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ORIGINAL PAPER

A holistic approach to model electricity loads in cities

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Abstract

Time-resolved, occupancy-dependent electricity load profiles at building level for city quarters or entire cities are important for planning authorities, project developers, utilities or other stakeholders in order to develop energy saving strategies and meet climate targets. Firstly, this information enables a more accurate modelling of renewable energy systems. Secondly, aspects like sector coupling, storage decisions and the impact of technologies such as electric vehicles or heat pumps on the grid can be considered. Thirdly, it allows a more detailed economic analysis. This paper contains the newly added features to the simulation environment SimStadt, which is used for strategic modelling of sustainable urban or regional areas with a spatial resolution at the building level. SimStadt interlinks 3D CityGML models with parameters for buildings physics to simulate energy demands and renewable energy potential. It was enhanced by the development of an electricity load profile generator with variable resolution and the addition of an hourly resolved PV potential analysis including a variable economic analysis. This enables e.g. the evaluation of photovoltaic potential with the associated investment, operating and levelized costs over the lifetime of hundreds of individual buildings in parallel. Together with additional electric building demand from heat pumps, electric vehicles or load shifting options through the use of battery storage, it will be possible to assess and compare the feasibility, benefits and economic viability of energy/electricity-related urban renewal measures in even greater detail and with a holistic perspective. The simulation platform enables the development of granular sustainable urban (sub)strategies and energy concepts through a holistic, time-resolved, building-specific approach to support transformation of the building stock to a sustainable, low-carbon one.

Keywords Energy Simulation Tool · Urban Modelling Environment · Urban Energy Concepts · Feasibility and Efficiency of Renewable Energies · Neighborhood Strategies · Stepless Scalability

Ein ganzheitlicher Ansatz zur Modellierung des Stromverbrauchs in Städten

1 Introduction

As buildings are responsible for about 40% of energy consumption and 36% of CO_2 emissions in the EU, making them the single largest energy consumer in Europe (European Commission 2020), mitigations in GHG emissions must still focus on the reduction of energy demands and energy systems in buildings. The use of renewable energy technologies, in particular in the building stock, needs to be considerably increased and smart energy system solutions need to be found. Additionally, these solutions should consider not only the technical feasibility but also financial aspects. Especially for key stakeholders like city officials or project developers and planners such solutions in the form of tools or approaches that simplify the energetic assessment of the building stock while considering technologically and financially feasible options for sustainable city quarter designs are needed. Such tools should enable a quantitative and technology-neutral verification of the technical and financial feasibility as well as local energy concepts on a granular level.

When looking at urban building energy modeling (UBEM) (Reinhart and Cerezo Davila 2016) differences

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regarding inputs, outputs and capabilities of available tools are noticeable. These differences are:

- Using 2D or 3D data as input data basis
- Modeling/Simulating demands or (renewable) energy system potentials or both
- Modeling/Simulating one energy system or several
- Modeling/Simulating one or several final energies
- Temporal resolution of modeling/simulating inputs and outputs
- Spatial resolution of modeling/simulating inputs and outputs
- Considering technical or financial parameters or both

Well-developed tools in this area like *TRNSYS* (Thermal Energy System Specialists, LLC 2020) or *EnergyPlus* (U.S. Department of Energy's Building Technologies Office 1996–2021) in combination with the graphical interface of OpenStudio (Brackney et al. 2018) offer user-friendly interfaces, operate on 3D building information and use very detailed information but because of their level of detail they cannot consider larger number of buildings, in particular in early planning stages, either due to lack of detailed information or due to computational constraints.

