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Review

Review of Existing Tools for the Assessment of European Building Stock Energy Demand for Space Heating and Cooling

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Abstract: There is currently a growing interest in lowering energy demand and, consequently, greenhouse gas emissions in all sectors. Several attempts by national governments to reduce energy demand are centered on the residential sector, since it accounts for a significant amount of the final energy demand. In order to estimate its energy demand and to evaluate the techno-economic effects of adopting energy efficiency and renewable energy technologies, there are comprehensive models suited for residential applications, since energy demand characteristics of the residential sector are complicated and interrelated. Based on these models, several tools are nowadays available to support designers and policymakers. These tools are designed to be user-friendly and to include the possibility to develop simulated scenarios for energy demand, production of CO_2 emissions, and economic costs. The present study aims to offer an up-to-date extended overview of the most functional and widespread tools for the assessment of the current energy demand of the European building stock for space heating and cooling demand, both regarding open source and commercial licenses. Results highlighted the tools most commonly used by examining real applications, identifying their strengths and weaknesses and pinpointing the primary deficiencies for the benefit of future developers.

Keywords: tools; space heating and cooling demand; energy planning; data-driven energy assessment; strengths and weaknesses

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1. Introduction

The energy demand of the European building stock accounts for approximately 40% of the total [1] and is a critical contributor to pollution [2]. Reducing energy demand and greenhouse gas emissions is crucial for climate change mitigation [3]; indeed, climate change is obviously impacting thermal comfort, and energy demand for heating and cooling [4]. Consequently, an increase in building energy performance can constitute an important instrument in efforts to outweigh this effect and to alleviate EU energy import dependency [5] (at about 48% [6]). For this reason, energy refurbishment of buildings has been promoted by national and European authorities through several initiatives and norms, e.g., building energy certifications, development of minimum standards for new and renovated buildings and economic incentives. On a large scale, public authorities are called upon to perform the task of energy planning on the district, city, regional and national levels, in order to ensure security of supply while increasing the use of renewable energy sources, reducing costs and CO_2 emissions and avoiding any energy waste [7]. For this purpose, there is a need to perform status quo energy analyses and planning studies of different project scenarios, which include optimizations of the best possible options [8], in order to achieve the ambitious targets set in national and European plans to reduce energy demand and CO_2 emissions [9]. However, these kinds of analyses require the development of appropriate methodologies and tools to help designers in the definition, simulation, and evaluation of sustainable space heating and cooling strategies. First, a clear visualization of the existing building stock energy dataset has to be provided [10]. Afterwards, analysis for future energy scenarios must be designed on this basis. Nowadays, several planning models exist [11], called Urban Building Energy Modelling (UBEM) [12]. Some methodologies are top-down while others are bottom-up. This classification is present in the study of Swan et al. 2009 [13], which has clarified the distinction between top-down and bottom-up approaches applied specifically to building energy modelling. Top-down methodologies work with aggregated data to build low-scale data through statistical and economic data, and bottom-up methodologies rely on building scale data, to build up a comprehensive energy panorama. Top-down methodologies can be mainly classified into econometric and technological approaches. While econometric models make use of energy demand data (e.g., energy bills or energy demand per area), technological models extend user behaviour information, which are usually location-specific, to the overall local building stock, to calculate its total energy demand. Other models also exist that combine both approaches. On the other hand, in the last two years, the bottom-up approach has gained momentum and has received special attention in several research works [4]. Bottom-up methods usually rely on two different approaches: statistical methods and engineering methods. Statistical methods [14] use data regarding the trend use of buildings, to attribute building energy demand to a set of representative buildings; afterwards, those representative buildings are used to build the overall building stock demand. Engineering methods [15], instead, rely directly on power ratings and use of equipment and systems and/or heat transfer and thermodynamic relationships, although they present the limitation that those data are usually not differentiated between the use and energy efficiency of the buildings. Both methods have strengths and weaknesses, and the choice may depend on the final purpose of the user. On the one hand, top-down models can be useful without complex input information and are able to encompass trends, macroeconomics and socioeconomic factors; yet on the other hand, those methods are only able to produce coarse analysis, which usually relies on historical information. The bottom-up models, instead, are able to provide more detailed analysis, which can include the effect of new technologies, producing ground-up data for final uses. Conversely, this method requires detailed input information and may result in a computationally intensive effort [16]. In order to ensure the usability of the described methodologies by designers (architects, building engineers, urban planners) and public authorities, and in general to make the visualization and use of these data possible for nonproficient users, a number of user-friendly tools were developed in the framework of research projects or by commercial companies. Most of the available tools are multi-objective and employ various simulation engines and Graphical User Interfaces (GUIs). Hence, a comparison can assist in understanding the advantages and disadvantages of each one of them. Several tools are, in fact, available nowadays, with open-source or commercial license. It has to be pointed out that most of the tools focus on space heating energy demand. Today, climate change, the increasing rate of adoption of space cooling systems and the resulting growth in energy demand from space cooling make even more evident the need to conduct dedicated studies to the reduction of the space cooling demand.

Scope and Overview of the Paper

Today, there is a jagged horizon of tools that perform energy assessments [17] and some clarity is needed about their possibilities and limitations to orient the user and to identify future developments. The objective of this study is to provide an updated and comprehensive overview of the most commonly used tools, both open source and commercially licensed, for assessing the current energy demand of buildings in Europe for space heating and cooling purposes. Moreover, the study aims to gather experiences of use for the mentioned tool, in order to assess their effective use.

Usually, open-source tools are developed in the framework of funded research projects; this is the case of the 11 open-source tools presented in Section 2: Hotmaps Toolbox, PlanHeat, THERMOS, Heat Roadmap Europe 4, CitySim pro, CEA, TEASER, EnerMaps, DREEM, IDA ICE and EnergyPlus (from Sections 2.1 to 2.11, plus 2.17 EMB3Rs). Conversely, the commercial tools guarantee technical, a user friendly-data access method and compliance with standards. Section 2 also includes five commercial tools: Invert/EE-Lab, CityBES, SimStadt, UMI and Apache (from Sections 2.12 to 2.16). In the cases where it was possible, the effective use of several of the mentioned tools (Hotmaps Toolbox, PlanHeat, THERMOS, City Energy Analyst, Heat Roadmaps Europe, CEA, EnergyPlus, Invert/EE-Lab, SimStadt, UMI, Apache) by public authorities was investigated in terms of real applications (Section 3) and discussed (Section 4). Finally, a summary of the conclusion is provided (Section 5).

2. Analysis of the Most Widespread Tools for the Assessment of European Building Stock Energy Demand for Space Heating and Cooling

The aim of this section is to provide a description of the existing tools, which are most promising to produce comprehensive assessments of the European building stock's energy demand for space heating and cooling. The most popular ones are listed and described below, considering 11 open-source and five commercial tools. Among the open-source software, are Hotmaps Toolbox, PlanHeat, THERMOS, Heat Roadmap Europe, EMB3Rs, CitySim, CEA, EnerMaps, DREEM, and EnergyPlus (Sections from 2.1 to 2.11). The commercial options are Invert/EE-Lab, CityBES, SimStadt and UMI (Sections from 2.12 to 2.16). Table 1 presents a summary of the main characteristics of the investigated tools for the assessment of the European building stock energy demand on space heating and cooling.

