A Multi-Scale, Web-based Application for Strategic Assessment of PV Potentials in City Quarters

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Keywords: Energy Simulation Tool, Urban Modeling Usability, Web-based Application for Energy Concepts, Feasibility and Efficiency of PV Systems, Neighborhood Strategies, Stepless Scalability.

Abstract: This paper introduces a web-based application that visualizes building specific simulation results regarding renewable potentials and economics for entire city quarters. Focusing on the building stock, this application enables decision-makers to consider energy related aspects in early-stage city quarter planning. The application builds on the existing energy simulation platform, SimStadt, which allows the detailed assessment of buildings' energetic performance or photovoltaic rooftop potentials based on 3D CityGML models. A new, user-friendly and browser-based graphical user interface (GUI) makes energetic modeling more accessible and independent of a user's operating system. Furthermore, a customizable economic analysis was added to the pre-existing workflow to calculate rooftop PV potentials, allowing the evaluation of renewable energy potentials with their associated total investments or levelized cost of electricity (LCOE) at building level. Combined, these improvements create new use cases for modeling environments previously reserved for researchers, such as enabling utilities and their house-owning customers to identify PV potentials and costs, or PV project developers to more easily and accurately locate neighborhoods with high potential. Further functionalities such as building heating and cooling demand assessment will be included in a next step to extend the scope of this application towards a versatile urban energy system simulation platform.

1 INTRODUCTION

The European Commission's plan for a Green New Deal proposes raising its greenhouse gas (GHG) emissions reduction target for 2030 from 40% to 55% compared to 1990 levels (European Commission, 2020). As buildings are responsible for about 40% of energy consumption and 36% of CO_2 emissions in the EU and are by this the single largest energy consumer in Europe (European Commission, 2020), any reduction in GHG emissions must focus on cities, where the use of renewable energy technologies, particularly in the building stock, needs to be increased.

Hence, approaches and tools that simplify the energetic assessment of the building stock and that propose technologically and financially feasible options towards sustainable city quarter planning are needed. Such tools should feature a high level of detail regarding spatial and/or temporal resolution in order to provide meaningful information for key stakeholders such as city officials or project developers to act upon.

A review of existing modeling approaches and tools for energy system simulation on the scale of city quarters are presented in (Allegrini et al., 2015), underlining the challenges that arise, such as the provision of an intuitive tool capable of supporting decision-makers at an early stage in the planning process or the need for tools that can perform parametric analyses at neighborhood level, taking into account economic and environmental parameters. This is supported by (Meskel & Weber, 2017), while reviewing seven European cities and their tools for energy and urban planning, finding a lack of adequate instruments for energy planning at urban scale as well as

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Köhler, S., Sihombing, R., Duminil, E., Coors, V. and Schröter, B.
A Multi-Scale, Web-based Application for Strategic Assessment of PV Potentials in City Quarters.
DOI: 10.5220/0010406201100117
In *Proceedings of the 10th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2021)*, pages 110-117
ISBN: 978-989-758-512-8

the need for improvement of diagnosis tools to support early-stage decision-making. In addition, (Mavromatidis et al., 2019) concludes that any energy modeling and simulation application on city-quarter scale should be user-friendly, meet the industry´s needs and be available either commercially or as open source. Lastly, (Schoof et al., 2013) shows that tools that assess for example solar potentials based on Geographic Information Systems (GIS) allow to improve interactions between key stakeholders, such as communal planners and energy producers.

Using 3D building stock models allows to process exact building volumes, surfaces, roof shapes etc., whereas 2D data can lead to inaccurate information in particular regarding PV potentials, if roof geometries or shadowing effects cannot be assessed properly.