Simulation tools that aggregate data across districts, e.g. *FlexiGIS* (Alhamwi et al. 2018, 2019) or *EnerGIS* (Fazlollahi et al. 2014) are usually not accurate enough to provide meaningful results at the individual building or building block level (Schmid et al. 2018). Platforms like the Smart City Energy Platform *iGUESS* uses 2D data models and calculates PV systems or geothermal potentials, but does not consider cost parameters (Sousa et al. 2012). Urban platforms such as *Solarpotenzial 3D-Stadtvermessung Wien* use 3D data as an input and focus on the simulation of photovoltaic and solar potentials, but do not take cost parameters or other technologies into account (Stadt Wien 2018). A holistic approach is given by the platform *Re3ason* (Mainzer 2019) which analyzes energy demands, renewable energies as well their potentials (wind, photovoltaics, biomass), and adds a techno-economical optimization. The 2D spatial resolution however is restricted to municipal boundaries.

An overview of current GIS-based UBEMs gives (Alhamwi et al. 2019) whereas (Allegrini et al. 2015) shows an overview of some modeling approaches and tools for energy system simulation on the scale of city quarters thereby pointing out the challenges, such as providing and intuitive tool which is capable of supporting decision-makers at an early stage in the planning process as well as the need for tools that are able to perform parametric analyses at neighborhood level, taking economic and environmental parameters into account. (Meskel and Weber 2017) support these statements, based on a study of seven European cities and their applied tools for energy and urban planning. A lack of adequate tools for energy planning at city level and the need to improve diagnostic tools to support decision making at an early stage is identified.

The presented work summarizes and enhances an approach that on the one hand balances the complexity of modeling energy demands and potentials of renewable energy supply systems at building level for entire neighborhoods, city quarters or cities in stepless scalability with a high accuracy while applying necessary simplifications. On the other hand, it provides a structure and visualization, which enables the assessment of a quantitative and technology-neutral verification of the technical and financial feasibility using the 3D City Geography Markup Language (City GML) standard. The approach is demonstrated using the simulation platform SimStadt (Nouvel et al. 2015) and the therein newly implemented features of modeling building electricity demands and photovoltaic potentials together with a financial analysis.

2 Methodology

The methodology explained in this paper is divided in three sections. The first section briefly introduces the simulation platform SimStadt and its functionalities. The second and third section explain the newly added features to SimStadt.

2.1 Simulation platform SimStadt

The aim of SimStadt is the conception and development of an innovative and regionally usable software system for strategic low-carbon energy planning. With a 3D city model as the data basis, it can analyze the feasibility of energy efficiency and building refurbishment measures on the one hand and the integration of renewable energies including their grid-connected distribution on the other hand, and therefore offers new simulation and visualization possibilities. SimStadt has been developed in various research projects since 2012 and therefore already has a solid set of databases and calculation routines implemented (Nouvel et al. 2017; Romero Rodríguez et al. 2017). It is structured along modular workflows, whereby each workflow represents either an energy technology or a demand calculation.

SimStadt uses the open City Geography Mark-up Language (CityGML) (Coors et al. 2016), which describes a 3D urban building model, as main input source. Depending on the given information, a distinction of the CityGML files is made between the different levels of detail (LoD), in which LoD1 gives the extruded shape of the floor plan, LoD2 adds the roof shape, LoD3 windows, and LoD4 information about the building's interior layout (Groeger et al. 2012). For determining more realistic results, especially for photovoltaic rooftop potentials or refurbishment scenarios, LoD2 is essential.

On the basis of the imported 3D CityGML file and various databases, SimStadt utilizes the dynamic simulation engine INSEL (Schumacher 2021) by taking building geometries and local weather patterns into account.

So far, the photovoltaic rooftop potential (Romero Rodríguez et al. 2017), building heating/cooling demands (Braun et al. 2018; Nouvel et al. 2017) refurbishment scenarios and water demand calculations (Bao et al. 2020a) are implemented and validated workflows in SimStadt. Several more workflows e.g. biomass potential (Bao et al. 2020b) and heat pump feasibility (Weiler et al. 2019) can be assessed at the level of individual buildings and are undergoing a validation process.