Table 1. Summary of the main characteristics of the investigated tools for the assessment of the European building stock energy demand on space heating and cooling.

Name	Access	Short Description	Receiver
Hotmaps Toolbox	Open source https://www.hotmaps.eu/map (accessed on 15 January 2024)	Database of the energy demand for space heating in EU-27+UK; data are visualized on a map in QGIS format, project scenarios can be generated.	Researchers, public authorities
PlanHeat	Open source https://planheat.eu/energia-renovable-e-inteligencia-artificial/ (accessed on 15 January 2024)	Tool for local authorities to evaluate low carbon and economically sustainable alternative scenarios for space heating and cooling.	Local administrations
THERMOS	Open source https://www.thermos-project.eu/thermos-tool/ (accessed on 15 January 2024)	Database with high resolution European energy mapping; it includes fast algorithms for modelling and optimizing thermal systems, incorporating real world cost, benefit and performance data, and operating both in wide area search, and local system optimization contexts.	Public authorities
Heat Roadmap Europe 4	Open source https://heatroadmap.eu/peta4/ (accessed on 15 January 2024)	A European database of space heating/cooling demand and future forecasts, available heat volumes from power plants/industry/waste, renewable resources for district heating (solar/geothermal/heat pumps),	Local, national and EU public authorities

		comparison of cost between heat savings and sustainable supply, hourly models simulating district heating/cooling impact on electricity/industry.	
CitySim pro	Open source www.citysim.pro (accessed on 15 January 2024)	This tool is able to simulate energy demand of buildings including energy sources and sinks coming from the urban context.	Urban energy planners, public authorities
City Energy Analyst	Open source https://www.cityenergyanalyst.com/ (accessed on 15 January 2024)	This tool is able to perform multidisciplinary analysis, simulating energy demand of buildings, CO_2 emissions, economic analysis, use of renewable sources and industrial waste heat.	Urban designers, public authorities, researchers
TEASER	Open source https://github.com/RWTH-EBC/TEASER (accessed on 15 January 2024)	This tool can be used with few input data to obtain coarse energy scenarios for building stocks.	Researchers, urban planners
EnerMaps	Open source www.enermaps.eu (accessed on 15 January 2024)	Visualizer foropen-sourcee datasets, with seven calculation modules to build possible scenarios.	Researchers, public authorities, energy planners
DREEM	Open source https://github.com/TEESlab-UPRC/DREEM (accessed on 15 January 2024)	Hybrid approach for Demand-Side Management (DSM) in buildings. Evaluates demand-flexibility. Modular structure emphasizes interdependence, independence, and hierarchical dependence of modules.	Researchers
IDA ICE 5	Open source https://www.equa.se/en/ida-ice (accessed on 15 January 2024)	A dynamic simulation tool evaluating building performance, as it allows to model the building, its systems, and controllers.	Energy planners, researchers, urban planners
EnergyPlus 23.2.0	Open source https://energyplus.net/ (accessed on 15 January 2024)	The tool is an energy analysis and thermal load simulation program, aimed at modelling both energy demand and water use in buildings.	Engineers, architects, and researchers
Invert/EE-Lab	Commercial licence www.invert.at (accessed on 15 January 2024)	Invert/EE-Lab simulates policy impacts on energy demand, CO_2, and costs in buildings. It uses detailed data on building geometry, age, and space heating systems.	Public authorities
CityBES	Commercial licence https://www.buildingenergysoftwaretools.com/software/citybes-city-buildings-energy-sustainability (accessed on 15 January 2024)	This tool produces analysis at high scale through the simulation engine of Energy Plus, using the widespread CityGML data format.	Urban planners, city energy managers, energy consultants and researchers

SimStadt	Commercial licence http://simstadt.hft-stuttgart.de/ (accessed on 15 January 2024)	This tool gives the possibility to include real urban data to develop high scale energy scenarios.	Architects, engineering offices, urban planners and municipalities
UMI	Commercial licence http://web.mit.edu/sustainabledesignlab/projects/umi/index.html (accessed on 15 January 2024)	This tool works with Rhinoceros 3D geometries and UBEM, providing energy simulation scenarios, with extendible multidisciplinary modules.	Researchers and consultants
Apache	Commercial licence https://help.iesve.com/ve2021/ (accessed on 15 January 2024)	This tool performs heating and cooling load calculations.	Energy planners, energy managers
EMB3Rs	Open source https://www.emb3rs.eu/ (accessed on 15 January 2024)	This tool will allow energy-intensive industries and other excess heat and cold sources to explore ways of reusing their excess thermal energy.	Public authorities

2.1. Hotmaps Toolbox

The Hotmaps Toolbox [18] is a tool for the mapping of space heating/cooling energy demand of the building stock at the European, national and local levels, and is designed to help public authorities plan future energy strategies. This tool was developed within the context of a homonymous European research project (2016–2020), with 16 partners involved and committed to its development. The tool provides a detailed representation of the energy needs of the building stock, in order to help the analysis for the development of future scenarios to quantify and compare costs and CO_2 emissions. Moreover, in the project, the following seven pilot areas were involved to test the tool, through the design of a high-scale space heating and cooling energy strategy: Aalborg (Denmark), Bistrita (Romania), Donostia/San Sebastian (Spain), Frankfurt-am-Main (Germany), Geneva (Switzerland), Kerry County (Ireland) and Milton Keynes (United Kingdom). The tool, which is available in open source, has been tested through the whole design phase until the analysis phase, in order to be as user-driven as possible. It also needed to be user-friendly in order to extend the readability of the dataset to planners of the local authorities of the EU27 + UK nations.

2.2. PlanHeat

PlanHeat [19] is a completed Horizon 2020 European research project whose main goal was to develop and demonstrate an integrated and user-friendly tool to support local authorities (at all levels) in selecting, simulating and comparing low-carbon alternatives and economically sustainable scenarios for space heating and cooling. Those scenarios could even involve alternative energy supply solutions. This tool was, in particular, intended to estimate the forecasted energy demand, mapping the potential low-carbon energy sources available, test the economic viability of the proposed solutions and identify the potential for further extension and upgrading of district space heating and cooling networks. Also, the tool allows evaluating the benefits of the new scenarios compared with the current situation via energetic, economic and environmental KPIs. Finally, training and replication strategies involving public authorities have been set up towards the empowerment of targeted users.

