COST Action 19126

Positive Energy Districts European Network

Deliverable 2.1

Report on existing technical PED guides and tools

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Executive Summary

The goal of the deliverable of Task 2.1 is to create a collect and review existing technical tools related to the design, planning and operation of PEDs.

The main goal was to provide pointers for tool selection and categorization for both researchers and practitioners designing, planning and operating PEDs.

The work below summarizes the work done between 11/2020 and 11/2021 on the collection and categorisation of technical tools. As the field is an emerging and dynamic one, it should be noted that this collection of tools reflects the the situation as of 10/2021 and will be worked on continuously.

The document is made up of the following parts:

Definition of technical tools: Definition of tools used for PED implementation, and definition of technical tools as a subset of tools used for PED implementation.
Collection of technical tools: Collection of technical tools from the literature and from expert knowledge. Relevant tools are collected and given a short introductory description of the most important features for researchers and practitioners.
Framework and characterisation of technical tools:
Most important factors and features for choosing tools are defined and described. Collected tools are categorised according to the described features. Finally, a preliminary framework of tools is presented.

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Tartalom

1. Introduction

1.1 Short introduction to PEDs based on literature.

Positive energy districts (PEDs) are urban areas where the annual energy demand is fully covered by the inside energy generation (renewable and zero-net produced energy). It required minimizing energy demands, and smart systems for generation and distribution of energy. PED is connected to the regional energy system but has the intention to be independent. Lindholm et al. (Lindholm, Rehman and Reda, 2021) determined the PEDs as autonomous, dynamic, and virtual. They defined autonomous PED as district with strictly defined system boundaries that does not allow import of energy and at the same time the district can export the surplus energy generated from renewable energy sources. The dynamic PED is not isolated from other PED or surrounding energy grids to interact with energy import/export, but the sum of annually generated energy must be bigger than the total annual energy demand. Finally, the PED that includes virtual renewable energy sources and energy storage located far from PED physical boundaries, and its energy generation is higher than the energy demand is defined as virtual PED. There is not a determined source of electricity. Whether the electricity is generated from non-renewable or renewable energy sources is not given precisely. However, the requirement for the use of renewable energy sources logically determines the source of electricity as energy generated from renewable energy sources.

The meaning of Positive Energy District is defined in different ways according to the boundaries and elements involved in the urban system. The Urban Europe (Gollner *et al.*, 2020) defines PED as "*Positive Energy Districts are energy-efficient and energy-flexible urban areas which produce net-zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require the integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while optimizing the livability of the urban environment in line with social, economic and environmental sustainability.*" Similarly, it is defined as "PEDs require interaction and integration between buildings, the users and the regional energy, mobility, and ICT systems, as well as an integrative approach including technology, spatial, regulatory, financial legal, social and economic perspectives. Ideally, PEDs will be developed in an open innovation framework, driven by cities in cooperation with industry and investors, research and citizen organizations" (Clemente, Civiero and Cellurale, 2019a).

One of the key questions regarding PED is how some districts can become a Positive Energy District. Many procedures are developed for that purpose. According the Urban Europe (Gollner *et al.*, 2020), designing of PED is not only input and output of energy. It is a framework that include the three most important functions of urban areas within their urban and regional energy systems (see Figure 1). The first important function is energy production based only on renewable energy sources. The second one is the most efficient utilization of produced energy (energy efficiency). And the third important function is the energy flexibility – optimal act of consumers for beneficial energy systems.

Energy efficiency function – is considering the optimal reduction of energy consumption inside PED with balancing energy needs of different sectors.

Energy flexibility function – resilience and balancing of the regional energy system with demand management, coupling and storage.

Energy production function – local and regional production of renewable energy. That includes optimal reduction of Green House Gases and economic viability. In addition, all these depend on the local conditions and transformation paths.

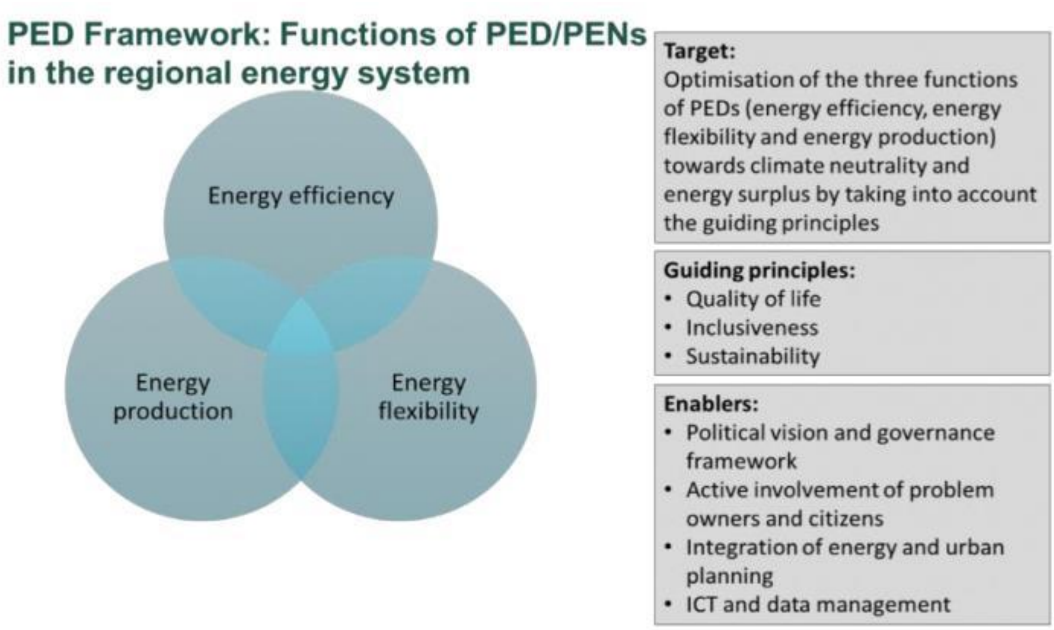

Figure 1. Functions of PED in the energy system (Bossi, Gollner and Theierling, 2020)

Clemente et al. (Clemente, Civiero and Cellurale, 2019a) completed information for PED development based on previous PED projects. They compared steps in the PED development pathways (Figure 2). There are four steps such as PED labs, PED guides and tools, PED replication and mainstreaming, and PED monitoring with evaluation.

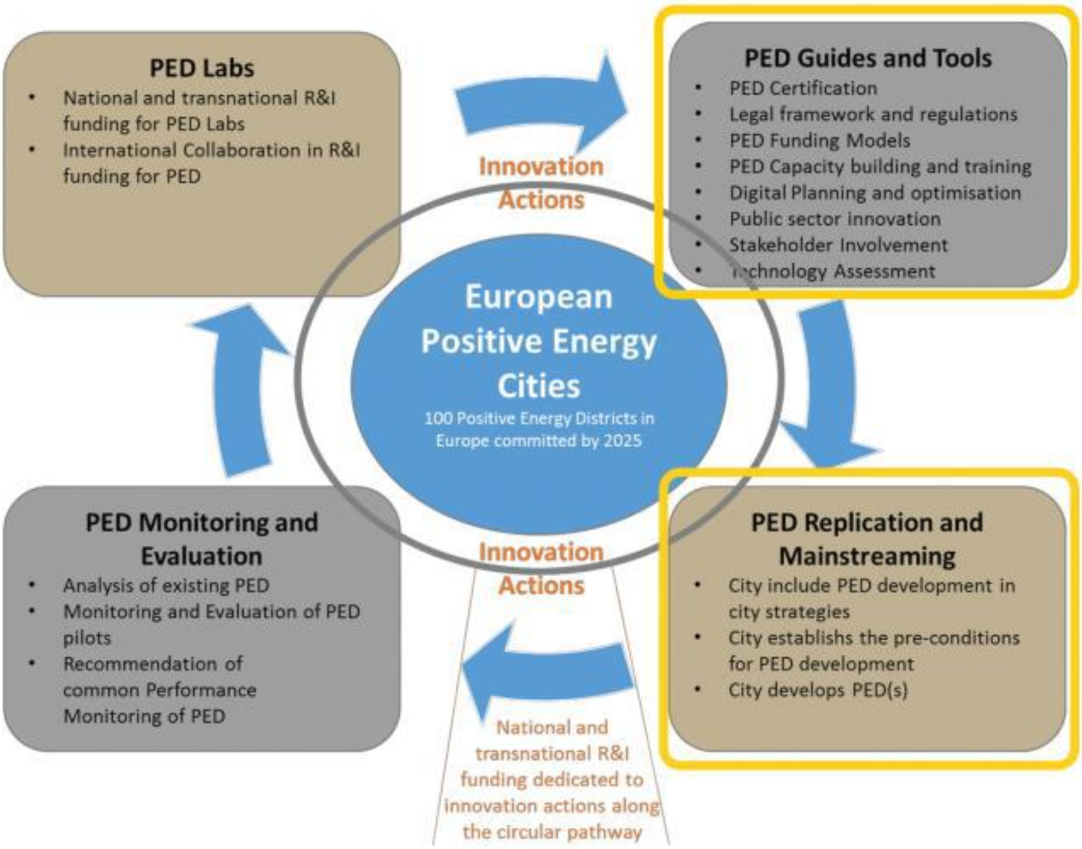

Figure 2. PED pathways based on SET-Plan ACTION No. 3.2

Moreno et al. (Moreno *et al.*, 2021) proposed methodology for calculation of PED based on eight steps – determination of PED boundaries (step 1), calculation of the energy needs (step 2), calculation of energy usage (step 3), on-site energy generation (step 4), estimate the energy delivery (step 5), a series of iterative steps for calculation of the equivalent primary energy (step 6), the primary energy balance (step 7), and the associated Sankey diagram (step 8)

1.1. Structure and main research questions:

Main objective is to scope existing technical and non-technical guides and tools, which can support the design, planning and operation of PEDs.
Create a base for the framework that can identify gaps in existing guides and tools and initiate framework for the development of new guides and tools to fill these gaps.
This document will create a basis for the future work, where the aim is to create a framework, which empowers stakeholders to identify the tools and guides best suited for them at certain life cycles of the project.
This is important as the government's role is defined in the paradigm shift in urban energy systems as creating the underlying conditions in the market in a way that all participants will take decisions not just based on their own, but also on the general public's interest. Furthermore it is also known, that in a liberalized energy market, the success of a new paradigm is strongly attached to market competitiveness and not only on environmental and energy performance of the competing options (Manfren, Caputo and Costa, 2011). Some of the capabilities of these tools (i.e. benchmarking, validation etc) encourages transparency (Perez-Lombard *et al.*, 2009) and where transparency increases, trust and investments tend to increase as well (Kanagaretnam *et al.*, 2013).

The document will be structured in the following in the following chapters. For every chapter, the research question and a short description of the content is given:

Chapter 1.2 :

How to define relevant technical and non-technical guides and tools for design, planning and operation of PEDs?
A clear definition on technical and non-technical tools for design, planning and operation of PED is desperately needed. In this chapter a definition for technical tools is proposed based on literature review on existing definition and expert knowledge.

Chapter 1.3 :

What are the existing guides and technical tools?
In this chapter tools and guides are collected fitting the previously described definition. The collection is based on available literature and expert knowledge from the action participants.

Chapter 1.4 :

How to categorize the existing guides and technical tools collected from literature?
Existing literature frameworks need to be categorized in a way that will let the actual stakeholders help to make decisions. Most important factors of technical tools are chosen and described.

1.2. Definition of technical tools for PEDs

Review of existing definition on technical tools for PED

Available definition of a tool varies largely among sources in academia. Most definitions describe tools as something used for carrying out a particular function. To make it clear what are the technical tools that fit the description, an effort is made to define tools and technical tools for the sake of the current deliverable.

Oxford languages describes tool as a „device or implement, especially one held in the hand, used to carry out a particular function", while Merriam-Webster defines tool as „ an element of a computer program (such as graphics application) that activates and controls a particular function. Macmillan dictionary defines tool as „ something that you use in order to perform a job or to achieve an aim" while Oxford collocation dictionary defines as „sth that helps you do/achieve sth". It is also worth looking at the definition of a synonym for tools i.e contrivance is best defined as „a thing which is created skillfully and inventively to serve a particular purpose".

Common thing between these definitions is that a tool is used by someone (actor) to carry out or perform a job or activity (act). Hence it is clear, that by definition a tool is best described by two things: the actor that can utilize it, and the act it can help to carry out or perform.