In this paper, two further innovations of SimStadt are presented. Firstly, a prototype workflow for generating electricity load profiles has been developed, producing highly resolved electricity demand profiles for residential buildings. For this purpose, a methodology for determining the number of households and number of occupants per households for all types of residential buildings has been also established (Chap. 2.2). Secondly, the PV workflow was enhanced allowing hourly PV production calculations. Also, a size-dependent and user-modifiable economic analysis for PV systems was added (Chap. 2.3).

2.2 Household electricity load profiles

Since electricity consumption strongly depends on the behavior and the number of occupants in a household, the geometric building data derived from CityGML files, was linked to data from the German census. In a first step, the total number of households in a residential building is determined by dividing the heated area of a building (Nouvel et al. 2017) by the average German household area for multi-family houses (80.2 m²), apartment blocks (62.4 m²) and high-rise buildings (54.3 m²) (Destatis 2018). For these residential building types, the heated area is reduced by a factor of 41% in advance in compliance with (VDI 3807 Part 1, 2013) to account for service, circulation and structural areas of a building. The result is rounded to an integer. Single-family houses are exempt from this procedure as they are only supposed to have one household. Based on the reduced heated area and the total number of households per building, a frequency density distribution (FDD) derived from the German Census 2011 and a greedy algorithm are applied to assign the household areas to a building. The distribution of the FDD is divided into ten household area classes. With the exception of the first class, which contains the frequency of all households in Germany under 40 m², the following classes have a step size of 20 m², e.g. 40–59 m², 60–79 m², etc. Depending on the frequency, the heated area and the determined number of households per building, e.g. a multi-family house is filled up with households, whereby the value within a class is chosen randomly. After determining the household areas for each household in a building, the allocation of occupants to individual households is performed using a second FDD that links the household area to an estimated number of occupants. The second FDD is also derived from statistical data (Destatis 2014). It couples the household area classes to the probability of how many occupants are expected to live there, e.g. in 69.9% of all cases only one occupant lives the household area class of 40–69 m². The probability that two occupants reside in the same household area class is only 24.1% and the likelihood of three (4.5%) or four (1.5%) occupants is even lower. With these steps, every residential building is filled up with households and occupants.

The annual electricity demand of each household is thereafter estimated. For this purpose, the annual electricity demand specified in VDI 4655 Sheet 1, page 11 in kWh/occupant was modified. It is assumed that 75% of the annual electricity demand depends on the number of occupants and 25% on the area of the household (Pflugradt 2016). This modification was made to ensure a wider bandwidth in the calculation results of the annual electricity demand. Therefore, the annual electricity demand given in VDI 4655 is split into a 75% component share and a 25% component share. The occupant-dependent share is incorporated directly. The area-dependent share is converted into an area-related performance indicator (kWh/m²) using the average household area per person of 46.5 m² per occupant (Umweltbundesamt 2020). The resulting values for the occupant and area-dependent share are shown Table 1:

Table 1 Characteristic values for determining the annual electricity demand in households

No. of occupants	Occupant-dependent demand (75%)	Unit	Area-dependent demand (25%)	Unit
1 occupant	1763	kWh/Pers	12.6	kWh/m²
2 occupants	1515	kWh/Pers	10.9	kWh/m²
3 occupants	1238	kWh/Pers	8.9	kWh/m²
4 occupants	1125	kWh/Pers	8.1	kWh/m²
5 occupants	1050	kWh/Pers	7.5	kWh/m²
6 occupants (and more)	1013	kWh/Pers	7.3	kWh/m²

After the determination of the annual demand, the method of (Köhler et al. 2019) is applied for all residential buildings in order to generate load profiles in variable resolution.

2.3 Hourly PV potential and economic analysis

The workflow that calculates rooftop photovoltaic potentials within SimStadt (Eicker et al., 2018) was enhanced in order to model the hourly yield for PV systems of each roof top. A detailed weather model, which is simulated in the INSEL environment, is a prerequisite for the hourly PV potential analysis. Monthly values from a weather database with ground surface measurement data in INSEL are converted into hourly global horizontal solar radiation according to (Gordon and Reddy 1988), which is used to create a sky model according to (Hay 1993). With this weather model, the hourly yield is determined and normalized for each individual roof orientation that occurs. These normalized, hourly yields are then assigned to the geometry of the roofs.