2.3. THERMOS

THERMOS (Thermal Energy Resource Modelling and Optimization System) [20] is an ended Horizon 2020 research project, which ran from October 2016 to March 2021, whose goal was to increase and accelerate the development of new low-carbon heating and cooling systems in Europe and to propose refurbishment of existing installations. There is an unquestionable potential for energy savings in space heating and cooling of the building stock, which has not been properly realized. Within the THERMOS project, eight partners collaborated to enable public authorities to undertake more sophisticated thermal energy system planning at the local level, rapidly, cheaply, and precisely. Public authorities involved in the project overcame these challenges through project planning (management, optimization and expansion of current and new systems) and strategic planning (quantification of technical potential and discovery of new prospects) through the THERMOS software, in order to become a model for the rest of Europe. The software had the goal of implementing fast algorithms for the simulations of different energy scenarios, including complex variables (effective costs, emissions, energy sources potential and energy wastes). For this purpose, the software had to be user-friendly, free and open-source. The tool was used in the UK, Spain, Poland, Latvia, Denmark, Germany, Portugal, and Romania as part of the THERMOS EU Horizon 2020 funded research project. Although the project ended in March 2021, the software and partner support continue to be available.

2.4. Heat Roadmap Europe 4 (HRE4)

The goal of Heat Roadmap Europe 4 (HRE4) [21,22], which is an Horizon 2020 European research project, has been to develop low-carbon space heating and cooling strategies, called "Heat Roadmaps", through the analysis of the existing energy demand and simulations of future scenarios at the national level for European member states. There is special attention on promoting transparency in energy demand data by sharing results, models and methodologies through an open platform, which is developed within the project: the first ever pan-European thermal atlas (Peta) of the space heating and cooling demand in Europe was built and shared online, with space heating and cooling energy demand hourly data in Europe, both for today and the forecast of their future development. The quantification of renewable resources available in Europe is also included, with large-scale solar thermal, direct geothermal, and heat pumps, with the possibility to make comparisons at the European level. The Heat Roadmap Europe (HRE) study series started in 2012 and is now in the 4th edition. In the latest edition, HRE4 supported the decarbonization of the space heating and cooling sector in Europe and developed strategies for redesigning this sector by combining the knowledge of local waste heat conditions and potential savings with an energy system analysis.

2.5. CitySim Pro

The software CitySim pro [23,24] is a decision support tool for urban energy planners and all involved stakeholders, created to minimize nonrenewable energy source use and the linked emissions of CO_2. In CitySim, 3D models with the district thermo-physical properties can be imported to simulate the energy demand of these buildings, while respecting the stochastic nature of occupants' presence and behaviour and accounting for a range of commonly used heating, ventilation and air conditioning (HVAC) systems. It is also possible to simulate the renewable energy supply, including energy inputs coming from the urban context (i.e., radiation exchange, etc.). It includes a solver for simulating the energy demand of buildings for space heating and cooling through buildings' geometry and climate files.

2.6. City Energy Analyst (CEA)

The City Energy Analyst 3.35.4 (CEA) [25] is an urban building simulation computation tool for the design of low-carbon and highly efficient strategies at city scale. This tool combines knowledge of urban planning and energy systems, and, thus, allows studying the effects and synergies of urban design scenarios and energy infrastructure plans. CEA is addressed to practitioners, researchers and urban planners and is able to perform analysis of CO_2 emissions, financial analysis for building retrofits (appliances and lighting, building envelope, HVAC systems), integration of local energy sources (renewable and waste heat), and district energy networks (decentralized and centralized thermal microgrids and conversion technologies).

2.7. Tool for Energy Analysis and Simulation for Efficient Retrofit (TEASER)

TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit) [26] has been developed at the RWTH Aachen University to spread the use of Building Performance Simulation for building stock on an urban scale. TEASER has a simple interface with low input requirements (building function, net leased area, year of construction and rough cubature) for multiple data sources and is able to return energy scenarios for extended building stocks.

2.8. EnerMaps

EnerMaps [27] offers a visualization of complete open-source datasets regarding the EU27 + UK territory. It includes climatic data, emissions, renewable energy effective or potential generation, building geometrical data and energy production. It also includes the building heating energy demand. The tool is equipped with seven calculation modules, which help users build scenarios for district heating (DH) economic assessment, building space heating and cooling load, scenarios of space heating and cooling degree days, DH potential, estimated building energy demand, refurbishment rate impact and a statistic module.

2.9. DREEM

The DREEM 1.0 model is a cutting-edge, hybrid bottom-up approach that combines statistical and engineering models to enable Demand-Side Management (DSM) modelling in the building sector. It expands the computational capabilities of existing Building Energy System (BES) models to evaluate demand-flexibility benefits and limitations for consumers and other stakeholders. What sets the DREEM model apart is its modular structure, which follows the principles of components and a modular-based system modelling approach. This approach emphasizes the interdependence of decisions within modules, the independence of decisions between modules, and the hierarchical dependence of modules on components that embody standards and design rules.

2.10. IDA ICE

IDA Indoor Climate Energy 5.0 (IDA ICE) by EQUA Simulation Technology Group is an innovative and trusted whole-year detailed and dynamic multi-zone simulation application for study of thermal indoor climate as well as the energy demand of the entire building. It allows combining buildings, systems and control modelling. It can display interactive 3D with visualization for input and results. The tool relies on a modular structure, with access to the model source code and the possibility to apply the preferred extensions. IDA ICE offers separated but integrated user interfaces to different user categories:

- Wizard interfaces lead the user through the steps of building a model for a specific type of study. The Internet browser based IDA Room wizard calculates space cooling and heating load.
- Standard interface for users to formulate a simulation model using domain-specific concepts and objects, such as zones, radiators and windows.
- Advanced level interface, which allows the user to browse and edit the mathematical model of the system.
- Open versions for developers.

Overall, the tool allows for optimizing criteria like system selection, equipment sizing, control strategies and set points, guaranteeing flexibility in its development through either in-house development or by experienced users.

2.11. EnergyPlus

EnergyPlus 23.2.0 is a free, open-source and cross-platform building simulation program that models both energy demand—for space heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings. Among the features of EnergyPlus are the following:

1. an integrated simultaneous solution of thermal zone conditions and heating, ventilation, and air-conditioning (HVAC) systems response;
2. heat balance-based solution of radiant and convective effects;
3. sub-hourly customizable time steps for interaction between thermal zones and the environment (or HVAC systems);
4. combined heat and mass transfer model;
5. advanced fenestration models;
6. illuminance and glare calculations;
7. component-based HVAC;
8. built-in HVAC and lighting control strategies;
9. functional mockup interface import and export;
10. standard summary and detailed output reports as well as user-definable reports.

The U.S. Department of Energy (DOE) makes use of this tool using the OpenStudio 3.7.0 software development kit. The DOE generally releases major updates to EnergyPlus 23.2.0 twice annually.

2.12. Invert/EE-Lab

Invert/EE-Lab [28] is a bottom-up commercial simulation tool that evaluates the effects of different policy packages on the total energy demand, energy mix, CO2 reductions and costs for space heating, cooling, domestic hot water and lighting in the building stock. The model includes disaggregated data regarding the building stock for all countries of the EU-27 (plus the UK), containing construction period, geometry data, U-values of building components, age and type of installed plants. This tool has been developed by the Vienna University of Technology/Energy Economics Group (EEG) in the framework of the project Invert (2003–2005). Afterwards, the model was extended and applied to various European regions. This software was used, for example, to simulate the scenarios of development of the building stock and its energy demand in the EU27 (plus the UK) up to 2030/2050/2080 for various scenarios, in the framework of the European comprehensive assessments or by public authorities at national level. In 2010, the model was extended to include the inhomogeneous structure of decision makers in the building sector and corresponding distributions [29,30], while in 2014, the model was extended with an agent-specific decision approach integrating stakeholder behaviors [31]. Finally, a district heating and gas grid optimization module was added [32].