In the available academic literature, there are also attempts to characterize technical tools. Nielsen et al. (Nielsen, Baer and Lindkvist, 2019) defines the meaning of "tool" as "device or an implementation used for carrying out a particular function". They analyzed "smart city" projects for seven Norwegian cities. According to their research, Nielsen et al. (Nielsen, Baer and Lindkvist, 2019) divided tools as *explorative* and *exploitative* innovation process tools.
Exploratory innovations are closer to socio-economic factors such as visions (citizen knowledge, citizen expectations, citizen engagement, social visions, mobility, visualization of energy use, multiple energy scenarios, feeling of safety, integrated and cross-disciplinary ideals, political visions and promises, collaboration focus, participatory approaches) that can be implemented with usage of exploitative innovations.
Exploitative innovation is built on improvement, refinements, efficiency, and implementation of current skills and processes in organization. It has an incremental character and focuses on the needs of existing customers and leads to incremental product changes (*Dictionary Search | IGI Global*, no date) (Exploitative innovation, although profitable, is subtle and incremental in nature and the risk involved in this approach of innovation is limited. For example, most companies update or innovate within the services or features of the products that already exist in their portfolio, for example, Coca Cola, Cadbury, etc.)
Exploratory innovations respond to and affect latent environmental trends through creating new products or services and new markets. It deals with offering innovative designs and creative ways to satisfy customer and market needs (*Dictionary Search | IGI Global*, no date). (For example, development of a distribution channel that is new to the market is a form of exploratory innovation).

Exploitative tools included planning and building activities, documentation, property regulation, climate and energy strategy, tools for calculating impact, technical requirements for buildings, sound shadow modeling, Norwegian standard, application procedures, localization. *Explorative* tools are determined as scenario building tools, simulation tools, stakeholder workshops, better integration of energy into urban planning, visualization, experience, incremental learning, and buildings that facilitate sustainable behavior. Nielsen et al. (Nielsen, Baer and Lindkvist, 2019) selected and grouped all identified tools (Figure 3).

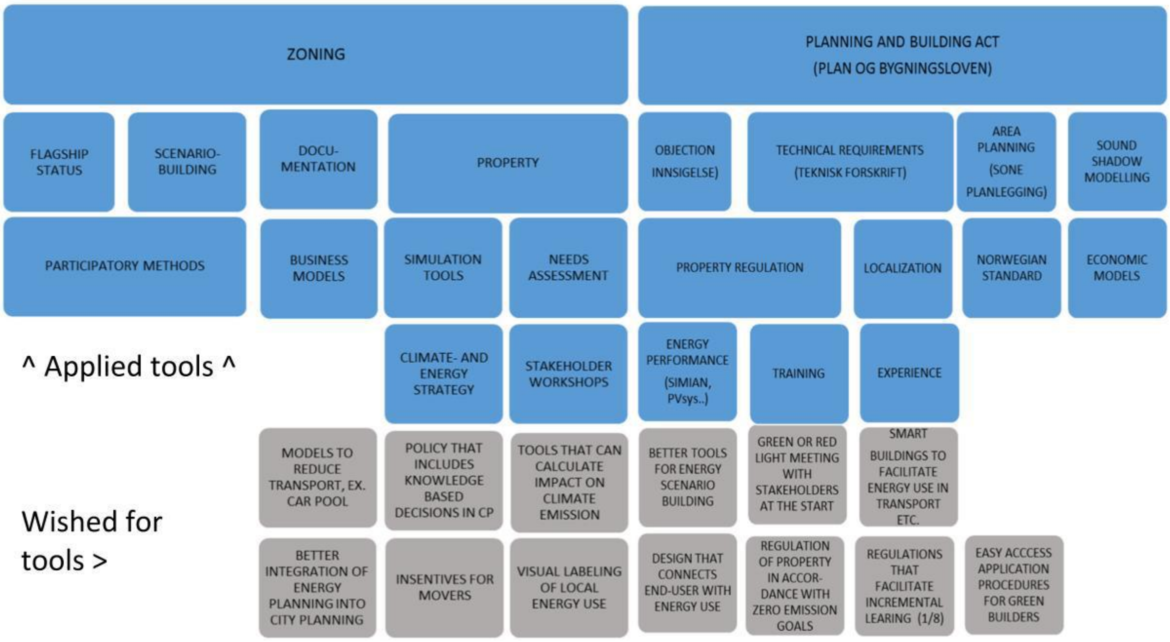

Figure 3. Tools of importance for the planning of energy ambitious neighborhood pilots (Nielsen, Baer and Lindkvist, 2019)

Rehman et al. (Rehman *et al.*, 2019) described mathematical models and software for simulation and optimization as technical tools in the design and analysis of the system.
Clemente et al. (Clemente, Civiero and Cellurale, 2019a) determined different areas and key-tools that should be involved in the transition of smart cities into PED. They determined the eight areas given in Figure Figure *4.*

Table 2: SCC Solutions areas of Urban Dilemmas. Implementation of solutions/services according to [11,12]

			Key tools/technologies answer in areas
	Areas	**Class of solutions**	**Solutions**
1	**Safety & Security**		real time crime mapping smart surveillance body worn cameras disaster early warning systems predictive policing emergency response optimization crowd management building security and safety system personal alert applications gunshot detection data driven building inspections
2	**Health**		telemedicine online care search and scheduling real time air quality information infectious disease surveillance lifestyles wearables remote monitoring applications and medication adherence tools data based population health interventions first aid alerts integrated patient flow management system
3	**Education**		e-learning platform augmented reality tools building automation simulator Education&Training platforms energy management awareness real time behavioral impact personalized education applications open data/data management platform
4	**Mobility**	sharing/ e-hailing/ autonomous driving	private e-hailing bike sharing car sharing autonomous vehicle pooled e-hailing demand-based micro transit traffic management and data services real time road navigation
		traffic management and data sharing	real time road navigation integrated multimodal info digital payment in public transit intelligent traffic signals and vehicle preemption real time public transit info smart parking predictive maintenance of transit infrastructure congestion pricing
		urban cargo	smart parcel lockers parcel load pooling and urban consolidation centers

	Areas	Class of solutions	Solutions
5	Energy		distribution automation system dynamic electricity pricing building energy consumption tracking smart streetlights building automation systems building energy automation systems
6	Water		leakage detection and control water consumption tracking water quality monitoring smart irrigation
7	Waste		waste collection route optimization digital tracking and payment for waste disposal
8	Economic Development Housing and Community		local connection platforms peer to peer accommodation platforms digital administrative citizen services local civic engagement application local e-career center online retraining programmes

Figure 4. Key-tools for determined areas of smart cities transition to PED (Clemente, Civiero and Cellurale, 2019b)

With the help of these defined areas, the task of categorizing tools can be reduced into categorizing the above mentioned areas into technical and non-technical subgroups. This can be useful for further definition of technical and non-technical tools. This work also poses the question whether the categorization of technical and non-technical is fit enough to describe the range of tools used for PED creation.

According to the analyzed articles related to the meaning of technical tools used for PED, can be suggest the following definition for technical tools and technical tools for PED.

Technical tools are physical or virtual devices that use various methods or methodologies which usage is based on the physical and chemical properties of analyzed systems for easier and faster solution of a certain problem.
Technical tools for PED are physical or virtual devices that use various methods or methodologies which usage is based on the physical and chemical properties of analyzed objects or systems for the purpose of PED creation.

1.3. Review of existing technical tools for design, planning and operation of PEDs

In the following sections tools that fit the technical tool description were identified. The collection of these tools is based on previous literature reviews and professional knowledge of COST action participants.
At the current stage both tools that are market ready and already in use by professionals, and also the ones that are more experimental were considered. The latter will be referred as “pre-tools”. These are mostly important for researchers and research purposes, while the other set of tools is important for both the academia and professionals.

Collection of available market-ready tools:

Performance design tools (multiple scales):

Modelling the energy flows in a building or a neighbourhood is an essential task to plan resource usage.
To model the complex effect of energy flows and other influencing factors in PEDs it is not sufficient to use the tools made to analyse energy flows on building level. It is well researched, that there is a need for tools and approaches to have a better understanding of the optimum combination of building and area specific measures and interchange of energy (Monti *et al.*, 2017)
Thus urban energy modelling considering not just energy flows inside of a building, but multiple buildings and other standalone energy con- or prosumers. The literature differentiates the modelling tools capable of modelling complete energy flows in a city considering both supply and demand side, and also infrastructural elements. These Urban Scale Energy Modelling (USEM) tools often comprise of multiple smaller sub-models (Sola *et al.*, 2019) dealing with wide array of issues like mobility, energy generation, energy demand of buildings.

Intelligent Community Design (iCD):

iCD software of the platform Integrated Environmental Solutions (IES) allows to perform and visualize analysis of energy consumption, water use, solar and other renewables potential, and integrate simulation results with recorded and measured data. The integration of iCD as plugin of the design and modeling software SketchUp permits the energy design at the district scale to be included from the early stages of the architecture and urban design process (*Intelligent Community Design (iCD) | IES*, no date).

Insight:

Insight is a building performance analysis tool developed by Autodesk to be used inside the BIM software Revit. It allows to perform dynamic thermal simulations on single and multiple buildings, making it suitable also for PED design. Additionally, it can perform solar, daylight and electric lighting simulations. The integration in the BIM environment permits the designer to create an energy analytical model and to compare the performance of different design solutions and constructions against selected performance indicators, including costs, through an interactive interface. (Section, Mechanics and Section, 2015)
https://www.autodesk.com/products/insight/overview

Umi:

Urban modelling interface (UMI) has been developed by the Sustainable Design Lab of the MIT (Reinhart *et al.*, 2013). This software allows for energy and daylight modelling at the neighbourhood and district scale using the simulation software EnergyPlus (*EnergyPlus*, no date) and Radiance (Ward, no date) through processes optimized for a large number of buildings inside the architectural modelling environment of Rhinoceros. Additionally, the software allows for LCA analysis and walkability and bikeability assessment of the district under study. Demand calculation happens with an energyplus solver, custom weather files can be generated with an approach called UWG. This software is able to produce output data from yearly to hourly resolution.(Reinhart, Christoph F *et al.*, 2013)

Sefaira:

This plug-in integrates daylight, whole energy analysis, carbon emission and thermal comfort with architectural and urban modeling in the software SketchUp. It allows the creation of simple yet useful infographics for architects and planners to chose the most performative design strategies for the task at hand. Energy, carbon, daylight and HVAC simulation results are evaluated against metrics and thresholds derived from scientific literature(*Energy Efficient Design Software | Green Design | Sefaira*, no date).
https://www.sketchup.com/products/sefaira

ClimateStudio

ClimateStudio (*ClimateStudio — Solemma*, no date) for Rhinoceros (*Rhino - Rhinoceros 3D*, no date) and Grasshopper (*Grasshopper - algorithmic modeling for Rhino*, no date)allows to integrate architecture 3D modeling with energy and daylight simulations, renewable energy assessments through photovoltaics performance and embodied energy analysis. The suitability of the tool for design at the district scale is due to optimized processes of the simulation software EnergyPlus and Radiance(*ClimateStudio — Solemma*, no date).
https://www.solemma.com/climatestudio

Ladybug Tools

A large quantity of tools is available in the suite Ladybug Tools (Roudsari and Pak, no date), a plug-in for Grasshopper, for climatic analysis, solar and renewable energy design, daylight and thermal modeling, HVAC design, indoor and outdoor thermal comfort. Though specialized on the building scale it can be applied also to group of buildings at the block and neighborhood scale. It performs simulations through external validated software such as EnergyPlus and Radiance. The plug-in Butterfly of Ladybug Tools permit also to perform wind simulations at the district scale through the validated software Open-FOAM (*OpenFOAM*, no date). The simulation results are evaluated against the most advanced key performance metric(*Ladybug Tools | Home Page*, no date). https://www.ladybug.tools/

Dragonfly (Ladybug Tools)

The tool Dragonfly is a plugin for Rhinoceros/Grasshopper which allows district energy modeling through the software URBANopt and the simulation engine OpenStudio. Thus Dragonfly allows to integrate the analysis of the interactions between buildings energy use, distributed energy resources, energy systems at the district scale and the distribution grid with architecture and urban design, parametric design, design exploration and optimization at the neighborhood and district scale(*GitHub - ladybug-tools/dragonfly-core: dragonfly core library*, no date). https://github.com/ladybug-tools/dragonfly-core