Well-developed tools for energy system analyses like TRNSYS (Thermal Energy System Specialists, LLC, 2020) or EnergyPlus (U.S. Department of Energy's Building Technologies Office, 1996-2019) in combination with the graphical interface of OpenStudio (Brackney et al., 2018) simulate energy demands, peak loads and consider a wide range of technologies. These tools feature user-friendly interfaces and operate on 3D building information. However, since they need detailed inputs for each building, they are not applicable to city quarters, in particular in early planning stages. In contrast, urban information platforms such as Solarpotenzial 3D-Stadtvermessung Wien use large scale 3D data as input and focus on the simulation of solar potentials, but does not take other technologies into account. (Stadt Wien, 2018)

(Alhamwi et al., 2019) gives an overview of current GIS-based urban energy system models, like City-Sim, DUE-S and others, introducing the platform *FlexiGIS. FlexiGIS* uses 2D GIS data as input and the open-source toolbox *urbs*, which is an extendable tool for the investigation of energy scenarios at urban scale, considering PV, solar, wind, biomass and hydropower (Alhamwi et al., 2018). As a case study the city Oldenburg, Germany was assessed, but not on a single-building basis (Alhamwi et al., 2019).

Re3ason is another platform that analyzes energy demands, renewable energy as well as technology potentials (wind, photovoltaics, biomass), and adds a techno-economical optimization for the energy system on top. However, the 2D spatial resolution is restricted to municipal boundaries. (Mainzer, 2019)

This work introduces a web-based tool that on the one hand handles the complexity of calculating energy demands, evaluating and dimensioning possible renewable energy supply systems scenarios with a solid understanding of the associated potentials at a detailed, sub-city level. On the other hand, it provides a clear, user-friendly 3D visualization, which enables the assessment of a quantitative and technology-neutral verification of the technical and financial feasibility as well as the efficiency of neighborhood strategies and local energy concepts on a granular level in real time. The work is presented in five chapters. Following the introduction, the methodology is explained in Chapter 2. Chapter 3 summarizes the results and gives a case study demonstration, followed by a discussion in Chapter 4 and a conclusion in Chapter 5.

2 METHODOLOGY

The proposed tool enhances the already established energy simulation platform SimStadt. SimStadt uses the open data model *City Geography Mark-up Language* (CityGML) (Coors et al., 2016), i.e. 3D building models, as principal source of input. SimStadt has a range of databases and calculation routines, e.g., photovoltaic rooftop potentials (Nouvel et al., 2017), building heating/cooling (Eicker et al., 2018) or water demands (Bao et al., 2020b) implemented and validated. It utilizes the dynamic energy simulation engine INSEL (Schumacher, 2020) and is structured along modular workflows that allow its users to evaluate different energy technologies, making it easier to compare different technologies and create combined scenarios. The simulation within SimStadt can be performed on user-defined areas, as long as a CityGML file is available, enabling the simulation of both a few individual houses and entire cities. Provided its base of 3D city models is geometrically correct, SimStadt can assess building energy and water demands, refurbishment measures, and the integration of renewable energy systems (PV, solar thermal, biomass) with high accuracy, and offers the option of 2D visualization and results in csv-format (Bao et al., 2020a; Braun et al., 2018). SimStadt has been successfully applied to inner-city quarters (Dochev et al., 2020), quarters dominated by single-family houses (Weiler et al., 2019) with hundreds of buildings as well as to larger ensembles such as Brooklyn, a district of New York (Eicker et al., 2020), featuring thousands of buildings.

The present work enhances the existing tool by adding a method for assessing key financial metrics to the preexisting workflow calculating rooftop PV potentials and establishes a web based user-friendly GUI.

2.1 3D User Interface

In the context of smart cities, geovisualization and visual analysis are applied to better understand underlying data and identify trends, patterns and contexts, making a city's economy, mobility, environment, people and management smarter (Harbola & Coors, 2018). Compared to 2D, a 3D geovisualization offers a more realistic (over-)view and can include detailed features, such as building specifications and physical representations, that provide better understanding of the urban environment (Esri, 2014). With regards to 3D urban visualization options, the Web Graphics Library (WebGL) (Khronos Group, 2020) is a cross-platform web standard for rendering interactive 2D and 3D graphics in a compatible web browser without requiring plug-ins (Evans et al., 2014).

A study comparing X3DOM (ICG, 2020), three.js (*Three.Js*, 2020) and CesiumJS (CesiumJS contributors, 2020) as an open-source WebGL framework in web-based geospatial applications is presented in (Krämer & Gutbell, 2015). The study reveals that it is possible to develop a geospatial application using three.js or X3DOM, even though, unlike CesiumJS, these two frameworks do not explicitly support the geospatial reference system. In conclusion, the study reveals that the investigated frameworks were developed from different approaches and goals, e.g., aiming at geospatial or non-geospatial applications, and that the selection of the right framework depends on the use case.

