekh S, Stadler M, Yin R, Liu Z. Distributed energy systems integration and demand optimization for autonomous operations and electric grid transactions. Appl Energy 2016;167:432–48.
[59] Milan C, Stadler M, Cardoso G, Mashayekh S. Modeling of non-linear CHP efficiency curves in distributed energy systems. Appl Energy 2015;148: 334–47.
[60] Litchy AJ, Pourmousavi SA. Technology selection and unit sizing for a combined heat and power microgrid: comparison of WebOpt and HOMER Application Programs. In: Proceedings of North American power symposium (NAPS); 2012. Champaign, USA, September 9-11.