Eddy

The tool Eddy (*Eddy3D - Airflow and Microclimate Simulations for Rhino and Grasshopper*, no date)performs wind pedestrian comfort and outdoor thermal comfort analysis in Grasshopper using simulations of wind patterns and velocities through the validated software Open-FOAM(*Eddy3D - Airflow and Microclimate Simulations for Rhino and Grasshopper*, no date). https://www.eddy3d.com/

Morpho

The Grasshopper plug-in Morpho permits to connect ENVI-met (*ENVI-met - Decode urban nature with Microclimate simulations*, no date)(https://www.envi-met.com/) , the state-of-the-art software to simulate energy exchanges and microclimate in urban environments and outdoor thermal comfort, with architecture and urban design parametric models (*GitHub - AntonelloDN/Morpho: A plugin to create Envimet 2.5D models (INX), write configuration files (SIMX) and run simulations*, no date). https://github.com/AntonelloDN/Morpho

CityBES

The City Building Energy Saver is a web-based platform created by Hong et al. It works with its very own CBES toolkit that can generate output data up to sub-hourly resolution. Since it is an online platform, it's computational ability is the same wherever it is run. With its parallel computing architecture CityBES can model more than 10000 buildings and identify deep energy savings up to 50% with multiple pre-programmed energy conversion measures. Energyplus engine is utilized to calculate demand, and it is visualized with the help of Openstudio. (Hong *et al.*, 2016)

UrbanOPT by NREL

Web based tool created by the National Renewable Energy Laboratory (NREL). Urbanopt uses energyplus engine with Openstudio gui to visualize the output results. It heavily relies on the pre-existing Openstudio measures and it's backup database called DEnCity database. While iterating each design solution they are translated into Openstudio measures. Thus the models are created as a chain of Openstudio measures. Furthermore with utilising the DEnCity database, if a simulation has already been run for a building, the database can just give back the existing results and save computation for the user.(Polly *et al.*, 2016; Kontar, Polly and Charan, 2020)

COFFEE

Customer Optimization For Furthering Energy Efficiency or COFFEE is also an Openstudio and energyplus based tool to perform optimization based calibration against monthly utility bills. This tool has the capability to evaluate multiple ECMs (Energy Conversion Measure). COFFEE uses commodity cloud computing resources such as Amazon's Elastic Compute Cloud (EC2) hence it is able to quickly evaluate multiple buildings. The workflow for constructing a model consists of both Openstudio measures , and measures from NREL (from specific NGrid enterprise systems) with also pre-defined archetypes defined in North American Industry Classification System (NAICS) and HVAC systems by ASHRAE 90.1. From these measures, a baseline model is constructed, and then it is calibrated against real monthly consumption data. The system optimization happens in line with the ASHRAE 14 guideline. Much like in the previous example COFFEE also has a NoSQL database, where the already run ECM analysis results are stored to make it the reruns reconstructable and quicker. COFFEE was developed to provide help in the utility energy efficiency programs. It can be used to define incentives for different ECM measures and to optimize marketing expenditures this way.(J. Brackney and NREL, 2016)

CitySim.

CitySim has been developed from the SUNtool with a java based GUI. Citysim uses an RC thermal model (Lefebvre, 1997) that was refined by (Nielsen, 2005)and the simplified radiosity algorithm radiation model from SUNtool. Deterministic rules and profiles are used to describe occupant behaviour in buildings. Outputs can be produced with hourly resolution.(Robinson *et al.*, 2009)

SEMANCO

Semanco is an extensive integrated platform working with the Semantic Energy Information Framework. This platform uses a simulation engine named URSOS for calculating the building or building stock's energy demand. SEMANCO is a platform that uses numerous different submodels and tools to provide a comprehensive tool enabling users to participate in assessing planning maintenance or operation of urban energy system models.(FUNITEC, 2013)

Simstadt

Simstadt couples top-down and bottom-up approaches on 3D cit model CityGML with highly modular and extensible workflow. Energy demand calculation is done here on a building per building basis. Weather data can be obtained via the WFS WeatherProcessor from different databases.(Nouvel *et al.*, 2015)

LakeSIM

LakeSIM is a tool capable to model the short and longterm effects of interdependencies between major infrastructural systems while allowing users to visualize the modelled urban environment. This tool is used to facilitate the design of a US based brownfield development.
It uses CityEngine to allow users to reach and edit the virtual city representation. For calculating demands, LakeSIM employs a method developed by Argonne named EECalc, based on ISO 13790. Outputs can only be given in monthly resolution. This makes the simulations faster and less computationally expensive. Also simulations can be more easily scalable. LakeSIM is also capable for comparing and analyzing different scenarios.(Bergerson *et al.*, no date)

City Energy Analyst

City Energy Analyst is a complex integrated framework using a single interface connecting a series of detailed sub-models for building demand forecasting, resource availability assessment, conversion simulation, storage and distribution technologies bi-level optimization multi-criteria assessment and four-dimensional visualization.
CEA is built on Python and is an extension to ArcGIS. This offline tool uses 7 different databases and 6 calculation modules (Fonseca *et al.*, 2016). CEA has therefore a pretty woven architecture of these modules and databases. Output resolution can be decomposed

to hourly results at qualitative and quantitative levels. Weather is obtained from Meteonorm 7.0.This platform uses top-down statistical method as well as bottom-up engineering method. For occupant behaviour modelling, a deterministic approach is used. The simulation time of this platform can be rather high due to the somewhat complicated architecture.

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

TEASER has the capability to create full scale building or neighbourhood datasets with minimal data inputs. This is a reduced order modelling tool, so normally it would require full building physics data from the set of modelled buildings and all boundary conditions. However TEASER uses a data enrichment function to complement any missing data. Reduced models can be created in TEASER with two approaches: Either modelling walls with reduced number of RC or at Zone levels with merging several walls into one. TEASER then is able to calculate the parameters for reduced order modelling for AixLib (*GitHub - RWTH-EBC/AixLib: A Modelica model library for building performance simulations*, no date)[https://github.com/RWTH-EBC/AixLib] and IEA-EBC Annex 60 library (*GitHub - ibpsa/modelica-ibpsa: Modelica library for building and district energy systems developed within IBPSA Project 1*, no date)[https://github.com/iea-annex60/modelica-annex60] both in Modelica. The entire tool is written in python and has three packages : a GUI, Logic (data manipulation) and data (data input and output).

Calliope

Calliope is an open source optimisation framework for energy system models based on Python. It can be applied for several sectors (user-dependent) and multiple technologies (renewables, conventional, cogeneration), for a user-dependent geographical and temporal resolution. The objective function is also user-dependent, such as financial cost, carbon dioxide emissions, and water consumption. Calliope can be used for energy planning at various scales, between urban districts and entire continents. Additionally, it can be used for simulating a pre-defined system under different conditions(Pfenninger and Pickering, 2018).

energyPRO

energyPRO is a software used to model energy projects for electricity and thermal energy supply. It can be used for technical and financial analysis of existing and new projects, following a bottom-up approach. energyPRO can be used to model energy systems from a local up to a regional geographical coverage covering the sectors of electricity, heating, and cooling for a temporal resolution of minutes. It is a commercial software(*EnergyPro*, no date).

Oemof

Open Energy Modelling Framework (oemof) is a flexible and generic open-source tool that can be used to model energy systems based on LP and MIP. Geographic coverage, time horizon, and temporal resolution can be user defined. It can cover the sectors of electricity, heating, hydrogen and fossil fuels. Moreover, all technologies (renewables, conventional, storage) can be modelled. Additionally, there is the option for demand response modelling. Energy systems modelling is carried out through the oemof.solph package, which is under the umbrella of oemof and the assessment criteria can be financial, environmental, energy efficiency, and/or social(*A modular open source framework to model energy supply systems*, no date).

MANGO

MANGO (Multi-stAge eNerGy Optimization) is a novel optimization model that incorporates a multi-year planning horizon, and flexible multi-stage investment strategies for the long-term design of decentralized multi-energy systems (D-MES). It follows a dynamic approach where changes in the values of parameters over time, such as the annual energy demands, prices, emission factors, technical and economic characteristics of technologies, and technology degradation are considered. It can be used to design DMES based on the following options: (a) one D-MES installed at each node with no interconnections, (b) one D-MES installed at each node with possible interconnections, and (c) D-MES installed at one or more locations to satisfy end-users at other locations via interconnections. MANGO is formulated as a multi-objective MILP model, with the two objective functions being the minimization of the total energy system cost and of the total CO2 emissions, over the time horizon(Mavromatidis and Petkov, 2021).

Decision support tools:

DER-CAM:

A flexible decision support tool aiming to identify the optimal distributed energy resource portfolio either in buildings or in multi-energy microgrids. It is based on MIP and it produces the optimal capacity of the selected technologies, their operational profiles, the detailed cost breakdowns, and associated emissions. The objective function can be either the cost or environmental criteria. The tool can be used for free, and it offers a sectoral coverage of electricity, heating, and fossil resources. (*DER-CAM | Grid Integration Group*, no date)

GIS-based tool for the identification of PED Boundaries in Cities:

MAKING-CITY project (funded by H2020 n°824418) focuses on a flexible GIS-based Multicriteria assessment method that identifies the most suitable areas to reach an annual positive non-renewable energy balance. For that purpose, a GIS-based tool is developed to indicate the boundary from an energy perspective harmonized with urban design and land-use planning. The method emphasizes evaluation through economic, social, political, legal, environmental and technical criteria and results present the suitability of areas at macro and micro scales in cities.

PED Technologies Selection Tool:

MAKING-CITY developed a methodology for designing PEDs, and one of the phases refers to the selection of the PED technologies in cities that they want to apply. But most of the cities struggle in this decision making-process due to the lack of information of innovative technologies and specially on how they can achieve a positive energy balance at district level, integrating different energy carriers and technologies. A tool has been developed within MAKING-CITY, with the collaboration of ATELIER project, to assist in this process, empowering cities with information and recommendations, in line with their district context and city objectives.

Collection of pre-tools (experimentary methods, frameworks) :

Performance design tools (multiple scales):

Calibrated Building Energy Models for Community-Scale Sustainability:

An iterative calibration approach to create a set of building energy models representing the dominant building classes in NYC. This framework uses a bottom-up deterministic approach. Building typology is created with the most common buildings. Performance of these pre-defined buildings are then scaled up. This approach is able to produce output data up to hourly resolution. In the case study data was calibrated with actual NYC data and reached a mean square deviation of 7% from actual average electricity demand (Waite and Modi, 2017).

High resolution energy simulations at city scale:

This approach is based on an automated process for extracting geometry information from high resolution mapping databases for UBEM modelling. It tackles the lack of reliable data in this regards, which is also mentioned by the academic literature. The authors used Digital boundary maps from the UK with key geographic features, orientation, height, space of use and information of building usage per polygon.
Energy modelling has been done with energyplus for more than 100000 individual models with the use of computing clusters. Validation happened with spot checks and also with a macro level comparison (depending on the availability of the data) (Tian, Wei, Rysanek, Adam, Choudhary, Ruchi, Heo, 2015).

Integration of reduced order energy model with geographical information:

This method uses a reduced order model coupled with GIS data. The physical part of the model relies on Energy Performance Certificate calculator in line with ISO 13790. This is based on quasi steady-state equations. To account for the discrepancies caused by the ignorance of dynamic effects, this approach uses so-called utilization factors. The model is built up by pre-defined building archetypes. This method also considers the effect of UHI. Since it is a reduced order model it is an efficient and computationally effective method. It can simulate around 46000 buildings in under 40 minutes. Flipside of this efficiency is the resolution. Output data can only be given on a monthly basis (Li *et al.*, 2015).

OpenIDEAS:

An open framework developed for district energy simulation. Consists of different submodels, so it can be stated that this is a co-simulation platform. Sub-models are IDEAS, StROBe, FastBuildings and GreyBox. The IDEAS (Integrated District Energy Assessment by Simulation) library is a transient simulation platform of thermal, control and electric systems at both building and neighbourhood levels. This uses the Modelica modelling language. StRObe is a python package short for Stochastic Residential Occupancy Behaviour. This can provide stochastic input and boundary conditions for IDEAS. The FastBuildings submodel is also a Modelica library implementing low-order building models compatible with IDEAS.

The GreyBox submodel is a python toolbox implementing semi-automatic parameter estimation for the FastBuildings model. This can provide a control method for IDEAS framework(*OpenIDEAS · GitHub*, no date).