Additionally, the PV workflow was extended by a further workflow step that enables the financial assessment of PV systems for each roof of a building. Several parameters are decisive for calculating the economic performance of PV systems. The necessary technical parameters are already known from previous workflow steps in SimStadt, such as the possible installed nominal power [kW_p], the potential electricity yield [MWh/a] and the specific electricity yield [$kWh/(kW_p$ per a)].

The newly added financial parameters and their default values are seen in Table 2. Each parameter is modifiable allowing parameter studies and the creation of simple scenarios to be carried out in real-time.

It should be noted, that the workflows for the generation of household electricity load profiles and the PV potential analysis with the economic assessment are not yet coupled yet, which is why the self-consumption rate has been set as a fixed value for the time being. This will be processed in future work.

Table 2 Default financial parameters for PV rooftop system assessment

Parameter	Value	Unit
Asset life time [a]	20	Year
Self-consumption rate [a]	30	%
Operating/maintenance cost as share cost of installation	1.0	%
Electricity cost (Germany) [b]	30.0	EURct per kWh
Feed-in tariff [c]	8.0	EURct per kWh
Cost of capital [d]	2	%

[a] (Fraunhofer ISE 2020) p. 24,71,8
[b] (Statistisches Bundesamt 2020) p. 48
[c] (Bundesnetzagentur 2020)
[d] (KPMG International 2020)

Since the costs for installing a PV system depends on the size of the system, a cost function that takes this dependency into account was created for the installation costs. The cost function is spanned through two customizable data points (S1 and S2), whereby S1 represents the installation costs in EUR/kW_p for a small rooftop PV system, e.g. 10 kW_p, and S2 a larger one, e.g. 100 kW_p. A logarithmic fitting function (see Eq. 1) is then applied through the two support points S1 and S2 and the installation costs are calculated accordingly.

$$C_i = A - B * \log(P_n/1kW_p) \tag{1}$$

where:

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

The cost digression factor dependent on S1 and S2. This factor is determined by Eq. 2:

$$B = \frac{(C_2 - C_1)}{\log(P_2 - P_1)} \tag{2}$$

where:

- C_1 = installation cost defined for S_1 [EUR]
- C_2 = installation cost defined for S_2 [EUR]
- P_1 = nominal power defined for S_1 [kWp]
- P_2 = nominal power defined for S_2 [kWp]

The operation and maintenance costs also depend on the size of the PV system and are therefore expressed as a percentage share of the costs of installations.

With these parameters, the values for the total investment [EUR], operation and maintenance costs [EUR/a], levelized costs of electricity (LCOE) [ctEUR/kWh], net present value (NPV) [€], internal rate of return (IRR) [%], payback period [a], discounted payback period [a] as well as a statement on financial feasibility [yes/no] are calculated.

3 Case study and results

To demonstrate the new features and the implemented methodology in SimStadt a section of the Stöckach district (see Fig. 1), a city quarter in central Stuttgart, was used as a case study. This area was selected based on the fact that it is a grid island and transformer measurements are available at 15-minute resolution. Additionally, annual building

Fig. 1 **a** Boundaries of grid isle in Stöckach, Stuttgart (OpenStreetMap contributors 2021); **b** 2D SimStadt GUI colors indicating the building height, *yellow* = lower buildings, *blue* = taller buildings, *red* = some of the missing buildings

electricity consumptions are available for evaluating the demand simulation.