2.13. City Building Energy Saver (CityBES)

City Building Energy Saver (CityBES) [33] is an energy modelling and analysis tool for city building stock, designed to support district or city-scale efficiency programs. CityBES uses an international and open data format, CityGML [34], to simplify the input of city models, while it employs the simulation engine of EnergyPlus to estimate building energy use and potential savings from energy retrofits. CityBES receivers are urban planners, city energy managers, energy consultants, and researchers.

2.14. SimStadt

SimStadt 2.0 [35] is an urban simulation environment, developed at the HFT Stuttgart in the framework of the homonymous project, which is able to use data of a real urban planning situation or design scenarios for energy demand of buildings, city quarters, or entire cities or regions to develop energy simulations. The tool includes the study of renewable energy supply scenarios, photovoltaics scenarios, and simulation of building refurbishments. This tool is addressed to architects, engineering offices, urban planners and municipalities to develop integrated planning and to define measures towards a sustainable refurbishing of cities.

2.15. Urban Modeling Interface (UMI)

The Urban Modelling Interface (UMI) [36] was developed by the "Sustainable Design Lab" to develop an urban modelling platform to evaluate the environmental performance of neighborhoods and cities. Among other parameters, it simulates operational and embodied energy use, and district-level energy supply analysis. The tool works with input files generated from Rhinoceros 3D and UBEM.io and includes an application programming interface where additional performance modules and metrics can be added. UMI is addressed to researchers, urban designers and planners, municipalities, utilities, sustainability consultants and other urban stakeholders.

2.16. Apache

Apache Loads (also known as ASHRAE Heat Balance Method) by Integrated Environmental Solutions (IES) performs space heating and cooling load calculations according to the ASHRAE Heat Balance Method. The tool offers two types of analysis. On the one hand, it specifies the "Room and Apache system loads" to analyze room space heating and cooling loads. On the other hand, it proposes the "ApacheHVAC system loads" to analyse loads on a specified ApacheHVAC system.

2.17. Specific Tools: Energy-Matching and Business Prospection Tool for Industrial Excess Heat/Cold Reduction, Recovery and Redistribution (EMB3Rs)

EMB3Rs stands for user-driven "Energy-Matching and Business Prospection Tool for Industrial Excess Heat/Cold Reduction, Recovery and Redistribution" and is a specific tool for encouraging and planning the use of waste heat. The idea behind this EU-funded research project is to provide a mapping tool for waste heat from the industry sector in order to use it as energy source for heating residential building stock. This is not yet available but will be completed soon. This project involves 16 companies and institutes from all over Europe to build a tool for the optimization of this energy source at local level, to provide a comprehensive quantification of the waste heat through data coming from the participants, recollected on a platform and then the potential reduction of the costs. There are four analysis modules (GIS, TEO, MM and BM) that perform simulations. The Geographical Information System (GIS) model aims to connect sources and sinks and create a network for offer and demand of heat. The model uses the existing Open Street Map (OSM) Road Network. The Techno-Economic Optimization (TEO) module provides optimization of the best simulation scenarios. The objective of the optimization is to find the least-cost technologies and match between sources and sinks that satisfies the demands, under all the constraints dictated by norms. The Market Module (MM) provides the user with economic market indicators like energy transactions, market price, social welfare, fairness among prices, by short- and long-term market analyses. Finally, the Business Model (BM) module evaluates various business models for the use of the excess heat for the investors. The project includes seven case studies of buildings with different uses to validate the tool.

3. Real Applications of the Tools and Comments from the Users

The objective of this section is to present an analysis of the efficacy of the tools described, by providing information on the actual instances of their use, thereby offering insights into the level of success associated with these tools. Moreover, (when available) a number of comments from the users (municipalities) were collected, which will help to underline strengths and weaknesses of a number of the described tools. In this study, a total of 16 tools were analyzed, while information on the use of 10 of them was collected. Thus, approximately 63% of the reported tools have been studied in their real applications and further development. In this section, the Hotmaps Toolbox (Section 3.1), PlanHeat (Section 3.2), THERMOS (Section 3.3), Heat Roadmaps Europe 4 (Section 3.4), City Energy Analyst (Section 3.5), EnergyPlus (Section 3.6), Invert/EE-Lab (Section 3.7), Simstadt (Section 3.8), Urban Modeling Interface-UMI (Section 3.9), and APACHE by IES (Section 3.10), are presented, with specific details on the current application of tools by municipalities at the local level.

3.1. Hotmaps Toolbox

The Hotmaps Toolbox has been used by national and local authorities and in the framework of several European Horizon 2020 projects. On the nationwide level, the tool was used for the Comprehensive Assessment of six countries: Austria, Bulgaria, Estonia, Germany, Portugal, and Slovenia [37]. Locally, Hotmaps was first used by the following municipalities that were selected as pilot areas: Geneva (Switzerland), Bistrita (Romania), Frankfurt (Germany), San Sebastian (Spain), Milton Keynes (UK) and Kerry County (Ireland). Here is a brief summary of the implementation of the tool for the selected pilot areas, and its contribution to the preparation of specific studies and plans (please see [38] for further details).

Geneva (Switzerland). The Hotmaps Toolbox brought concrete benefits to the planning process with the aim to (i) identify local energy resources and (ii) adapt them to urban development and high concentrations of energy consumed throughout the municipal territory of Geneva. The city developed a medium-long-term energy plan, which is consistent with its "100% renewable vision by 2050". Thanks to the Hotmaps Toolbox, the city can now assess the impact of projects already in the pipeline (such as "GeniLac", a scenario developed by the Canton and the industrial service of Geneva based on the use of the lake for space heating and cooling of buildings) in terms of economic and climate impacts.

Bistriţa (Romania). The Hotmaps Toolbox allowed developing a heating strategy for Bistriţa, a city in the northern part of Romania near the border with Ukraine. The main challenge was initially to overcome the barrier of a relatively inefficient local heating system and the reaction of citizens towards the development of a district heating based on excess heat and renewable energy. The contribution of Hotmaps was to first identify local, regional and national targets for GHG emission reduction, and then develop specific quantitative scenario assessments to develop a comprehensive strategy for the city. Eventually, results from Hotmaps were to be included within the main strategic documents of the city, namely the Action Plan for Climate and Energy 2030, Local Development Strategy 2010–2030 and Energy Vision 2050.