Climate tools:

Sanchez et al. (Sánchez *et al.*, 2020) suggested methodology for experimental analysis of long-term climate impact to building energy performances. It is implemented in Madrid and Tabernas with real meteorological data. The proposed method is consisted of weather monitoring (long-term campaigns, two weather stations, measurement accuracy, remote access data), data processing (delete out of range records, delete outliers, fill data gaps, create multilayer weather data) and climate analysis (climate bias, average and extremely hot patterns, building energy demands, bioclimatic strategies). All these are based on eight climate indices have been evaluated for Csa and BWk cases: extreme temperature range (ETR), growing season length (GSL), summer days (SU), frost days (FD), tropical nights (TR), sunshine duration (SS), relative humidity (RH) and wind strength (FG).

Using this methodology, Soutullo et al. (Soutullo *et al.*, 2020) compare the impact that the climate trend has on the energy performance of residential buildings. The case study is placed in Madrid and it is characterized by two normative residential buildings, one constructed with Spanish regulations prior to 1979 and the other built with Spanish regulations of the last decade. Three climate files are used to compare the influence of the climate change with two conventional climate files. The experimental file is created with long-term measures of the last decade (Exp10) in Madrid, while the two typical meteorological years (TMY) are created with weather data measured before 2000. To quantify the climate impact on the thermal conditioning of these normative building models, two methodologies are applied: Degree Days and dynamic simulations with TRNSYS. The annual results obtained with the Degree Days methodology show that the heating requirements are 22% lower while the cooling requirements are 22% higher, both using the Exp10 file. The annual results obtained with TRNSYS show that cooling loads are increasing its relevance on the annual buildings loads. When the building models use regulations prior 1975, the cooling loads represents 35% of the total values for the Exp10 file and 21% for the TMY files. With more restrictive construction normative, the cooling loads with Exp10 climate file are 82% versus 65% with the TMY files.

Tool combinations, tool chains, or approaches with multiple tools:

Pless et al. (Pless Ben Polly Sammy Houssainy Paul Torcellini William Livingood *et al.*, 2007) used and suggests various software as tools for design and optimization of systems in districts.
The software that can be used depends on the type of the system that is analyzed. That kind of tools are: URBANopt (Polly *et al.*, 2016) and DERopt (*Microgrid Labs - Microgrid,*

Microgrid, Modeling Software, Consultant, no date) are software for establishing quantifiable criteria for development decision; disaster prediction software; computer modeling software for refining the design of buildings, energy systems, and entire districts; NREL's PVWatts (*PVWatts Calculator*, no date) as district energy planner; REopt Lite web tool(*REopt Lite | REopt Energy Integration & Optimization | NREL*, no date) helps evaluate the economic viability of grid-connected PV, wind, and battery storage at a site; identify system sizes and battery dispatch strategies to minimize energy costs; and estimate how long a system can sustain critical load during a grid outage.

Laitinen et al. (Laitinen *et al.*, 2021) made an optimization of the self-sufficient district. That is based on techno-economic parameters. They used two methods, optimization and rule-based control method (EnFloMatch tool). Optimization method is used on the selected parameters of their model. The EnFloMatch tool is used with strictly defined rules applied for maximizing energy matching. The analyzed system contains electricity for electricity demand (generated from PV, wind, battery, and electricity grid supply), heat for heat demand (heat storage, heat distribution) and heat pump connected to both subsystems for electricity and heat, as well as borehole heat source. The rule-based control method used Danish software EneryPLAN (*EnergyPLAN | Advanced energy systems analysis computer model*, no date), which is used for regional energy planning or energy planning for countries or group of countries. Furthermore, any optimization method can be used with various of software solutions. There, the most important part is creating the mathematical model and its closeness to the real system.
The Life Cycle Cost (LCC) is used for economic optimization by many authors (Laitinen *et al.*, 2021). Guarino et al. (Guarino *et al.*, 2020) used Life Cycle Assessment (LCA) in the design of neighborhood solar communities. The energy use and generation is simulated with TRNSYS. They designed common district heating system with certain number of heat storage systems as part of heat distribution system.

Tools optimising urban energy systems:

Simultaneous system sizing, operation and district heating network layout:

This is a multi-objective optimization tool based on an energy hub approach, where there are candidate technologies for each building. Furthermore, buildings can be interconnected through a district heating network. The objective functions are the minimization of total costs and the minimization of carbon dioxide emissions. This tool can cover the electricity and heating sectors, modelling the following technologies: photovoltaics, CHP, boiler, solar thermal collectors, and thermal storage. It has been applied to a case study of eleven residential and one commercial buildings in Zurich, Switzerland. The tool can be adapted to examine several scenarios (Morvaj, Evins and Carmeliet, 2016).

Distributed or centralized? Designing district-level urban energy systems by a hierarchical approach considering demand uncertainties:

This is a hierarchical based approach for decomposing a district-level problem into sub-problems at a neighbourhood level, using clusters. There are two technical routes, one being the energy hub approach with Graph theory techniques, and the second the distributed mode which is more computationally expensive. This is a MILP model minimizing total cost, and also the uncertainties of several parameters are examined by the introduction of several scenarios (Jing *et al.*, 2019).

Multi-objective operation optimization of DER for short- and long-run sustainability of local integrated energy systems.

A multi-objective model for designing local integrating energy systems and forming energy communities. Buildings can share thermal energy via a district heating network. The objective is to minimize the total daily operation cost and the cost of carbon emissions (Yan, Di Somma and Graditi, 2021).

1.4. Framework of technical tools:

To support the selection of the most fitting technical tools for stakeholders it is crucial to create a framework that has the ability to filter and categorize tools based on different aspects. Relevant actors usually have to make decisions considering multiple different, and sometimes overlapping factors. As these kinds of decisions are complex, it is thoroughly important to categorize the available tools across all important and distinct categories. Technical tools can be differentiated along multiple factors. To find the most relevant ones, aspects from the available literature (Abbasabadi and Ashayeri, 2019; Ferrari *et al.*, 2019; Sola *et al.*, 2019; Bukovszki *et al.*, 2020; Hong *et al.*, 2020) were chosen and complemented based on expert opinion.

In the following points short reasoning and description can be found for every aspect.

Modelling capabilities and inputs:

Energy generation modelling:

As described in (Sola *et al.*, 2019) tools implement different type and number of modelling approaches when it comes to energy generation technologies. To design and implement a PED, a crucial part is to discover the possibilities for energy generation and storage. There are multiple different ways of energy generation, and with respect to climatic zones, and other environmental or legislative constraints the possibilities can change rapidly. Thus, it can be important for the chosen tool to have the capability of modelling district heating, district cooling, effect of local and external storage solutions, renewables and also CHP systems.
District heating and cooling is a very efficient and beneficial solution towards low or zero energy districts (Nielsen and Möller, 2012). Therefore, countries and their renewable share

depends more and more on such solutions. For example, in Austria the country aims to phase out oil and gas heating completely by 2030 (BMWi, 2013). The implementation of renewable powered district heating is crucial to achieve the goals set out. Therefore, in the energy planning of buildings, district and even cities it is a necessity to use tools that allows for evaluating the effect of district heating on buildings.
Furthermore, the rapid evolution of smart energy systems cannot be neglected. Smart energy system is defined in the literature as “ an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system” (Lund *et al.*, 2017)
Thus, it is evident that by a smart energy system multiple synergies and their interconnected effects needs to be evaluated. To do this, technical tools that allow the evaluation of different energy generation are needed.

Energy services

As energy usage on both supply and demand side makes up a big part of a PED, it is really important to describe what kind of energy services can be assessed. There are completely differing energy calculation methodologies by countries (Zirngibl *et al.*, 2015), and with different methods there are different scopes that needs to be modelled in order to evaluate the energy performance of buildings.
For stakeholders it can be crucial to evaluate multiple energy services, and filter between them. This is relevant not just because of national calculation methodologies, but also due to the rise of sustainability assessment methods like : BREEAM, LEED, DGNB etc (Schwartz and Raslan, 2013).
When stepping into district or neighbourhood scale, decision making gets more complex. Due to the number of synergies between buildings and other entities (energy storage, energy generation etc) it is even more important to let stakeholders model the widest range of energy services and their interconnections.
Decision makers are often tasked with finding the best way to distribute incentives in order to lower either energy consumption, or GHG emissions. To understand the range of possible interventions and validate their choices, they need to get data on all existing energy uses.

Weather data:

Weather data is an essential input in annual building performance simulations. In the PED design process, weather data are taken as a set of constant parameters for underlying simulation equations because typically the location of the development is known and unalterable, and therefore, the influential parameters that have an impact on the building performance are all linked to the inputs such as shape, layout, orientation, materials, systems, operational schedules, i.e. building design characteristics in a broad sense. Weather data for building simulations must include information about location coordinates, temperature, relative humidity, and solar irradiance; but can also include other parameters such as cloud coverage, precipitation, or illuminance. What is used in annual building simulations of many kinds, including solar radiation studies, is the so-called reference year. It contains one year weather data, a typical meteorological year (TMY), with one value for every hour and every parameter and is based on 10 or more years of meteorological observation data. European standard ISO 15927-4:2005 describes the method of constructing a reference year. Every month in the reference year is carefully chosen from the multi-year observation data set as the representative typical month of the given time period, which is done by means of cumulative distribution function and calculation methods covered in the standard. For computer simulation purposes, reference year weather data is written into a text file suitable to be read by software of choice. The most common building performance indicators simulated using reference year weather data involve energy use, daylighting, and radiation. The latter is frequently used in solar design studies and for generating solar maps.

Certain types of solar design analysis do not require annual weather data input. Those are usually point-in-time calculations. Some solar access metrics are geometry-based only which means all is needed is the urban geometry model and its location data, particularly the latitude, because it carries information about the positions of the sun at any time in a year. For those metrics, the actual local insolation is not considered; it is rather the theoretical access to direct solar rays assuming sunny weather.

Weather observations are presently affected by progressing climate change. The so-called "typical" weather data based on past time periods might no longer be representative of current and future climate patterns. For instance, the web-available Swedish weather data files, compatible with a number of tools in Rhino and Grasshopper environment (epw format, https://www.energyplus.net/weather), are based on observation data from time periods of at least 10 years within the time between 1883 and 1996. Several studies advocated for the use of not just the historical weather, which is the standard type of meteorological data used for performance predictions at present (reference year or TMY), but also future climate scenarios (Robert and Kummert, 2012; Naboni *et al.*, 2019; Ren *et al.*, 2019)

Geometrical data:

An adequate choice of PED design tools is, amongst others, dependent on the available input data for creating surface model representations and the methods used for that are intrinsically different when digitalising existing or new urban developments. The latter is done by architects and urban planners who use Computer Aided Design (CAD) software often from the very early stages and throughout the entire urban planning and building design process. In such case, the model is digital from the start which makes it accessible for further performance evaluations using computer-based tools. There are still some obstacles to overcome in the process because there is limited intra-software integration possibility, meaning a digital model saved in a certain file extension might need to be converted, refined and/or cleaned to make it compatible with a different software environment. Existing buildings, on the other hand, often do not have a digital model representation in the databases because they predate computers and CAD.