While the intention of CityGML is per se not to visualize 3D buildings in a web-browser, it can be converted into *3D Tiles* format, applying CesiumGS (CesiumGS contributors, 2020), without losing substantial properties, such as building or surface IDs. 3D Tiles is an open specification for streaming massive heterogeneous 3D geospatial datasets across desktop, web, and mobile applications.

The realization of a browser-based visualization in the front-end, based on CesiumJS and 3D Tiles, allows users to interact with SimStadt, INSEL and other data sources running in the back-end, without installing new software. For technical and financial assessments, users can submit their input data and parameters to SimStadt in the back-end via the web-based GUI. After calculation, the result is sent back to the front-end and visualized in 3D in the web-browser. The visualization is carried out by mapping the result data to 3D Tiles, which holds the building and surface IDs from the CityGML file used in the analysis process. Additionally, the CesiumJS-based browser can be underpinned with OpenStreetMap satellite image (OpenStreetMap contributors, 2020).

To evaluate the usability of the new web-based application, a survey and a structured interview was conducted with five users. Participant A is the head of climate department of a mid-sized German city, while participants B to E are computer sciences graduate students at University of Applied Sciences Stuttgart. While the interview with participant A aimed at evaluating the usability of the new application for strategic energy planning at city level, participants B to E were expected to provide more general feedback on the technical implementation and potential improvements of the GUI and background processes. Participant A did the following tasks under supervision:

- Find the address in an urban area that is sought in the task.
- Run the newly implemented PV potential and financial analysis workflow within the web-based GUI and assess its results (with the default input values and participant-defined input values).

After these tasks were finished, the participant gave feedback on the 3D visualization and the user-friendliness of the application. The evaluation with participants B to E aimed at assessing the application's usability for persons with less knowledge of the energy sector. Without assistance, the participants were asked to do the following tasks:

- Find a specific house by the address in the target urban area.
- Run the PV potential and financial analysis with default input parameters.

While working on the tasks, measurable indicators were recorded, such as the number of clicks or the time taken for above-mentioned tasks. Furthermore, the targeting of participants' clicks or whether participants encountered problems was assessed and rated from 1 to 5, with 1 being the best and 5 worst score.

2.2 Dynamic Cost Analysis of PV Rooftop Installations

To assess the financial feasibility of a given technology, a flexible economic analysis was established using the example of the workflow that calculates rooftop photovoltaic potentials within SimStadt (Eicker et al., 2018). Based on data from the CityGML file (building geometries and orientation), the pre-existing PV workflow calculates physical parameters, relevant for assessing installation cost or LCOE, in particular the installed power in kW_p, annual yield in kWh/a and specific yield in kWh/(kW_p a) on a single-building level.

Since installation cost are subject to economies of scale, i.e., specific cost for larger installations are lower than for smaller ones, all else being equal, dynamic cost functions are established. The cost function is determined by two customizable data points (S1 and S2), which represent the installation cost in EUR/kW_p for a small system (S1), e.g., $10kW_p$, and a larger rooftop PV system (S2), e.g., $100kW_p$. A logarithmic fit function through S1 and S2 establishes the dynamic cost function (1) as:

$$C_i = A - B^* \log(P_n / 1kW_p) \qquad (1)$$

With:
C_i = installation cost for a PV system of a given size $[EUR/kW_p]$
A = installation cost for a PV system with $1kW_p$ $[EUR/kW_p]$
B = cost digression factor $[EUR/kW_p]$
P_n = nominal power [kWp]

Figure 1 shows a graph of a potential cost function, with S1 defined as ($10kW_p$ | $1,300EUR/kW_p$) and S2 as ($100kW_p$ | $1,000EUR/kW_p$), based on (Fraunhofer ISE, 2020). In that case, specific installation cost decrease by -23% from $10kW_p$ to $100kW_p$.