Frankfurt Germany). The Hotmaps Toolbox led to clarifying where the heat demand is high enough to suggest an investment in district heating pipelines in the city of Frankfurt, which are part of the key pillars of the sustainable energy action plan. The toolbox calculations showed that a reduction in heat demand in buildings of between 40 and 50% is needed to reach the city's goal. Moreover, the updated planning process in the context of the Hotmaps project reinforced the links between the city and the local utility Mainova, which will likely lead to concrete projects such the heat recovery from data centers.

San Sebastian (Spain). The Hotmaps Toolbox gave birth to the first space heating and cooling plan for the local 2050 strategy of the city. The municipal company Fomento De

San Sebastian (partner of Hotmaps) runs the first public District Heating (DH) of the city in the district of Txomin-Enea, powered by biomass, representing the first publicly owned DH system in the Basque Country. Among ongoing studies regarding long-term sustainability in San Sebastian, the City Council already approved the Climate Change Strategy 2050, Sustainable Urban Mobility Plan 2008–2024, Green Sustainable City Plan, and Energy Efficiency Municipal Directive in Buildings. In particular, the Green Sustainable City Plan and the Climate Change Strategy set important goals and targets for 2030 and 2050 regarding the use of renewable energy sources (RES), CO_2 emissions reduction and heat demand reduction in buildings. Notably, similar strategies and plans are in place for the region of Gipuzkoa and the whole Basque Country.

Milton Keynes (England). Within the city's sustainability strategy for 2019–2050 approved in 2019, the Hotmaps Toolbox has been key to promoting the action plan to support the strategy of the municipality. Specifically, the analysis enabled identifying additional resources in the area, both for space heating/cooling solutions and for other sources of locally generated energy. There are three areas of interest for potential DH projects: central Milton Keynes, where the existing DHC system could be expanded, Old Wolverton and Fullers Slades, where urban refurbishment is foreseen.

Kerry County (Ireland). Kerry County was the first county in Ireland to have a fully operational biomass district heating system in the town of Tralee, commissioned in 2008. Specific studies examined the extension of this project, enlarging the district heating (DH) to 53 of the largest energy users in the area. The Hotmaps Toolbox was also crucial to evaluate viable space heating technologies as options for renewable space heating outside the towns of Tralee, Killarney and Dingle.

Today, the number of users of the Hotmaps tool among local public authorities is expected to increase, due to the new European requirement to draft a local strategy for energy planning. The required energy strategy, according to current European legislation, must be planned for the following 10 years (at a minimum). Authorities are required to update this planning with a frequency of every 6 years. As said, Hotmaps was also used in European Horizon 2020 research projects, which contributed to spreading its use among public authorities and producing advancements in research. A few projects are mentioned below, although the total number will increase in the coming future. In the framework of the "PATH2LC" [39] research project, the Hotmaps tool had an important role in estimating the potential of renewable energy sources (RES), and heat recovery at district level. Several public administrations took part in this project., including the following:

- Rhône Network (ALTE69)—France: CCMDL (Monts du Lyonnais), CCSB (Saône-Beaujolais), COR (Ouest Rhodanien), SOL—(Ouest Lyonnais). (41 cities in total);
- SCN—Greece: Oichalia, Ierapetra, Korinth, Vari-Voula-Vouliagmeni, Messinis;
- UCSA—Italy: Palma Campania, San Giuseppe Vesuviano, Striano;
- CNNL—Netherlands: Groningen, Assen, Emmen, Leeuwarden;
- Oeste Sustentàvel—Portugal: Arruda dos Vinhos, Nazaré, Alcobaça, Alenquer, Bombarral, Peniche, Caldas de Rainha, Torres Vedras, Obidos.
- Moreover, Hotmaps is used in the "Act!onHeat" [40] research project by three administrations that applied for technical assistance from the Support Facility:
- Macedonian Academy of Sciences and Arts: Research Center for Energy and Sustainable Development;
- Province Limburg;
- San Lucido.

Furthermore, Hotmaps is one of the tools identified for the development of additional tools in two other European projects: SAPHEA [41] and OpenGIS4ET [42].

3.2. PlanHeat

PlanHeat was developed by 13 partners from across Europe: RINA Consulting S.p.A. (IT—Coordinator), Technische Universiteit Delft (NL), Sveuciliste Uzagrebu (HR), National Observatory of Athens (GR), Vlaamse Instelling Voor Technologisch Onderzoek (BE), Fundacion Tecnalia Research and Innovation (ES), Stad Antwerpen (BE), Grad Velika Gorica (HR), Regional Environmental Center for Central and Eastern Europe (HU), Euroheat and Power (BE), Comune di Lecce (IT), Geonardo Environmental Technologies LTD (HU) and Artelys (FR). Within the same project, testing activities are developed in order to validate the integrated tool. Such activities are performed on three real cases, which provide real case studies in three different European countries:

- Lecce (Italy);
- Antwerp (Belgium);
- Valika Gorica (Croatia).

3.3. THERMOS

The tool was tested in eight project ambassadors and in more than 150 energy plannings from Europe and beyond. A complete training program was held to increase the users of the tool, with good results; by the end of the project (March 2021), more than 1400 users from New Zealand to South America had already started developing 3000+ maps and projects with THERMOS for professional use. There has undoubtedly been a good response and high interest in the tool; thus, partners struck a partnership agreement on a software as a service model at the end of the project. This agreement allows them to maintain the server and eventually provide technical and planning user support services beyond the project's lifetime. Finally, as the Hotmaps Toolbox, it was included as the main tool of the "Act!on Heat" [43] research project. Regarding practical applications, THERMOS has supported advancing project case studies, national district heating and cooling (DHC) planning, and local energy decarbonization plans, while being adopted by research centers and universities. Here is a brief overview of the current status of applications of THERMOS. Please consult [44] for the reference.

Advancing project case studies. Eurométropole de Strasbourg, application to a DH network for the area of Lingolsheim, France (Dec-19), SF2E—Manergy, application for a DHC network in Meylan, France (Dec-19), and ALL ing ABATE, study of a Heat Network for municipal buildings in San Lucido, Italy (Dec-19).

National DHC planning. Analysis of the Spanish DHC potential, performed by Creara on behalf of IDEA (Institute for Energy Diversification and Saving), which acts as a managing branch of MITECO (Spanish Ministry for the Energy Transition and Demographic Challenge).

Concerning local energy decarbonization plans, there have been several applications of THERMOS at the municipality level, mainly due to its relevant support in enhancing the quality of heat and cold network planning and strategies.