In modelling of existing built environments, common urban tissue digitalisation methods are Geographic Information Modelling (GIS)-based and involve the use of images (aerial or satellite photographs in a raster format) and point clouds (from LiDAR scanning technology) as raw input data that it largely simplified and reduced but carries building height information among other things (Freitas *et al.*, 2015). Rasters that contain pixel-based raw photogrammetric topography information are known as Digital Surface Models (DSM) whose heights are given as absolute values as they cover on-ground objects such as buildings, and Digital Terrain Models (DTM) whose height information refers only to the ground elevation disregarding the height of objects on top of it. The raster models are often used in combination with GIS shape files, typically available from city urban planning databases, which provide planimetric information about building footprints and street layouts in a 2D format. The abovementioned terrain survey data can be used to generate 3D models, and there are available tools which make it possible to automate, to a varying degree, the topography digitalisation process (Moreia *et al.*, 2013; Peronato, Rey and Andersen, 2016). Another common application of raster urban models is simply graphical; 2D height-coloured layouts are used to illustrate the scope of a large case study area, even though the core analysis is done using another modelling approach (Chatzipoulka *et al.*, 2018). The 2D modelling approach is also directly used for calculation of shadow casting and Sky View Factor (SVF) evaluation in the urban models, both essential to solar potential assessments, as the algorithms used for that purpose are efficient and compute faster(Dirksen *et al.*, 2019).
Raster data is particularly used in generation of digital solar maps, which provide solar potential information over large territories. Solar maps or solar cadastres, that offer solar potential mapping on building roofs and other horizontal surfaces, usually achieve an adequate level of detail with 2D or 2.5D rasters. Nowadays, thanks to the improvements of computer-based processing tools, It is not uncommon to also add the third dimension in order to represent vertical surfaces in the city model even though it is challenging (Freitas *et al.*, 2015)because creating the third dimension from a 2D data takes additional steps in the model generation phase and there are special methods for achieving this, for example a "hyperpoints" method (Desthieux *et al.*, 2018). Although 3D models can be derived from 2.5D DSM data using modern tools and methods, they do not carry information about architectural details such as balconies, windows, or other complex facade elements (Freitas *et al.*, 2015) because creating the third dimension from a 2D data takes additional steps in the model generation phase and there are special methods for achieving this, for example a "hyperpoints" method (Desthieux *et al.*, 2018). Although 3D models can be derived from 2.5D DSM data using modern tools and methods, they do not carry information about architectural details such as balconies, windows, or other complex facade elements.
It is nowadays standard to model individual buildings or small building complexes using a full 3D model in a CAD environment. Such single-building models can exhibit a sophisticated level of detail (LoD), which is particularly crucial for daylight performance assessments, without an unreasonable amount of time and resources spent on creating detailed 3D representations. Manual labour input required for CAD modelling can usually be justified so long as the model is reasonably sized. Similarly, higher model accuracy is also manageable in terms of hardware computational and graphical strength. However, the larger the model gets, it becomes

increasingly more difficult to maintain high model accuracy i.e. LoD, because of greatly increased time investment, memory and computational weight for creating 3D models covering large neighbourhood or city scales (Freitas *et al.*, 2015)

A more advanced form of the CAD program is BIM (Building Information Modelling) involving the generation and management of digital representations of physical and functional characteristics of places (Abanda *et al.*, 2021). Many BIM programs are able to perform shadow studies and has become more common that advanced Building Performance Simulations can be run in the BIM environment itself. In some cases, advanced solar and daylight studies can be performed, as well as an evaluation of the PV potential.

Stand-alone programs for solar energy are mainly focused on the detailed planning of the setup of a solar thermal or PV system. In these programs, it is possible to analyse advanced settings, like types of inverters, load profiles etc.

Level of detail (LoD) classification is frequently used in 3D city modelling to indicate the degree of accuracy and sophistication in a digital model representation of a built environment. LoD range from lowest (0) to highest (4), and the numbers indicate the following aggregate building model precision: 0 – 2D footprint representation, 1 – simple rectangular building massing with flat roofs and homogenous vertical surfaces, 2 – added roof slopes, 3 – added window placements and façade details, 4 – added layouts and features of the interiors (Nouvel et al., 2013).

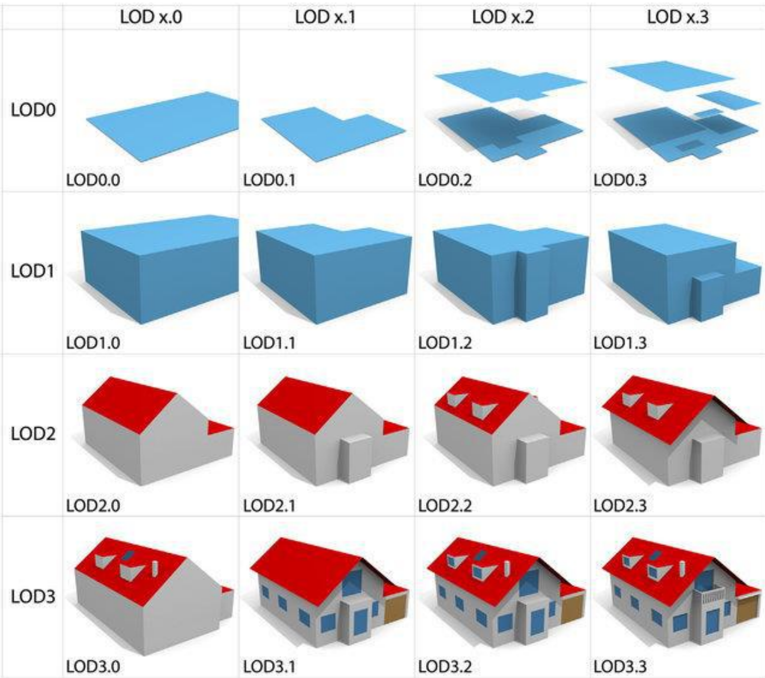

Figure 5. of LOD from (Biljecki, Ledoux and Stoter, 2016)

LoD 1 is very common in large-scale urban studies, because it is not computationally heavy, as high-accuracy models of large areas greatly exacerbate workflow efficiency, and because very often simple LoD 1 building massing is readily obtained from survey data without the need for laborious manual override. Common applications of LoD 1 include calculations of: Sky View Factor (Chatzipoulka *et al.*, 2018) irradiance (Carneiro *et al.*, 2010) heating demand (Nouvel *et al.*, 2013), and combinations of solar and daylight availability predictions (Compagnon, 2004). Generally speaking, in the estimation of the solar potential at the urban scale, small construction details are often omitted as they have a much lower impact on the annual potential compared to the massing of building forms and urban layout (Dogan et al., 2012). The choice of LoD for urban analyses can be influenced by the raw input data; for instance, LiDAR data offers possibility to generate 2.5D and 3D city models with LoD of maximum 2(Desthieux *et al.*, 2018). Adding details beyond LoD 2 often entails using typically survey-based building archetype characteristics applied as reduction factors which express proportions of different urban surfaces that are occupied by windows, balconies, HVAC installations, and other elements which make them unsuitable for other application such as active solar installations (Lobaccaro *et al.*, 2018). This model accuracy which is accounting for surface elements using reduction factors is known as LoD 2.5. Studies showed that lower LoD in urban solar potential assessments can lead to underestimation of irradiance when roofs are modelled flat instead of pitched (Peronato *et al.*, 2016) of irradiance when reduction factors are used instead of true representation with LoD 3 (Saretta, Bonomo and Frontini, 2020) The importance of precise glazing modelling on facades was previously brought to attention; however, there is a lack of measurement data to assist digital modelling processes in order to reach LoD 3 (Compagnon, 2004; Nouvel *et al.*, 2013; Freitas *et al.*, 2015). This creates a barrier in modelling of existing buildings using LoD 3. Meanwhile, new developments do not face the same problems, as the model is nested in a 3D modelling space from the very early stages of the design process and is continuously refined there. LoD 4 is predominantly applied in daylighting studies, because the internal layout and surface features are significant in simulations of daylight metrics. Overall, high accuracy is desirable, but the LoD selection is often a compromise between a sufficiently detailed representation of built environment and the resources of time and processing power it requires for modelling and computation.

Output types:

Planning a PED on neighbourhood level is a complex task involving various technical, economical and legislative aspects (Stanica *et al.*, 2021). There are often different constraints present (time, computational power, money etc) which makes it impractical to simulate all aspects.

Defining the clear objective of different processes is also not straightforward since objectives of different stakeholders can often be conflicting (Bakhtavar *et al.*, 2020). In general, tools are able to provide data in multiple different aspects of PEDs.

For stakeholders with specific goals in mind, it is important to know in what aspects are the tools capable of providing information. These are not only connected to energy and environment, but also related to the other two aspects described in the three pillars of sustainability (Tanguay *et al.*, 2009) namely social (i.e. wellbeing, accessibility etc) and economical (i.e. investment strategies, life cycle costs etc.)

Output types can therefore be an important aspect when choosing tools and/or tool combinations for a certain goal or task.

KPIs or metrics

Key Performance Indicators (KPIs) or metrics represent the output variables that can be obtained from the listed tools, and can be therefore interpreted as a subset of output types described earlier (i.e. Energy Use Intensity, Daylight Factor, Walkability etc.).
Since goals, evaluation methods and metrics are plentiful, it is important to let actors choose their evaluation method and relevant indicators. There are already very well described and used methods that can help in the assessment of positive energy buildings like the ISO 52000-1:2017 (*ISO - ISO 52000-1:2017 - Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures*, no date) and the Energy Performance of Buildings Directive (EPBD)('Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings', no date). However when assessing a district instead of just a building there is a need to implement new aspects, and makes changes in the already existing frameworks. To correctly evaluate PEDs, the selection of the right set of indicators is necessary. As the operation of neighbourhood includes wider set of aspects from multiple discipline (economic, social, regulatory etc.) it is also clear, that PEDs cannot be evaluated based only on energy related indicators (Salom *et al.*, 2020).
There are different already existing indicator sets used to evaluate such districts (Alpagut, Akyürek and Mitre, 2019; Angelakoglou *et al.*, 2020; Salom and Tamm, 2020). Although there are overlaps between these indicator sets, there are also always some differences between them. The categorization of tools provided here can hopefully help in the selection of the right tools for the right set of indicators or evaluation methods.

Spatial scale:

Neighbourhood scale is considered to be a mediator scale between cities and buildings. Neighbourhood level synergies and differences start getting significant over 5 buildings(Goy and Finn, 2015). In order to successfully achieve this jump in scale, it is highly important to consider the neighbourhood as collection of its smallest element (buildings) and also it's role as part of a bigger ecosystem (cities).
As previously described, for building scale there are comprehensive and validated evaluation methodologies i.e. ISO 52000-1:2017 and EPBD and therefore tools that are capable of delivering the needed information to conduct these assessments.
When it comes to tools on different scales, there is often a trade off that has to be managed when calculating energy flows. Calculations on neighbourhood scale are much more computationally expensive, therefore the same calculation methodologies that work on building scale are not always viable. To achieve computational efficiency in the recent years the development of neighbourhood scale simulation had to implement various simplifications throughout different domains (Ghiassi, Tahmasebi and Mahdavi, 2017). There are also some tools that are adaptable enough to navigate between multiple scales (*Ladybug Tools | Home Page*, no date). Selection of tools should be always based on the end goal, with the available computational resources and time constraints in mind.

Modelling approach:

.When talking about energy modelling tools, there are two mainly different modelling approaches (Swan and Ugursal, 2009) the bottom-up or the white box models, and the top-down or the black box models.
White box models require a detailed set of inputs to create assumptions with good accuracy via a set of physics based mathematical equations(Wang, Yan and Xiao, 2012) These models are input sensitive and need lot of information.
On the other hand black-box models use aggregated, statistical data(Zhu *et al.*, 2012; Foucquier *et al.*, 2013). This approach can capture long-term changes in the energy sector much better, which can provide inertia to the model and makes it easier to collect data (Swan and Ugursal, 2009).
There are shortcomings for both methods. White box models are very data intensive, while for example for black-box models have hardships calculating energy conversion measures (Hong *et al.*, 2016). To deal with both sets of shortcomings, a combination of these two approaches, called grey-box modelling emerged.
Grey-box models consists of both statistical and physics based components. Generally white-box method can be altered with black-box method in order to correctly calculate for example the occupant behaviour, and black box models can be complemented with a modul that is able to calculate the effect of new technologies (Kavgic *et al.*, 2010).

Tool usability:

Offline vs Online

There are advantages and disadvantages for both on and offline tools. Stakeholders sometimes have limited accessibility to data storage and computational power, which they need to consider during tool selection. The trade-offs to consider here are the followings: Computational power, and storage; data privacy; and data sharing between entities.
Online tools often have the ability to let users access cloud-based data storage and store data online. There is an obvious trade-off that has to be made when using an online platform, which is data privacy.
Offline tools are often perceived as a better solution considering privacy than their online counterparts. This is due to the fact, that tools that are able to run without internet connection ensure, that both input and output data stays at the premise of computation. Where there is lack of computational power, but stakeholders are willing to give up some degree of privacy, online cloud based tools can be viewed as a viable option. It is important to mention, that tools being online focused do not necessarily mean that they don't have adequate level of privacy preserving measures.
Due to recent regulatory developments , online tools also pay attention to make their softwares collect less, and empower their users with the rights to their own data.

Target users:

Technical tools like simulational and other modelling tools can provide a scientific basis to maintain competitiveness and to help government entities analyze their decisions. However these tools are not solely important for government stakeholders.
Hong et.al (Hong *et al.*, 2020) defines 5 different potential stakeholder group for UBEM tools:

- Decision makers(urban policymakers and city program managers)
- Industry (investors, technology vendors, urban developers, utilities)
- City users (residents, local communities, visitors)
- Urban energy planners and consultants
- Urban researchers

Stakeholders usually have different goals, which are not yet fully understood. More in-depth analysis of stakeholder goals will be part of the future work of this action.