The section includes about 240 buildings in (OpenStreetMap contributors 2021). SimStadt, respectivly the available CityGML file recognizes 207 buildings, whereby three buildings are excluded due to geometrical issues. 113 buildings are primarily used as residentail buildings. 43 buildings are unheated e.g. garages, 21 buildings belong to the industry sector, 12 are retail stores, nine are primarily office or administration buildings and six buildings are used for storage. 176 out of 204 buildings have only one usage type. The other 28 are indicated as mixed-usage buildings. The year of construction varies between 1934 and 2015. The Stöckach district has a relatively high population density of 6531 inhabitants per km^2, leading to 4810 inhabitants in this area (Landeshauptstadt Stuttgart 2020). With the proposed method, SimStadt calculates 1284 inhabitants living in 728 households in the selected section, which measures approximately 0.2 km^2. This corresponds well with the official population density data for this district.

Based on the imported CityGML file for the selected area, a total roof area of 36,184 m^2 is determined. However, only 36,094 m^2 are suitable for PV systems, as areas smaller than 20 m^2 are not considered for reasons of practicability. Furthermore, it is assumed that 30% of a flat roof area is technically feasible area for PV modules, taking into account the inclination and shading of the modules as well as roof edges and further rooftop installations, e.g. HVAC systems. For tilted roofs, this value lies at 40% (Bergner et al. 2018). The minimum roof insolation is a customizable parameter in SimStadt. It was set as 950 kWh/(m^2*a) as restriction. This value represents 80% of the maximum usable irradiation energy in the region and is considered the lower threshold for the suitability of PV systems (Landesanstalt für Umwelt Baden-Württemberg 2021). Roof areas that face north or have a high degree of shading are therefore not included. In this simulation, the 20-year average for temperature and global radiation is used.

Fig. 2 Hourly electricity demand and possible hourly PV yield for January and July 2018

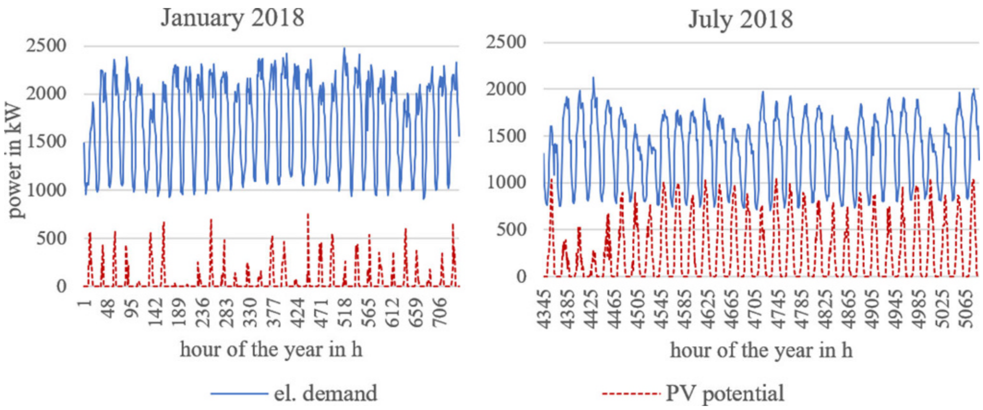

Table 3 PV coverage ratio of total electricity demand for selected area, aggregated hours over a year

PV coverage ratio	Hours in a year
≥ 100%	0 h
80–99%	2 h
60–79%	81 h
40–59%	640 h
20–39%	1172 h
> 0–19%	2141 h
= 0%	4724 h

Taking both restrictions into account, the utilizable roof area for PV is 31,186 m^2. On this basis, SimStadt calculates a total nominal power potential of 1427 kW_p with a potential yield of 1472 MWh/a. This potential contrasts with an annual electricity demand of the grid island of 12,808 MWh/a. At the city quarter level, the coverage rate of PV-produced electricity compared to the electricity demand is 11.5% on an annual average.

By looking at the grid island's time-resolved transformer data and comparing it to the hourly PV potentials for the entire quarter, a more detailed analysis is conducted. Fig. 2 shows the hourly electricity demand of the quarter for the months January and July in 2018 in blue. The hourly potential PV yield is indicated in red. Analyzing the time-resolved data over the whole year shows that the area's electricity demand can be met for more than 700 h a year by 40% or more. For approximately 1200 h per year, the coverage is between 20% and 40%; Table 3 summarizes these results.