- Identification of best zones for heat network development in six major cities in the UK (Bristol, Newcastle, Greater Manchester, Birmingham, Leeds and Nottingham), as part of a series of pilot City Decarbonization Delivery Plan (CDDP). Additionally, the results were exploited for developing effective national policies on heat to study the most cost-effective heat decarbonization options in the country.
- Planning and extension of current DH systems in the Zemgale region (Latvia), for the Sustainable Energy and Climate Action plans for the following municipalities: Jelgava, Jekabpils and Auce. The support was key to planning upgrades at the existing district heating systems and accelerating the local energy transition in the whole region.
- Revision of public energy efficiency policies in the municipality of Alba Iulia (Romania). THERMOS enabled to complement the previous Sustainable Energy Action Plan (SEAP) into the 2030 Sustainable Energy and Climate Action Plan

(SECAP), by integrating novel optimized energy planning measures and the outline of two major renovation investment projects targeting several public buildings. Use of THERMOS in Riga (Latvia) for developing the city's SECAP, to improve the strategic vision of the city and the process of gathering data for implementing the plan. The tool was also used by the municipalities of Tukuma, Siguldas, Lielvārdes, Ogres, Mārupes, Ādažu, Ķekavas, Salaspils and Ķeguma.
- Planning of appropriate measures for efficient heat supply in the city of Berlin (Germany), supporting the activity of the Berlin Senate Department for Economics, Energy and Public Enterprises**.** Afterwards, the city planning department of Berlin's Charlottenburg-Wilmersdorf district tested the tool and is planning to employ it for future heat transformation areas in the district.
- Mapping of new and expanded heat networks in Islington (UK), according to the strategy of Islington Council set out in 2020. THERMOS was specifically employed for mapping and modelling new heat networks, hence contributing to the refinement of the municipality's planning for heat networks in the borough.
- Rapid assessment of heat network connection requests in Bristol (UK). Specifically, THERMOS was used to generate quick checks of key parameters (like pipe size or heat supply capacity) for assessments of heat connection enquiries, whose results were compared with the existing hydraulic model previously created for the network. This enabled us to save time and money for the evaluation of potential new connections in Bristol's heat network.
- Mapping and potential expansion of biomass heat supply networks in the pilot city of Granollers (Spain). The tool allowed to assess alternative scenarios for the expansion of the supply network, while enhancing the quality of estimation of zonal heat demand per type of consumer. Once validated by local policymakers, the tool might be integrated into the city's SEAP to ease the whole process of planning and development of city's heat networks.

3.4. Heat Roadmap Europe 4 (HRE4)

Heat Roadmap Europe 4 (HRE4) has been used for the comprehensive assessment of Sweden [45]. Apart from the events that were organized or hosted by the project, members of the HRE4 consortium were invited to present the results of HRE4 at more than 120 events, ranging from one-to-one meetings with local, national, and EU policymakers to key industrial and research partners, such as Danfoss, Vattenfall, and the Joint Research Centre (which is the research branch of the European Commission). In June 2017, HRE4 was recognized as the most innovative project in the technology category of hybrid systems by the Steering Committee of the European and Technology Innovation Platform on Renewable Heating and Cooling (RHC-ETIP) [46]. The project was, in fact, recognized for using a holistic and comprehensive analysis—including both energy savings and different kinds of renewable heat supply—and by combining the expertise of different sectors in four models to quantify the impacts of energy efficiency and RES for 14 largest EU Member States (please see [47]). Beyond international and European recognition, the results from the HRE4 project (concluded in 2019) supported both regional and local policy interventions. Regarding regional applications, HRE4 insights and Peta4 (the Pan-European Thermal Atlas, developed as part of the work in Work Package 2—WP2 of HRE4) were used to develop a vision and goals for municipal heat planning for Lower Saxony (Germany), Strasbourg Metropole Region (France) and Treviso province (Italy). As concerns local policy interventions, HRE4 outcomes provided concrete solutions for the municipalities of Alba Iulia (Romania), Antwerp (Belgium), Lille (France), Murcia (Spain) and Strasbourg City (France) [48].

3.5. City Energy Analyst (CEA)

City Energy Analyst 3.35.4 (CEA) is an open-source software that started in 2013 at ETH Zurich and is now regularly used in common practice by architects, planners, and more generally contractors performing multiple local energy simulations and conducting research on multiple scales. An important case study is documented in the ENEFIRST [49] project (the EU project, which translates the Energy Efficiency First principle for System Decarbonization) to simulate various scenarios for a commercial area (Case study IV). At the municipality level, case studies include applications for the districts of Singapore and Zurich (please consult [50] for further details). In Singapore, the Building-Integrated Agriculture (BIA) research project running from March 2021 to September 2022, developed in collaboration between Singapore-ETH Centre (SEC) and the National University of Singapore (NUS), aimed at investigating the benefits of integrating agriculture into buildings. The study was part of the analysis of the City's master-planning scale in support of the national "30 by 30" goal, i.e., to produce 30% of its total food needs by 2030, an increase from the current 10%. For this purpose, an extension of the City Energy Analyst (CEA) toolbox was used. CEA was employed as part of the project to design and model urban energy infrastructure for the greenfield of Vale de Santo Antonio in the city of Lisbon ("Green Capital 2020"). For this project, three softwares were integrated (QGIS, CEA and Urbio). Specifically, CEA was used to model the neighborhood energy services (heating, cooling, domestic hot water, and electricity for other uses, including EVs) and simulate the operation of different thermal network layouts. Furthermore, CEA was used to test several real urban areas and other case studies. Among these, CEA supported the analysis of climate mitigation and adaptation strategies for Wesbrook Village (Vancouver) and was selected for the modelling of Amsterdam Positive Energy Districts (PED) of Buiksloterham and the analysis of potential District Cooling for 41 districts in Singapore.

3.6. Energy Plus

EnergyPlus 23.2.0 is one of the most widely used free energy simulation programmes in the world developed by the US Government's Department of Energy Efficiency and Renewable Energy (EERE). The software can be used to estimate heating, cooling, lighting and ventilation energy loads based on user-defined hourly or sub-hourly simulations. One of the main applications of the software is to analyze the thermal behavior of buildings and assess different alternative envelope solutions. Although several studies exist, we cite [51], about evaluating the optimal thermal insulation level for year-round heating and cooling in a tropical climate, and [52], about upgrading a glass facade in a data center. EnergyPlus was also used to determine the dynamic thermal and cooling loads of a studied building, e.g., in [53], while in [54], parametric simulations were conducted to assess the energy-saving potential for cooling at higher indoor air velocity values. Another application line considers not only the energy performance of the building but also thermal comfort aspects, as the software allows for calculating commonly used thermal comfort indices in both European and American contexts. An initial study aiming to connect energy demand with the level of indoor thermal quality was presented in [55], later expanded to various comfort conditions and the presence of an actual air conditioning system in [56]. The software was utilized to simulate the energy demand and thermal comfort conditions of passive solar houses [57] and for the analysis of summer thermal comfort in residential buildings [58]. Within the realm of building–system interaction, we find the study [59]. In this study, EnergyPlus 23.2.0, as in many others, is coupled with the optimization software GenOpt 3.1.1. The resulting scenario reveals widespread use of the software for estimating environmental heating and cooling needs, often in conjunction with parametric studies. However, its utilization for estimating energy demand and building–system performance is limited, especially when transitioning from parametric simulations to real case studies. Simulating heating, ventilation, air-conditioning (HVAC) systems proves to be considerably complex and has been addressed in only a few instances, primarily for detailed study purposes.