Integrated Design PED Tools

In recent years, software tools for the design of PEDs are being developed to integrate architecture and urban design with simulation and optimization. The goal of such design tools is that to help improving the quality of the urban environment for both the aspects the quality and liveability of indoor and outdoor areas on one side and the energy and resource efficiency on the other side. This can be achieved allowing also small design firms, architecture and planning professionals and researchers to participate in the development of PEDs. Differently only large consultancy, engineering companies and research institutions could be the actors in the development of PEDs for what concern the urban and technical design. The integration of a larger number of professionals with different but overlapping and complementing expertise is key for the realization of the holistic approach necessary in sustainable and regenerative design. Additionally, the PEDs software tools integrating architecture and performance designs can be easily introduced in architecture schools thus providing with the necessary expertise future generations of designers and planners.
The available integrated PED software tools are the following:

- Intelligent Community Design (iCD)
- Urban Modeling Interface (UMI)
- Insight
- Sefaira
- ClimateStudio
- Ladybug Tools

A large quantity of tools is available in the suite Ladybug Tools [7], a plug-in for Grasshopper, for climatic analysis, solar and renewable energy design, daylight and thermal modeling, HVAC design, indoor and outdoor thermal comfort. Though specialized on the building scale it can be applied also to group of buildings at the block and neighborhood scale. It performs simulations through external validated software such as EnergyPlus and Radiance. The plug-in Butterfly of Ladybug Tools permit also to perform wind simulations at the district scale through the validated software Open-FOAM [8]. The simulation results are evaluated against the most advanced key performance metric. https://www.ladybug.tools/

The PED software tools Intelligent Community Design, Urban Modeling Interface, Insight, and Sefaira are technical tools which present a first level of integration, i.e., they are integrated inside architectural and urban modeling tools, those used by architects and designers in their regular workflow, above all during the early stages of the design process. The tool iCD is integrated in the architectural modeling software SketchUp, UMI in the 3D and NURBS modeling software Rhinoceros, Insight and Sefaira are integrated in the leading BIM software for architecture Revit. The positive aspect of these tools is that they can be used when the most crucial design decisions are taken, during the early design stages. In this way the impact of the PED tools on the resource efficiency and livability of the new districts will be higher than if the tools would be applied only after the main design decisions are taken. The drawback of these integrated tools is that they cannot be integrated between each other and allow only for a trial-and-error design process which do not guarantee the selection of the most performative design solution. The tool ClimateStudio presents both, the integration at the level of the architectural and modeling software being included as a plug-in of Rhinoceros, and the second level integration as specified in the next paragraph.

The software tools ClimateStudio, Ladybug Tools, Dragonfly, Eddy and Morpho are technical tools which present a second higher level of integration, i.e., they allow the interoperability of the PED tools with architectural and urban design tools, with other PED tools and with computational design tools. This more advanced integration is possible through parametric design environments such as that of the Grasshopper for Rhinoceros software. A large ecosystem of tools is available in Grasshopper to create relations between different aspects of PED design, such as thermal modeling, active systems, renewable production, passive strategies, daylight and solar access, indoor and outdoor thermal comfort, and architectural and urban design. In the same ecosystem it is possible to link the mentioned design tools with design exploration and optimization methods to select optimal design configurations or trade-offs. This potential overcomes the limitations of the first level integrated tools that allow to design only through a limited number of design alternatives. In this way better informed design decisions can guide a bottom-up design process where the final results of PED design is characterized by the highest performance or by significant trade-offs of the most relevant design indicators. The computational design tools which are used in the integration of PED technical tools, architectural and urban modeling tools and various simulation tools are included in parametric design workflows of Grasshopper through software such as DeCodingSpaces Toolbox (https://toolbox.decodingspaces.net/), Urbano (https://www.urbano.io/) and DigiWo (https://toolbox.decodingspaces.net/digiwo/) for automatic district design, Design Explorer (http://tt-acm.github.io/DesignExplorer/) and Colibri (http://core.thorntontomasetti.com/colibri-release/) for design exploration, and Opossum, (https://www.food4rhino.com/en/app/opossum-optimization-solver-surrogatemodels) and Octopus (https://www.food4rhino.com/en/app/octopus) for optimization (single and multi-objective).

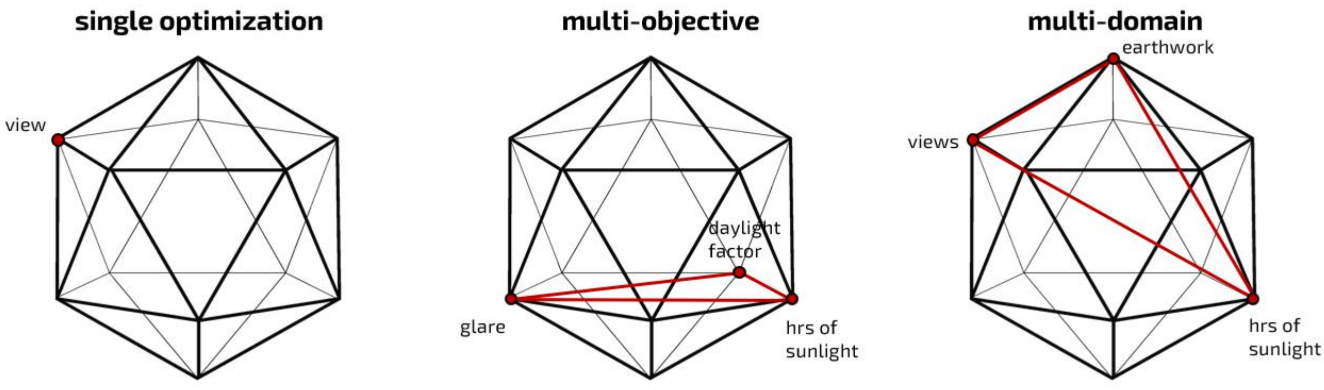

Figure 4 Type of optimisations. Author: Rafael Campamà Pizarro

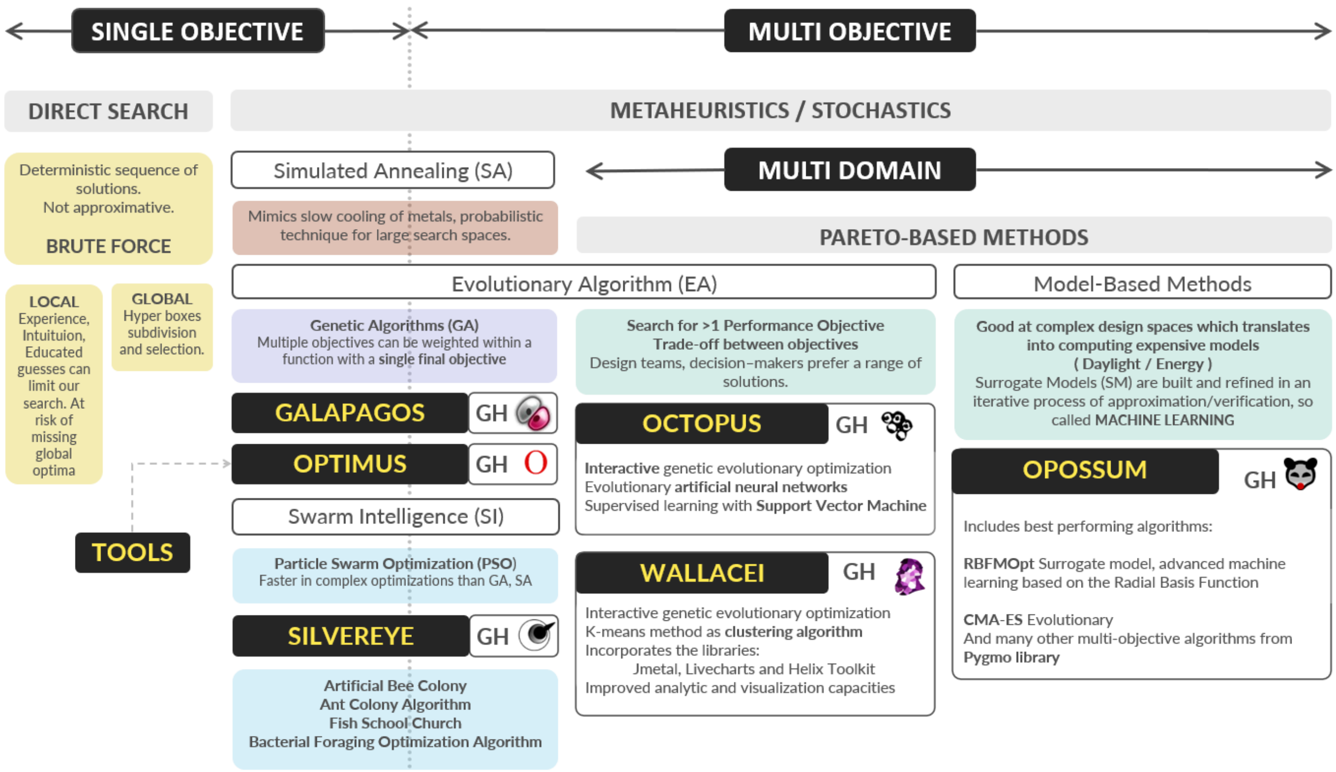

Figure 5 Review of optimisation tools in Grasshopper. Author: Rafael Campamà Pizarro

The tools presented in this section are used in research, design and planning in different ways depending on the size and scope of the project, on the professional figures involved and on the architectural and urban modeling software hosting the tool.

The platform Integrated Environmental Solutions (IES) and the tool Intelligent Community Design (iCD) are used in the work in progress of the smart city project +CityxChange. The project aims at developing low-carbon and climate-friendly neighborhoods and districts and at the same time guaranteeing livability and quality of the urban environment using as testbed the urban environment of the cities of Trondheim (NO), Limerick (IE), Alba Iulia (RO), Pisek

(CZ), Võru (EST), Smolyan (BG) and Sestao (ES). Through the iCD technology the project developed an Integrated Planning and Decision Support Tool to model the buildings, the grid infrastructure and the primary energy predictions together with socio-economic scenarios of Positive Energy Blocks. The scope is that to obtain a community with a yearly positive energy balance (Ahlers, Driscoll, *et al.*, 2019; Ahlers, Wienhofen, *et al.*, 2019)

Different energy scenarios of an urban neighborhood have been developed through the tool Urban Modeling Interface (UMI) in order to explore the potential of near-zero carbon planning solutions in the city of Dublin. The study integrated building archetypes information such as dimensions, material and energy systems, local energy sources and energy infrastructure. The results show the higher potential in reducing or even eliminating carbon emission related to energy management and consumption through the neighborhood approach instead than the single building approach. Additionally, the study used as energy scenarios future climate change projections and retrofit of existing buildings (Buckley *et al.*, 2021).

Several urban performance analysis tools such as energy demand and renewable energy, outdoor thermal comfort, daylight, wellbeing and biophilic experience were integrated in a digital workflow in order to quantify the potential of regenerative design strategies at urban scale. The different tools were used to realize a prototype workflow using the tools of Ladybug Tools in the software Grasshopper for Rhinoceros to be tested in a neighborhood in the city of Malaga, Spain. The workflow allowed as well to perform the different simulations using future weather scenarios in order to account for the effect of climate change on the local microclimate. The study showed the potential of integrating parametrically different analysis, simulations and, though the urban model used was that of an existing neighborhood, design tools as available in the parametric modeling environment, to assess comprehensive regenerative strategies for positive energy districts (Naboni *et al.*, 2019).

Different building and environmental simulations such as, indoor air temperature to evaluate occupant comfort and relative cooling energy consumption to maintain comfort, urban weather due to the Urban Heat Island effect, wind patterns and outdoor thermal comfort were integrated in a workflow developed using the tools of Ladybug Tools in Grasshopper and performed on a number of urban scenarios for a commercial district in Tallinn, Estonia through parametric design during the warm season. The workflow allowed to co-simulate the effects of the existing urban fabric and district's building layout on the solar gains, energy exchanges and shadowing, in order to quantify cooling energy demand and on the wind velocities, solar radiation and Mean Radiant Temperature that together with humidity and air temperature constitute the main factors for human comfort in urban environments. Through the workflow then it was possible to integrate energy and livability issues of a neighborhood which represent an important aspect in the design of PEDs (De Luca, Naboni and Lobaccaro, 2021).