However, the analysis at individual building level of the electricity demand for residential buildings in combination with the hourly PV potential analysis shows an even more differentiated picture. To demonstrate this, five buildings that show a small deviation from the simulated to the measured electricity demand were selected within the quarter for a more detailed analysis.

In the first part of Table 4, different simulated parameters for these five buildings are listed. Since a building can have several roof sections with different orientation and these may show different irradiances, several values can be displayed in the row for the specific yield. The second part of Table 4 presents the possible PV coverage rates, graded by percentage scales.

Building *A00033a9d* and building *A00011c5c* are both single-family houses with four occupants. Both show a comparatively low annual PV yield, and it can be seen that their roofs are not ideally oriented, as the specific yield only varies between 850–950 kWh/(kWp*a). Still, as expected, these single-family houses record high total annual coverage rates (32% and 40%) as well as a 100% coverage ratio for more hours per year than most of the other buildings, which are all multi-family houses. However, the largest multi-family house *A00014758* with 15 households and 29 occupants still achieves 16% total annual coverage through PV production, with about 900 h covered at 100% and another 900 h with a coverage between 60–100%. Nevertheless, this ratio is reversed when looking at the amount of possible surplus electricity. Here, the multi-family houses perform better due to their larger roof area and thus the higher installed nominal power. Since the feed-in tariff for PV production is steadily decreasing, but the price

Table 4 Top: simulated number of households, number of occupants and annual electricity demand in kWh for five residential buildings; Bottom: corresponding PV coverage ratios over the entire year 2018

Building ID	A00033a9d	A00014758	A00011c5c	A000278d8	A00010994
No. of households	1	15	1	7	5
No. of occupants	4	29	4	14	6
Annual el. demand in kWh	3757	36,602	4073	17,462	10,030
Number of feasible roof parts for each building	2	3	2	3	2
Annual PV yield in MWh	1.81	7.07	2.70	6.04	5.31
Specific yield in kWh/(kWp*a)	848/955	1000/1034	925/886	968/996/1017	995/862
Surplus electricity PV in MWh	0.51	1.22	1.07	2.27	1.77
Total annual PV coverage rate (%)	32	16	40	22	35
PV coverage ratio	Hours in a year	Hours in a year	Hours in a year	Hours in a year	Hours in a year
> 100%	1705 h	936 h	2119 h	1698 h	1720 h
81–100%	343 h	491 h	291 h	326 h	307 h
61–80%	353 h	508 h	344 h	376 h	331 h
41–60%	428 h	536 h	342 h	437 h	402 h
21–40%	500 h	638 h	386 h	467 h	489 h
> 0–20%	595 h	981 h	475 h	688 h	628 h
= 0%	4836 h	4760 h	4803 h	4768 h	4883 h