3.7. Invert/EE-Lab

Invert/EE-Lab was employed by national and local public authorities to evaluate the effects of different policy packages on total energy demand, energy carrier mix, CO_2 emissions reductions and costs for space heating, space cooling, hot water preparation and lighting in buildings. Different sets of national policy packages on the refurbishment of the existing building stock have been developed in close cooperation with national stakeholders as well as policymakers. Overall, the Invert/EE-Lab model was applied in more than 35 research projects [60]. Of those selected, on behalf of the European Commission, Invert/EE-Lab was applied to analyze the current and future (2020–2030) heating/cooling fuel deployment in the residential sector for all EU-28 countries (plus Norway, Switzerland and Iceland). The model was used particularly to derive useful energy demand for space heating and cooling in the residential sector of all analyzed states at present and to evaluate the effects of policies on useful and final energy needs.

The project progRESsHEAT (Fostering the use of renewable energy for heating and cooling) supported an in-depth analysis of six local authorities from six EU countries, namely Ansfelden (Austria), Litomerice (Czech Republic), Herten (Germany), Helsingor (Denmark), Matosinhos (Portugal) and Brasov (Romania).

Within the project ENTRANZE (Policies to ENforce the TRAnsition to Nearly Zero Energy Buildings in the EU-27), the Invert/EE-Lab model was applied to simulate the scenarios of development of the building stock and its energy demand in the EU-27 up to 2030, thus enabling the design of policy packages on the refurbishment of existing building stock in cooperation with national stakeholders and policymakers. Overall, nine countries (Austria, Bulgaria, Czech Republic, Finland, France, Germany, Italy, Romania and Spain) and the EU-27 group were broken down.

3.8. Simstadt

This software was used in many works and scientific studies, which have addressed (or aim to address) decision makers at regional and urban scales. Afterwards, some of those application case studies will be presented. The work by Bao et al. 2020 [61] assesses energy potential from natural land cover types and converts it into biofuels for thermal and electrical energy. The study includes two test cases in Germany, indicating that the current utilization of bioenergy potential is lower than its capacity. The workflow complements an existing simulation platform focused on urban energy demands. This other study [62] presents a new workflow for assessing regional bioenergy potentials and their impact on water demand. The workflow utilizes GIS-based land use data, satellite maps of crop and soil types, and biomass-to-bioenergy conversion factors. The energy potentials obtained refer to two case studies in rural and suburban areas of Germany. In the ongoing SimStadt 2.0 development, significant progress has been made by linking heat demand calculations with heat supply models. This novel development was put to the test in Mainz, Germany, focusing on a district comprising 65 buildings, as reported in the study by Weiler et al. [63]. The objective was to compare the technical and economic aspects of two types of energy network system.

3.9. Urban Modeling Interface (UMI)

This tool, called the Urban Modeling Interface (UMI), was applied in several urban-level simulation projects. In Table 2, the most important documented applications for the year of 2020 are presented, both developed at MIT (the developers) or with other partners worldwide. To explore further applications, please visit the website found at [30].

Table 2. Most important documented applications for the year of 2020 of the tool Urban Modeling Interface (UMI).

Year	Project Name	Authors	Location	Focus Area
2020	Toward a more sustainable Munich	Zach Berzolla, Niall Buckley, Claire Holley and Tristan Searight	Munich	Energy efficient and resilient cities
2020	South Chicago Masterplan	Yu Qian Ang, Jakub Szczesniak, Tessa Weiss and Moulshree Mittal	Chicago	sustainable, diverse and livable
2020	Zero Island	Mariana liebman-Pelaez, Hadley Piper, Ramon Weber and Elizabeth Young	San Francisco	low carbon, resilient energy and mobility
2020	Rooftop Wonderland	Eakapobh Huang Hanapan, James Kallaos, Shide Salimi, Pablo Taddei and Sara Toepfer	San Francisco	resilient, cost effective and healthy
2020	Chicago 2	Benjamin Tasistro-Hart, SungHwan Lim and KuanTing Chen	Chicago	efficient, connected and resilient
2020	Low-Carbon Climate Adaptation Strategies for Paris Center	Ruoyu Lan, Sacha Moreau and Olivier Faber	Paris	efficient, connected and resilient

3.10. Apache

Although this tool is oriented to buildings, it had several applications at urban scale. Afterwards, the most important of them were documented. First, an urban analysis for the redevelopment of the ZAC Gare des Ardoines brownfield site in Paris is mentioned. The study included a solar analysis to assess the heat island effect and a wind exposure study to understand airflow distribution. The project aims to redevelop the site by 2040, focusing on reducing emissions, fighting energy poverty, promoting energy conservation, developing renewable energy, and adapting to climate change. In this further application, IES Consulting assessed the suitability of proposed canopies for providing shade and comfort to external seating areas in a mixed-use development. Detailed external airflow analysis was conducted, considering solar conditions, temperature, surrounding buildings, and wind measurements. Simulation results determined the percentage of the year when the canopies would offer sufficient cooling without additional measures. IES Consulting recommended incorporating retractable features to counter the changing angle of the sun's influence. The analysis also considered the cooling effect of vegetation and waterbodies. The Aran Islands Energy Co-Op is working towards decarbonizing the islands by generating their own electricity. Integrated Environmental Solutions (IES) supports them with a research study using ICL Digital Twin technology for a microgrid. Inishmore, with a population of 800–900, is a pilot site for peer-to-peer trading of locally sourced renewable energy. The community aims to reduce reliance on carbonized energy and minimize electricity loss during transmission. IES conducted a detailed field survey and created an energy simulation profile to optimize energy demand. The Digital Twin model provides a baseline for energy demand and allows hypothetical scenarios for planning ahead, including retrofits and the establishment of a microgrid enable energy sharing and storage. Finally, in this application, an energy feasibility study for the regeneration of Queens Quay in Clydebank, Glasgow was conducted. The focus was on the potential for a Water Source Heat Pump system using renewable energy from the River Clyde. The study assessed heating, cooling, and hot water demands of existing and proposed buildings, considering future climate scenarios. The findings supported the implementation of a water-sourced district heating system, securing funding for the project. The proposed Energy Centre has received planning permission, contributing to Clydebank's sustainability goals.

4. Discussion

After gathering all the needed information in the previous sections, a comparative analysis is conducted. Table 3 shows an analysis of the main features of the listed tools, including the total number for each one. It shows that while many tools offer energy demand mapping, scenario development, and user-friendly interfaces, fewer provide specialized analyses like renewable energy sources analysis and economic viability analysis, despite being an important variable today [63]. Notably, certain tools are specifically designed with public authorities and urban planners in mind, indicating their targeted application areas. The presence of functionalities like CO2 emissions analysis and energy efficiency analysis across multiple tools underscores the sector's focus on sustainability and environmental impact reduction. The variation in tool capabilities suggests a broad spectrum of use cases, from detailed urban planning to broader policymaking and energy system analysis, catering to different user needs and expertise levels.

Table 3. Summary of the analysis of the tool’s main feature for the Assessment of the European Building Stock Energy Demand on Space Heating and Cooling.