Summary

This work provides a collection of the technical tools that my be used for the design, planning and operation of PEDs. Both the market-ready tools and the ones that are still in development were collected, making it useful and relevant for both practitioners and researchers in the field.

A framework of evaluation was also given for the collected tools. Most important factors and abilities of the said tools were collected and described. A categorisation of tools is provided based on the described aspects and factors. This can be found in *Annex A*. This work can hopefully help practitioners, municipalities and researchers in choosing the most appropriate tools at for their goals. The framework will also serve as a basis for future work towards a complete decision support framework for different stakeholders in order to select the most important tools at any given lifecycle of a PED project.

References:

A modular open source framework to model energy supply systems (no date). Available at: https://oemof.org/ (Accessed: 5 November 2021).

Abanda, F. H. *et al.* (2021) 'A literature review on BIM for cities Distributed Renewable and Interactive Energy Systems', *International Journal of Urban Sustainable Development*. Taylor & Francis, pp. 1–19. doi: 10.1080/19463138.2020.1865971.

Abbasabadi, N. and Ashayeri, J. K. M. (2019) 'Urban energy use modeling methods and tools : A review and an outlook', *Building and Environment*. Elsevier, 161(July), p. 106270. doi: 10.1016/j.buildenv.2019.106270.

Ahlers, D., Wienhofen, L. W. M., *et al.* (2019) 'A smart city ecosystem enabling open innovation', *Communications in Computer and Information Science*. Springer Verlag, 1041, pp. 109–122. doi: 10.1007/978-3-030-22482-0_9.

Ahlers, D., Driscoll, P., *et al.* (2019) 'Co-Creation of Positive Energy Blocks', *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, 352(1), p. 012060. doi: 10.1088/1755-1315/352/1/012060.

Alpagut, B., Akyürek, Ö. and Mitre, E. M. (2019) 'Positive Energy Districts Methodology and Its Replication Potential', *Proceedings*, 20(1), p. 8. doi: 10.3390/proceedings2019020008.

Angelakoglou, K. *et al.* (2020) 'From a comprehensive pool to a project-specific list of key performance indicators for monitoring the positive energy transition of smart cities—An experience-based approach', *Smart Cities*, 3(3), pp. 705–735. doi: 10.3390/smartcities3030036.

Bakhtavar, E. *et al.* (2020) 'Assessment of renewable energy-based strategies for net-zero energy communities: A planning model using multi-objective goal programming', *Journal of Cleaner Production*. Elsevier, 272, p. 122886. doi: 10.1016/J.JCLEPRO.2020.122886.

Bergerson, J. *et al.* (no date) 'LakeSIM INTEGRATED DESIGN TOOL FOR ASSESSING SHORT- AND LONG-TERM IMPACTS OF URBAN SCALE CONCEPTUAL DESIGNS'.

Biljecki, F., Ledoux, H. and Stoter, J. (2016) 'An improved LOD specification for 3D building models', *Computers, Environment and Urban Systems*. Elsevier Ltd, 59, pp. 25–37. doi: 10.1016/j.compenvurbsys.2016.04.005.

BMWi (2013) 'Integrated National Energy and Climate Plan', (663), pp. 1–262. Available at: https://ec.europa.eu/energy/sites/default/files/documents/de_final_necp_main_en.pdf.

Bossi, S., Gollner, C. and Theierling, S. (2020) ‘Towards 100 positive energy districts in europe: Preliminary data analysis of 61 European cases’, *Energies*, 13(22). doi: 10.3390/en13226083.
Buckley, N. *et al.* (2021) ‘Designing an Energy-Resilient Neighbourhood Using an Urban Building Energy Model’, *Energies 2021, Vol. 14, Page 4445*. Multidisciplinary Digital Publishing Institute, 14(15), p. 4445. doi: 10.3390/EN14154445.
Bukovszki, V. *et al.* (2020) ‘Energy Modelling as a Trigger for Energy Communities: A Joint Socio-Technical Perspective’, *Energies*. MDPI AG, 13(9), p. 2274. doi: 10.3390/en13092274.
Carneiro, C. *et al.* (2010) ‘Urban environment quality indicators: Application to solar radiation and morphological analysis on built area’, *International Conference on Visualization, Imaging and Simulation - Proceedings*, pp. 141–148.
Chatzipoulka, C. *et al.* (2018) ‘Sky view factor as predictor of solar availability on building façades’, *Solar Energy*. Elsevier Ltd, 170, pp. 1026–1038. doi: 10.1016/J.SOLENER.2018.06.028.
Clemente, C., Civiero, P. and Cellurale, M. (2019a) ‘Solutions and services for smart sustainable districts: Innovative key performance indicators to support transition’, *International Journal of Sustainable Energy Planning and Management*. Aalborg University press, 24, pp. 95–106. doi: 10.5278/ijsepm.3350.
Clemente, C., Civiero, P. and Cellurale, M. (2019b) ‘Solutions and services for smart sustainable districts: Innovative key performance indicators to support transition’, *International Journal of Sustainable Energy Planning and Management*. Aalborg University press, 24, pp. 95–106. doi: 10.5278/ijsepm.3350.
ClimateStudio — Solemma (no date). Available at: https://www.solemma.com/climatestudio (Accessed: 5 November 2021).
Compagnon, R. (2004) ‘Solar and daylight availability in the urban fabric’, *Energy and Buildings*, 36(4), pp. 321–328. doi: 10.1016/j.enbuild.2004.01.009.
DER-CAM | Grid Integration Group (no date). Available at: https://gridintegration.lbl.gov/der-cam (Accessed: 8 November 2021).
Desthieux, G. *et al.* (2018) ‘Solar Energy Potential Assessment on Rooftops and Facades in Large Built Environments Based on LiDAR Data, Image Processing, and Cloud Computing. Methodological Background, Application, and Validation in Geneva (Solar Cadaster)’, *Frontiers in Built Environment*. Frontiers, 0, p. 14. doi: 10.3389/FBUIL.2018.00014.
Dictionary Search | IGI Global (no date).
‘Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings’ (no date).
Dirksen, M. *et al.* (2019) ‘Sky view factor calculations and its application in urban heat island studies’, *Urban Climate*. Elsevier B.V., 30. doi: 10.1016/J.UCLIM.2019.100498.
Eddy3D - Airflow and Microclimate Simulations for Rhino and Grasshopper (no date). Available at: https://www.eddy3d.com/ (Accessed: 5 November 2021).
Energy Efficient Design Software | Green Design | Sefaira (no date). Available at: https://www.sketchup.com/products/sefaira (Accessed: 5 November 2021).
EnergyPLAN | Advanced energy systems analysis computer model (no date). Available at: https://www.energyplan.eu/ (Accessed: 5 November 2021).
EnergyPlus (no date). Available at: https://energyplus.net/weather (Accessed: 5 November 2021).
EnergyPro (no date). Available at: http://www.energysoft.com/ (Accessed: 5 November 2021).
ENVI-met - Decode urban nature with Microclimate simulations (no date). Available at: https://www.envi-met.com/ (Accessed: 5 November 2021).

Ferrari, S. *et al.* (2019) 'Assessment of tools for urban energy planning', *Energy*. Elsevier Ltd, 176, pp. 544–551. doi: 10.1016/j.energy.2019.04.054.
Fonseca, J. A. *et al.* (2016) 'City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts', *Energy and Buildings*. Elsevier B.V., 113, pp. 202–226. doi: 10.1016/j.enbuild.2015.11.055.
Foucquier, A. *et al.* (2013) 'State of the art in building modelling and energy performances prediction: A review', *Renewable and Sustainable Energy Reviews*. Pergamon, 23, pp. 272–288. doi: 10.1016/J.RSER.2013.03.004.
Freitas, S. *et al.* (2015) 'Modelling solar potential in the urban environment: State-of-the-art review', *Renewable and Sustainable Energy Reviews*. Elsevier, 41, pp. 915–931. doi: 10.1016/j.rser.2014.08.060.
FUNITEC (2013) 'SEMANCO: Prototype of the Integrated Platform'.
Ghiassi, N., Tahmasebi, F. and Mahdavi, A. (2017) 'Harnessing buildings' operational diversity in a computational framework for high-resolution urban energy modeling', *Building Simulation*, 10(6), pp. 1005–1021. doi: 10.1007/s12273-017-0356-1.
GitHub - AntonelloDN/Morpho: A plugin to create Envimet 2.5D models (INX), write configuration files (SIMX) and run simulations (no date). Available at: https://github.com/AntonelloDN/Morpho (Accessed: 5 November 2021).
GitHub - ibpsa/modelica-ibpsa: Modelica library for building and district energy systems developed within IBPSA Project 1 (no date). Available at: https://github.com/ibpsa/modelica-ibpsa (Accessed: 5 November 2021).
GitHub - ladybug-tools/dragonfly-core: dragonfly core library (no date). Available at: https://github.com/ladybug-tools/dragonfly-core (Accessed: 5 November 2021).
GitHub - RWTH-EBC/AixLib: A Modelica model library for building performance simulations (no date). Available at: https://github.com/RWTH-EBC/AixLib (Accessed: 5 November 2021).
Gollner, C. *et al.* (2020) *EUROPE TOWARDS POSITIVE ENERGY DISTRICTS | JPI Urban Europe*.
Goy, S. and Finn, D. (2015) 'Estimating demand response potential in building clusters', *Energy Procedia*. Elsevier B.V., 78, pp. 3391–3396. doi: 10.1016/j.egypro.2015.11.756.
Grasshopper - algorithmic modeling for Rhino (no date). Available at: https://www.grasshopper3d.com/?overrideMobileRedirect=1 (Accessed: 5 November 2021).
Guarino, F. *et al.* (2020) 'Life cycle assessment of solar communities', *Solar Energy*. Elsevier Ltd, 207, pp. 209–217. doi: 10.1016/j.solener.2020.06.089.
Hong, T. *et al.* (2020) 'Ten questions on urban building energy modeling', *Building and Environment*. Elsevier Ltd, 168, p. 106508. doi: 10.1016/j.buildenv.2019.106508.
Hong, T. (LBNL) *et al.* (2016) 'CityBES: A web-based platform to support city-scale building energy efficiency', *5th International Urban Computing Workshop, At San Francisco*, (August), p. 10. doi: 10.1016/j.jclepro.2015.05.105.
Intelligent Community Design (iCD) | IES (no date). Available at: https://www.iesve.com/icl/icd (Accessed: 4 November 2021).
ISO - ISO 52000-1:2017 - Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures (no date). Available at: https://www.iso.org/standard/65601.html (Accessed: 8 November 2021).
J. Brackney, L. and NREL (2016) 'Portfolio-Scale Optimization of Customer Energy Efficiency Incentive and Marketing Cooperative Research and Development Final Report', (February).
Jing, R. *et al.* (2019) 'Distributed or centralized? Designing district-level urban energy systems by a hierarchical approach considering demand uncertainties', *Applied Energy*. Elsevier, 252, p. 113424. doi: 10.1016/J.APENERGY.2019.113424.
Kanagaretnam, K. *et al.* (2013) 'Transparency and empowerment in an investment environment', *Journal of Business Research*. Elsevier Inc. doi: 10.1016/j.jbusres.2013.10.007.