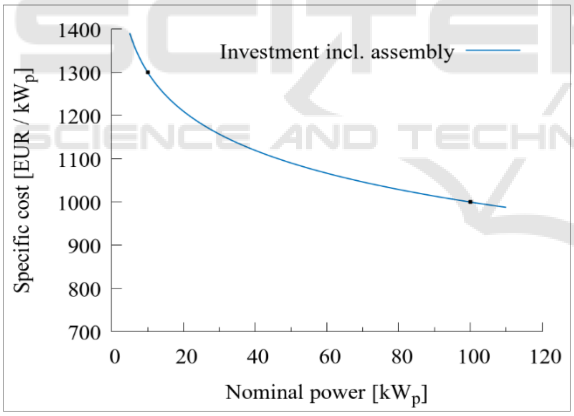

Figure 1: Dynamic cost function (1), with data points (10kWp | 1,300EUR/kWp) and (100kWp | 1,000EUR/kWp).

Further parameters that influence the economic attractiveness of a PV system, namely cost of capital as well as operating and maintenance cost as a percentage of installation cost, are also considered. To not only calculate system LCOE but to rate the financial attractiveness of a given system, information on local electricity prices and potential feed-in tariffs needs to be considered as well.

In all cases, users can either keep default values or customize parameters in the web-based GUI, allowing to conduct parameter studies and the creation of simple scenarios in real-time. Table 1 shows the parameters and their default value setting.

Table 1: Default financial parameters for PV rooftop system assessment, 1: (Fraunhofer ISE, 2020) p.24,71,8; 2: (Statistisches Bundesamt [Destatis], 2020) p.48; 3: (Bundesnetzagentur, 2020); 4: (KPMG International, 2020).

Parameter	Value	Unit
Asset life time[1]	20	year
Self-consumption rate[1]	30	%
Operating cost as share of installation cost[1]	1.0	%
Electricity cost (Germany)[2]	30.0	EURct per kWh
Feed-in tariff[3]	8	EURct per kWh
Cost of capital[4]	2	%

Results of the financial assessment of rooftop PV systems include total investment cost in EUR, operating and maintenance costs in EUR/a, LCOE in EURct/kWh, net present value (NPV) in EUR, internal rate of return (IRR) in %, the asset's (discounted) payback period in years as well as a statement on financial feasibility (yes/no) for each roof, assumed "yes" if the payback period is less than 20 years.

3 RESULTS

3.1 Visualization and Usability

The web-based user interface is split in two main parts, a menu window on the left, and a 3D visualization window on the right part of the screen. Figure 2 displays the GUI after starting the application and highlights four options a user can use to adjust the visualization window: No.1 defines the menu where the user choses the geographical location and technology to be assessed, and where parameters are customized. Furthermore, result graphs are shown therein. With No. 2, the user can set time, date and the rate at which time advances for visualizing shadowing effects, which are important for understanding inner city rooftop PV potentials. In the top right corner, No. 3 offers the option to search for an address, help navigating the map or running simulations. Lastly, No. 4 is an information window indicating specific building information, such as building ID and the year of construction, when moving the cursor over a particular building.

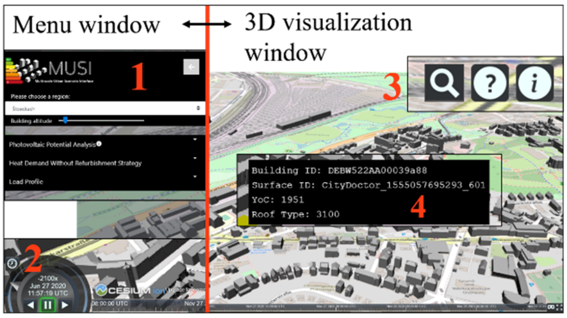

Figure 2: Screenshot of the web-based user interface, with four call-outs. 1: main menu, 2: time and date setter, 3: search and help options, 4: information pop-up for particular buildings.

When conducting the usability study with the climate protection manager (participant A) the given tasks were handled effortlessly. The feedback contained remarks such that the 3D map is intuitive, the 3D visualization as well as the summarized results in pie chart format are comprehensible, and the customizable parameters are beneficial for creating scenarios. Suggestions for further improvement included the need for pop-up information buttons explaining input parameters. Additionally, participant A asked for a more detailed coloring of the results and the possibility for a multidimensional result graphics e.g., plotting the total nominal power in kW_p of a whole urban area under a particular total investment in EUR value.