Functionality	**Hotmaps Toolbox**	**PlanHeat**	**THERMOS**	**Europe 4 Heat Roadmap**	**CitySim pro**	**City Energy Analyst**	**TEASER**	**EnerMaps**	**DREEM**	**IDA ICE**	**EnergyPlus**	**Invert/EE-Lab**	**CityBES**	**SimStadt**	**UMI**	**Apache**	**EMB3Rs**
Open Source	x	x	x	x	x	x	x	x	x	x	x						x
Commercial License												x	x	x	x	x	
Energy Demand Mapping	X	x	x	x	x	x		x		x	x	x	x	x	x	x	x
Scenario Development	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Renewable Energy Sources Analysis	x	x		x	x	x					x		x	x	x		x
Economic Viability Analysis		x		x		x						x	x	x	x		
CO2 Emissions Analysis	x			x		x						x	x	x	x		
User-Friendly Interface	x		x		x	x	x	x	x	x		x	x	x	x	x	
Energy Efficiency Analysis	x		x	x	X					x	x		x	x	x	x	
High-Resolution Energy Mapping	x		x														
Modular Structure	x		x						x	x							x

Demand-Side Management Evaluation									x								
Targeted at Public Authorities	x	x	x	x				x				x					x
Suitable for Urban Planners	x		x		x	x	x			x			x	x	x		
Total number of features	9	5	8	7	6	7	3	4	4	6	4	6	8	8	8	4	5

Moreover, it has to be pointed out that available tools are nowadays more focused on showing energy demand due to space heating of buildings. The increasing importance of space cooling strategies in the overall energy balance, partly due to climate change, is pushing researchers in analyzing with more detail the space cooling demand. The present analysis has identified three major issues related to the existing tools for the analysis of space heating and cooling demand and the simulation of future scenarios. None of them seems to be addressed properly. These issues are:

- There is a general lack of information about the methodologies and assumptions behind the presented datasets; as a consequence, the users experience the absence of publicly accessible comprehensive data regarding the assumptions and input data, as well as the underlying algorithms of the methodology used;
- When building a simulation scenario, there is a lack of publicly accessible information regarding the relative impact of input parameters to be set by the user;
- In specific cases, too much technical information could decrease the user friendliness of the tool, reducing the possibility of being used by a non-proficient audience; on the other hand, the multi-disciplinarity of the datasets included (e.g., energy, emissions, health, comfort, user-behaviour, costs) is important to generate comprehensive assessments and include synergy between engineers and public authorities.

Overall, a comparative analysis of existing tools and conditions for further development can be performed, by stressing three main intertwined dimensions: usability and transparency, access to the tool and success in real applications. Broadly speaking, literature acknowledges limitations on how much technological detail can be incorporated without running into computational and other issues in simulation tools. However, regarding usability and transparency, it can be pointed out that the simplicity of use (and compatibility with other software) positively encourages real applications of the tools, although all tools are addressed both to a technical (planners, researchers) and nontechnical public (local authorities). In specific cases, such as for TEASER, documentation for users was not user-friendly, with a lack of examples and/or simple handy screenshots of the tool's usage for non-proficient users. The absence of easy-to-use documentation and incomplete manuals is a strong disincentive to using the tool, making it a "black box". It has been claimed that municipalities do not need details on the underlying methodologies relatively to scenario assessments and effective policy implementation. Looking at the experience of Hotmaps, it has been observed that several territories, such as the City of Geneva, have more precise data (based on real data) than those offered by default on the Hotmaps platform, which are obtained by the process of modelling the territory. This was due to the process of rasterization (superposition) of OCEN (Office de l'énergie du Canton de Genève) data on the Hotmaps platform for the territory of the city of Geneva. Eventually, it may happen that local data are often preferred, also for the calculations.

The transparency in the user manual has been generally found to be a key success factor for the diffusion of PlanHeat. In this case, the documentation provides a list of available data, with a short description of them, together with the indication of the available time span. Furthermore, it is possible to use the PlanHeat database outside of the tool through the Client API (available as Python package). Moreover, a thorough documentation has been found for EnergyPlus, which provided manuals about "Getting started", "Interface Developer", "Module Developer", "Tips and Tricks" and "Output Details and Examples" to guide the user from scratch. Regarding THERMOS, the relative code is open-source, and based on a fully documented modelling method. It is agile, in the sense that there is only one model to be employed to solve different critical aspects (locations, energy supply mix, network flow/return temperatures, plant efficiencies, tariffs, etc.). All stages of the analysis are provided in a single web-based application, facilitating openness and allowing shared work among consultants, technicians, clients, and other stakeholders.

Major limitations were found and transparently documented by City Energy Analyst (CEA). First, the presence of several bugs depends on local data, mainly due to the fact that the tool is based on academic work and contributions by a wide set of users. Secondly, the first version of CEA V1.0b was only valid for the European context, so users are advised to create their own database based on local measurements, buoying a number of reliability risks with a lack of control of added data. Another development factor could have been to calibrate the tool with sensor data while implementing more advanced models for air ventilation and occupancy. Additionally, the project presented a limited analysis of alternatives for energy generation, thus neglecting economic and technical restrictions on infrastructure design and operation and lacking the possibility of "horizontal" energy policy recommendations. The paper by Monien et al. 2017 [63] reports that the SimStadt tool provides an automatic calculation (static energy balance) of heat demand at urban scale as well as at single building scale (scalability without loss of accuracy because of batch processing). For data input preparation, the tool provides detailed building geometry models while requiring only a CityGML file with information about building age and building usage.

Lastly, the modular-based system modelling approach has been found as a key driver of the tool's success, as in the case of DREEM. Flexibility in terms of possible system configurations and computational efficiency towards a wide range of scenarios is crucial, allowing to study different aspects of end-use energy (demand-side management).

Regarding access of the tool and sustainability of outcomes, many differences have been found. While open-source tools ensure wide dissemination of data, a significant plus of the commercial tools is the validation of all the procedures related to the development of new scenarios according to the updated standards and norms.

Regarding real application cases, in the previous section it has been reported that THERMOS and the Hotmaps Toolbox stand out from the others. In fact, they obtained a lot of effective applications, both in energy planning and in research activities. This is probably also due to the completeness of feature offered (with respect to the other open source-software), as described in detail Table 3.

5. Conclusions

This study has listed, described and analyzed the most widespread tools for the visualization of energy demand data for space heating and cooling at building, district, city, and regional/national scale; eleven open-source and five commercial tools were presented in detail. Afterwards, their real applications are investigated, in order to map their effective use. Among the analyzed tools, several resulted to have the possibility to include the development of new scenarios for future planning, with a multidisciplinary approach: energy, economic, environmental variables are included in most of the cases.

After the investigation of real use, a comparative analysis was performed, which has pointed out the most important lacks that those tools have: the general lack of transparency on the methodology and assumption on the datasets, the difficulty to find the perfect balance between the readability of data by nonproficient users and the coexistent necessity to tackle the multivariable problem of building a new energy planning scenario. The study covered a missing piece in the literature dedicated to this topic and is relevant for the user and developers of new space heating and cooling simulation tools.

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