Kavgic, M. *et al.* (2010) 'A review of bottom-up building stock models for energy consumption in the residential sector', *Building and Environment*. Elsevier Ltd, 45(7), pp. 1683–1697. doi: 10.1016/j.buildenv.2010.01.021.
Kontar, R. El, Polly, B. and Charan, T. (2020) 'URBANopt: An Open-source Software Development Kit for Community and Urban District Energy Modeling', *2020 Building Performance Analysis Conference and SimBuild*, (October), pp. 293–301.
Ladybug Tools | Home Page (no date). Available at: https://www.ladybug.tools/ (Accessed: 5 November 2021).
Laitinen, A. *et al.* (2021) 'A techno-economic analysis of an optimal self-sufficient district', *Energy Conversion and Management*, 236. doi: 10.1016/j.enconman.2021.114041.
Lefebvre, G. (1997) 'Modal-based simulation of the thermal behavior of a building: The m2m software', *Energy and Buildings*, 25(1), pp. 19–30. doi: 10.1016/s0378-7788(96)00984-x.
Li, Q. *et al.* (2015) 'BUILDING ENERGY MODELLING AT URBAN SCALE : INTEGRATION OF REDUCED ORDER ENERGY MODEL WITH GEOGRAPHICAL INFORMATION School of Architecture , Georgia Institute of Technology , Atlanta , USA School of City and Regional Planning , Georgia Institute of Technol', (Becp 2012), pp. 190–199.
Lindholm, O., Rehman, H. ur and Reda, F. (2021) 'Positioning Positive Energy Districts in European Cities', *Buildings*. MDPI AG, 11(1), p. 19. doi: 10.3390/buildings11010019.
Lobaccaro, G. *et al.* (2018) 'A holistic approach to assess the exploitation of renewable energy sources for design interventions in the early design phases', *Energy and Buildings*. Elsevier B.V., 175, pp. 235–256. doi: 10.1016/j.enbuild.2018.06.066.
De Luca, F., Naboni, E. and Lobaccaro, G. (2021) 'Tall buildings cluster form rationalization in a Nordic climate by factoring in indoor-outdoor comfort and energy', *Energy and Buildings*. Elsevier, 238, p. 110831. doi: 10.1016/J.ENBUILD.2021.110831.
Lund, H. *et al.* (2017) 'Smart energy and smart energy systems', *Energy*. Elsevier Ltd, 137, pp. 556–565. doi: 10.1016/J.ENERGY.2017.05.123.
Manfren, M., Caputo, P. and Costa, G. (2011) 'Paradigm shift in urban energy systems through distributed generation : Methods and models'. Elsevier Ltd, 88, pp. 1032–1048. doi: 10.1016/j.apenergy.2010.10.018.
Mavromatidis, G. and Petkov, I. (2021) 'MANGO: A novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems', *Applied Energy*. Elsevier, 288, p. 116585. doi: 10.1016/J.APENERGY.2021.116585.
Microgrid Labs - Microgrid, Microgrid, Modeling Software, Consultant (no date). Available at: https://microgridlabs.com/deropt-1 (Accessed: 5 November 2021).
Monti, A. *et al.* (2017) *Chapter One*, *Commentary on Genesis*. Elsevier Ltd. doi: 10.2307/j.ctt1d8hbgx.7.
Moreia, J. M. M. *et al.* (2013) 'From DSM to 3D building models : a quantitative evaluation', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. International Society for Photogrammetry and Remote Sensing (ISPRS), XL-1/W1, pp. 213–219. doi: 10.5194/ISPRSARCHIVES-XL-1-W1-213-2013.
Moreno, A. G. *et al.* (2021) 'How to achieve positive energy districts for sustainable cities: A proposed calculation methodology', *Sustainability (Switzerland)*, 13(2). doi: 10.3390/su13020710.
Morvaj, B., Evins, R. and Carmeliet, J. (2016) 'Optimising urban energy systems: simultaneous system sizing, operation and district heating network layout', *Energy*. Elsevier Ltd, 116, pp. 619–636. doi: 10.1016/J.ENERGY.2016.09.139.
Naboni, E. *et al.* (2019) 'A Digital Workflow to Quantify Regenerative Urban Design in the Context of a Changing Climate', *Renewable & Sustainable Energy Reviews*. Pergamon Press, 113(113), p. 109255. doi: 10.1016/J.RSER.2019.109255.

Nielsen, B. F., Baer, D. and Lindkvist, C. (2019) 'Identifying and supporting exploratory and exploitative models of innovation in municipal urban planning; key challenges from seven Norwegian energy ambitious neighborhood pilots', *Technological Forecasting and Social Change*. Elsevier Inc., 142, pp. 142–153. doi: 10.1016/j.techfore.2018.11.007.
Nielsen, S. and Möller, B. (2012) 'Excess heat production of future net zero energy buildings within district heating areas in Denmark', *Energy*. Pergamon Press, 48(1), pp. 23–31. doi: 10.1016/J.ENERGY.2012.04.012.
Nielsen, T. (2005) 'Simple tool to evaluate energy demand and indoor environment in the early stages of building design', *Solar Energy*, 78, pp. 73–83. doi: 10.1016/j.solener.2004.06.016.
Nouvel, R. *et al.* (2013) 'CITYGML-based 3D city model for energy diagnostics and urban energy policy support', *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, pp. 218–225.
Nouvel, R. *et al.* (2015) 'SIMSTADT , A NEW WORKFLOW-DRIVEN URBAN ENERGY SIMULATION PLATFORM FOR CITYGML CITY MODELS', (January).
OpenFOAM (no date). Available at: https://www.openfoam.com/ (Accessed: 5 November 2021).
OpenIDEAS · GitHub (no date). Available at: https://github.com/open-ideas (Accessed: 5 November 2021).
Perez-Lombard, L. *et al.* (2009) 'A review of benchmarking , rating and labelling concepts within the framework of building energy certification schemes', *Energy and Buildings*, 41, pp. 272–278. doi: 10.1016/j.enbuild.2008.10.004.
Peronato, G. *et al.* (2016) 'Sensitivity of calculated solar irradiation to the level of detail: insights from the simulation of four sample buildings in urban areas', *32rd PLEA Conference Proceedings*, pp. 702–707.
Peronato, G., Rey, E. and Andersen, M. (2016) '3D-modeling of vegetation from LiDAR point clouds and assessment of its impact on FAÇADE solar irradiation', *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*. International Society for Photogrammetry and Remote Sensing, 42(2W2), pp. 67–70. doi: 10.5194/ISPRS-ARCHIVES-XLII-2-W2-67-2016.
Pfenninger, S. and Pickering, B. (2018) 'Calliope: a multi-scale energy systems modelling framework', *Journal of Open Source Software*. The Open Journal, 3(29), p. 825. doi: 10.21105/JOSS.00825.
Pless Ben Polly Sammy Houssainy Paul Torcellini William Livingood, S. *et al.* (2007) *A GUIDE TO ENERGY MASTER PLANNING OF HIGH-PERFORMANCE DISTRICTS AND COMMUNITIES A GUIDE TO ENERGY MASTER PLANNING OF HIGH-PERFORMANCE DISTRICTS AND COMMUNITIES SUGGESTED CITATION*.
Polly, B. *et al.* (2016) *From Zero Energy Buildings to Zero Energy Districts*.
PVWatts Calculator (no date). Available at: https://pvwatts.nrel.gov/ (Accessed: 5 November 2021).
Rehman, H. ur *et al.* (2019) 'Towards positive energy communities at high latitudes', *Energy Conversion and Management*. Elsevier Ltd, 196, pp. 175–195. doi: 10.1016/j.enconman.2019.06.005.
Reinhart, Christoph F *et al.* (2013) 'UMI - AN URBAN SIMULATION ENVIRONMENT FOR BUILDING ENERGY USE , DAYLIGHTING AND WALKABILITY Christoph F Reinhart , Timur Dogan , J Alstan Jakubiec , Tarek Rakha and Andrew Sang Massachusetts Institute of Technology Department of Architecture', pp. 476–483.
Reinhart, C. F. *et al.* (2013) 'Umi - an Urban Simulation Environment for Building Energy Use , Daylighting and Walkability', in *Proceedings of BS2013: 13th Conference of International*

Building Performance Simulation Association.
Ren, G. *et al.* (2019) 'Spatial and temporal assessments of complementarity for renewable energy resources in China', *Energy*. Pergamon, 177, pp. 262–275. doi: 10.1016/J.ENERGY.2019.04.023.
REopt Lite | REopt Energy Integration & Optimization | NREL (no date). Available at: https://reopt.nrel.gov/tool (Accessed: 5 November 2021).
Rhino - Rhinoceros 3D (no date). Available at: https://www.rhino3d.com/ (Accessed: 8 November 2021).
Robert, A. and Kummert, M. (2012) 'Designing net-zero energy buildings for the future climate, not for the past', *Building and Environment*, 55, pp. 150–158. doi: 10.1016/J.BUILDENV.2011.12.014.
Robinson, D. *et al.* (2009) 'CITYSIM : Comprehensive Micro-Simulation of Resource Flows for Sustainable Urban Planning CITYSIM : COMPREHENSIVE MICRO-SIMULATION OF RESOURCE FLOWS FOR SUSTAINABLE URBAN PLANNING Solar Energy and Building Physics Laboratory (LESO-PB), Ecole Polytechniq', (November 2014).
Roudsari, M. S. and Pak, M. (no date) 'LADYBUG: A PARAMETRIC ENVIRONMENTAL PLUGIN FOR GRASSHOPPER TO HELP DESIGNERS CREATE AN ENVIRONMENTALLY-CONSCIOUS DESIGN'.
Salom, J. *et al.* (2020) *Methodology Framework for Plus Energy Buildings and Neighbourhoods*. Available at: www.synikia.eu (Accessed: 27 February 2021).
Salom, J. and Tamm, M. (2020) 'WP3 Technology Integration in Smart Managed Plus Energy Buildings and Neighbourhoods'.
Sánchez, M. N. *et al.* (2020) 'An experimental methodology to assess the climate impact on the energy performance of buildings: A ten-year evaluation in temperate and cold desert areas', *Applied Energy*. Elsevier Ltd, 264, p. 114730. doi: 10.1016/j.apenergy.2020.114730.
Saretta, E., Bonomo, P. and Frontini, F. (2020) 'A calculation method for the BIPV potential of Swiss façades at LOD2.5 in urban areas: A case from Ticino region', *Solar Energy*. Pergamon, 195, pp. 150–165. doi: 10.1016/J.SOLENER.2019.11.062.
Schwartz, Y. and Raslan, R. (2013) 'Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study', *Energy and Buildings*. Elsevier, 62, pp. 350–359. doi: 10.1016/J.ENBUILD.2013.03.022.
Section, B. P., Mechanics, A. and Section, E. C. (2015) 'PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT OPENIDEAS – AN OPEN FRAMEWORK FOR INTEGRATED DISTRICT ENERGY SIMULATIONS PRODUCED BY AN AUTODESK EDUCATIONAL PRODUCT ABSTRACT'.
Sola, A. *et al.* (2019) 'Multi-domain urban-scale energy modelling tools: A review', *Sustainable Cities and Society*. Elsevier, (February), p. 101872. doi: 10.1016/j.scs.2019.101872.
Soutullo, S. *et al.* (2020) 'How Climate Trends Impact on the Thermal Performance of a Typical Residential Building in Madrid', *Energies 2020, Vol. 13, Page 237*. Multidisciplinary Digital Publishing Institute, 13(1), p. 237. doi: 10.3390/EN13010237.
Stanica, D. I. *et al.* (2021) 'A methodology to support the decision-making process for energy retrofitting at district scale', *Energy and Buildings*. Elsevier, 238, p. 110842. doi: 10.1016/J.ENBUILD.2021.110842.
Swan, L. G. and Ugursal, V. I. (2009) 'Modeling of end-use energy consumption in the residential sector: A review of modeling techniques', *Renewable and Sustainable Energy Reviews*, 13(8), pp. 1819–1835. doi: 10.1016/j.rser.2008.09.033.
Tanguay, G. A. *et al.* (2009) 'Measuring the Sustainability of Cities: A Survey-Based Analysis of the Use of Local Indicators', *SSRN Electronic Journal*. Elsevier BV. doi: 10.2139/SSRN.1336649.

Tian, Wei, Rysanek, Adam, Choudhary, Ruchi, Heo, Y. (2015) ‘High resolution energy simulations at City Scale’.
Waite, M. and Modi, V. (2017) ‘CALIBRATED BUILDING ENERGY MODELS FOR COMMUNITY-SCALE SUSTAINABILITY ANALYSES’, pp. 1–9.
Wang, S., Yan, C. and Xiao, F. (2012) ‘Quantitative energy performance assessment methods for existing buildings’, *Energy and Buildings*. Elsevier, 55, pp. 873–888. doi: 10.1016/J.ENBUILD.2012.08.037.
Ward, G. J. (no date) ‘The RADIANCE Lighting Simulation and Rendering System’.
Yan, B., Di Somma, M. and Graditi, G. (2021) ‘Multiobjective operation optimization of DER for short- and long-run sustainability of local integrated energy systems’, *Distributed Energy Resources in Local Integrated Energy Systems*. Elsevier, pp. 89–123. doi: 10.1016/B978-0-12-823899-8.00001-7.
Zhu, D. *et al.* (2012) ‘Comparison of Building Energy Modeling Programs: Building Loads’, (June), p. 92. Available at: http://eetd.lbl.gov/sites/all/files/publications/lbnl-6034e.pdf.
Zirngibl, J. *et al.* (2015) ‘Technical assessment of national/regional calculation methodologies for the energy performance of buildings Service contract number: ENER/C3/2013-425/SI2.679523 Final report (2015-01-30)’.

Annex A