Participants B to E solved the given tasks in on average about three minutes. The majority of this time was related to the processing time of the application, i.e. the data flows to and from SimStadt as well as the simulation's calculation time. Of the four participants, one (D) was not able to find the target address and the survey was terminated after 4m15s. All results from this survey are summarized in Table 2.

In general, the participants found the 3D map to be intuitive. As potentials improvements, a more detailed interpretation of the analysis results was suggested, particularly when looking at the results of an individual building as opposed to a city quarter. Also, the menu options were considered as too complex. Based on that feedback, this feature was revised. As described in chapter 2, an expert user now choses two values for installation costs for PV rooftop systems of two sizes, as well as other parameters. This can either be done by moving slide bars or setting the parameter value in specified text boxes. The slide bars with predefined ranges were established in order give the users orientation about realistic price ranges, e.g. in terms of installation cost per kW_P. Additionally, further tooltips and user instructions have been implemented, in particular instructional videos that explain the most relevant steps and features.

3.2 Case Study Demonstration

To demonstrate the potential of the enhanced tool and GUI, a part of the inner-city quarter of Stöckach in central Stuttgart was assessed in detail. The CityGML file of Stöckach contains 187 buildings, of which 106 are residential. The year of construction of the buildings varies from 1934 to 2015. Furthermore, the total roof area is 29,901m², of which 25,151m² are assessed as in principle suitable for PV systems, as areas under 20m² are not considered for reasons of practicability. It is assumed that 30% of the area of flat roofs and 40% of the area of tilted roofs can effectively be covered with PV modules, taking the elevation and shading of the modules as well as roof edges and further rooftop installations, e.g. HVAC systems, into account. (Bergner et al., 2018).

A minimum insolation of 950kWh/(m² a) is set as threshold for installing financially feasible PV systems in Germany today (Fraunhofer ISE, 2020), effectively excluding north-facing areas or shadowed roofs. Taken these restrictions into account, SimStadt's rooftop PV workflow operating in the backend calculates the available effective roof area for PV with 8,974m², a total nominal power potential of 1,155kW_P with a potential yield of 1,187MWh/a.

Table 2: Results of usability study with participants B to E. Row 1 to 3 are measurable indicators, row 4 to 7 are observation indicators. For line 4 and 5, a rating was given based on participants performance, with 1 being best and 5 being worst.

	Participant B	Participant C	Participant D	Participant E
1. No. of clicks	7	20	26	5
2. Handling time	3 Min 23 Sec	2 Min 5 Sec	4 Min 15 Sec	2 Min 35 Sec
3. Finished task successfully?	Yes	Yes	No	Yes
4. Have first clicks been target orientated?	1	1,5	1	1.5
5. Did participant run into problems?	2.5	2.0	3.5	1.5
6. Most helpful feature	Intuitive map	-	Intuitive map	-
7. Feature that can be improved	Expert mode	Expert mode	Search for address	-

After running the analysis, a dropdown menu allows the user to choose which parameters is visualized, color coding all buildings of the chosen area. Moreover, pie charts evaluate the parameter of choice on an aggregated level. Parameters that can be chosen are: potential yield, specific yield, LCOE, total investment, discounted payback period, and financial feasibility.

Figure 3 summarizes some output options of the web-based application the case study of Stöckach. Photovoltaic yields in MWh/a per roof are colored in dark red to light yellow shades (top left). The specific yield in kWh/(m²a), in the top right corner, helps to identify roofs that are particularly attractive. Dark colors indicate higher (specific) yields. The bottom left corner shows the total investment per roof (dark blue shades represent higher investments), while the bottom right section marks the discounted payback period in green. The darker the shade the smaller the value for the discounted payback period.

Figure 3: Visualization of PV potentials and economics; Top left: PV yield in MWh/a; Top right: LCOE in EURct/kWh; Bottom left: total investment in EUR; Bottom right: discounted payback period in years.

By clicking on individual roofs, detailed results are displayed in a pop-up table in the upper right corner, providing an individual evaluation. All results can be downloaded as *.csv-files or in *.png/ jpeg-format. In addition to the 3D visualization, all result values can be exported in text or table format.

Table 3 shows an excerpt of the information that can be exported, with a focus on the newly added financial parameters.

Key results for the case study Stöckach include:

- Total investments per roof range from 1,550EUR to 42,890EUR
- LCOE ranges from 6.4 EURct/kWh to 13.5 EURct/kWh, comparable with (Fraunhofer ISE, 2020), where the LCOE ranges from 8 to 14EURct/kWh
- Discounted payback periods range from 7.1 years to 17.9 years

4 DISCUSSION

A server-oriented software architecture for urban simulations, based on standard interfaces (simulation as a service) and generally available data, with data integration via a 3D city model in a web browser, creates a tool that can reach a wide range of users. By enhancing the SimStadt energy simulation platform through linking it with a web-based interface and adding an economic analysis to a pilot workflow, such a tool was established. The tool´s usability has been tested with energy experts and non-experts, and their feedback was implemented. There is awareness that number of participants for the usability study was too very small to draw final conclusions, nonetheless the feedback was very valuable for the development of prototype layout of the GUI. More comprehensive usability studies with the revised tool are planned.

The tool in its current state allows users to calculate detailed photovoltaic potential in real-time; with this information, installation schedules can be devised that prioritize buildings based on amortization periods, or advertising campaigns that target neighborhoods with high PV yields first.

The simulation of the case study illustrates under which framework conditions the installation of inner-city PV systems is profitable. Since this kind of simulation depends on many factors such as local weather, costs or a given regulatory circumstances, it is important to be able to run multiple scenarios in real-time. In this respect, the presented tool provides the user with these options with a low entry barrier thanks to its browser-based GUI.

Table 3: Excerpt from the PV potential simulation and feasibility calculation of Stöckach for a selection of roof surfaces.

Building ID	Area	Irradiance	Nominal power	Yield	PV specific yield	Total investment	LCOE	Net present value	Internal rate of return	Financial feasibility
[-]	[m²]	[W/m²]	[kW_p]	[MWh/a]	[kWh/ (kW_p a)]	[EUR]	[EURct/ kWh]	[EUR]	[%]	[-]
0006b63	103.7	140.8	6	6.29	1,049	9,132	10.33	4,394	6.48	yes
0038d34	990.7	145.0	44	47.50	1,080	46,028	6.89	59,849	12.80	yes
001b05b	32.0	109.6	1	0.82	816	1,950	17.00	-320	0.21	no

5 CONCLUSION

The presented tool offers municipalities, urban planners, project developers or utilities the possibility to model costs and potentials of a renewable energy technology for areas comprising a few buildings up to an entire city, without sacrificing calculation accuracy. The browser-based architecture and GUI render the application accessible and intuitive, requiring no prior installation of software.

Applying the tool to a case study showed that the technical and financial results were consistent with other recent studies, both for the entire quarter as well as at individual building level. The fact that participant A in his function as climate protection manager applies the current version of the tool frequently to discuss potential PV locations with local businesses and the city council gives (anecdotal) evidence of its usefulness.

The advantage of the presented approach resides in the scalability of the application, which utilizes typically available 3D CityGML models as a foundation, which means that (i) spatial resolutions from single house perspective to whole cities are possible and (ii) further workflows, e.g. on building heating and cooling demands or refurbishment potentials, may be added with reasonable effort.

Since the methods presented here are generic, they will be transferred to other energy technologies that are already implemented in the desktop version of SimStadt, but also to new workflows, e.g., on socio-economic parameters such as income levels are rates of house ownership on district level. Such a tool can be an innovative, integral instrument enabling a more holistic planning of energy concepts at regional, city or neighborhood level early on in the decision-making process, as it integrates technical potentials, cost parameters and other decisive factors, such as rates of house ownership in a district, which is a relevant factor in decision making, e.g. with regards to building renovation or PV installations. Given its technology and manufacturer independent approach, such a tool would also create the necessary levels of transparency and trust in its results for decision makers to act upon.

ACKNOWLEDGEMENTS

The financial support provided by the Federal Ministry of Education and Research (BMBF) under the promotion and supervised by the project executing organization VDI Technologiezentrum GmbH for the project i_city is gratefully acknowledged. Furthermore, we like to thank Alexandra Mittelstädt and Chris Kesnar, which contributed also to the project.

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