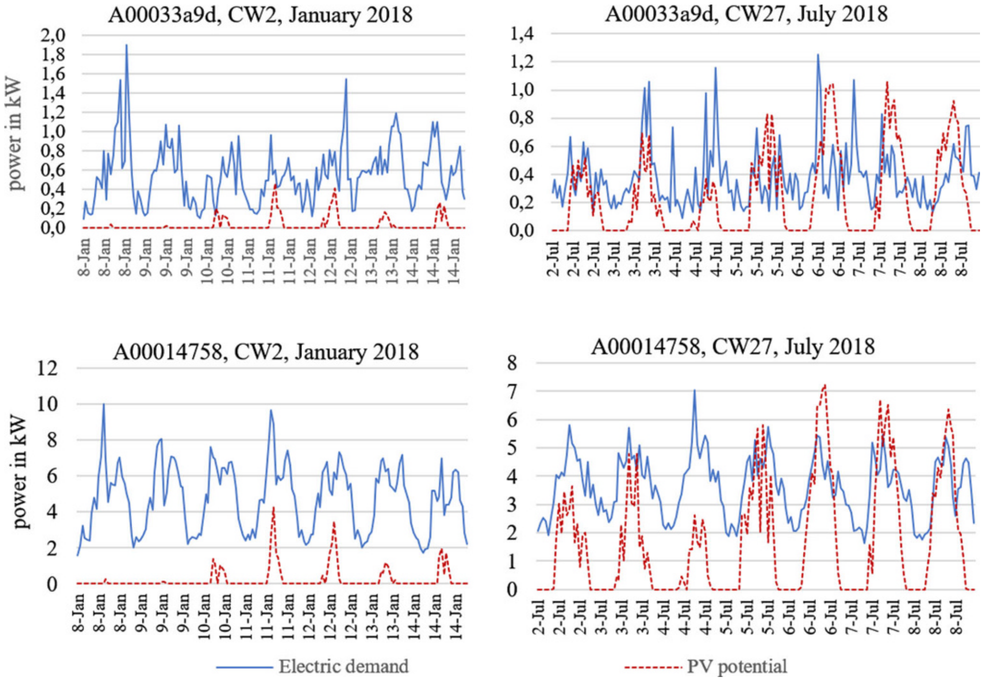

Fig. 3 Hourly simulated electricity demand and possible PV yield in kWh for calendar week 2 and calendar week 27, *Top*: for a single-family house; *Bottom*: for a multi-family house

for electricity from the grid is increasing, PV systems are becoming more and more attractive for multi-family houses as well. At the level of detail presented, the buildings that show the most promising technical and financial feasibility can be identified.

Fig. 3 visualizes the hourly simulated electricity demand and the potential PV yield for calendar week 2 in January and calendar week 27 in July 2018 for two of the buildings. Again, the electricity demand is shown in blue, while the red color marks the potential PV yield.

With the given opportunity of determining the technical potential of PV systems on a single-building level and on hourly basis, a detailed economic analysis can be performed. Using the default values in Table 2 and a cost function established with S1 referencing 1300€ for 10kW$_p$ and S2 referencing 1000€ for 100kW$_p$ (Fraunhofer ISE 2020), key parameters for the economic feasibility of PV systems in the chosen city quarter include:

- Total investments per roof range from 1600€ to 44,775€
- LCOE ranges from 7.38EURct/kWh to 13.95EURct/kWh, comparable with (Fraunhofer ISE 2020), where the LCOE ranges from 8 to 14EURct/kWh
- NPV ranges from 87€ to 50,998€
- IRR ranges from 2.55% to 11.63%
- Discounted payback periods range from 8.4 years to 18.8 years

Table 5 shows a sample of the layout of outputs from SimStadt. Each row indicates a roof part of a building. Therefore, the building ID A00033a9d appears two times, respectively building ID A00014758 three times because two/three suitable roof surfaces have been detected from the LOD2 CityGML file. Parameters marked in grey were already established, parameters in black are newly added through the introduced method in this paper.

4 Discussion

This paper introduces a methodology to simulate household electricity demand for all types of residential buildings as well as PV system potentials together with an economic analysis on a spatially and temporally resolved level. The results are presented at quarter level and on individual building level for a typical inner-city quarter stock in Germany, with predominately multi-family houses and perimeter block development. It is shown that supplying a dense inner-city quarter entirely with electricity from only local rooftop PV is not feasible and that PV can only act as a supplement and for peak shaving. This might imply that PV can only play a minor role in inner-city settings. Nonetheless, it is apparent, that high PV coverage ratios for some of the residential buildings can be achieved, which was not visible looking at aggregated city quarter scale. Furthermore, the influence of storage or demand side management possibilities from PV can be examined: while seemingly not necessary when looking at the whole area, surplus power is available for more than 2000 h for some buildings when taking the more granular view.

Table 5 Excerpt from the PV potential simulation and feasibility calculation of Stöckach for a selection of roof surfaces

Building ID	Azimuth	Tilt	Area	Irradiance	Nominal power	Yield	PV specific yield	Total investment	Operation & Maintenance costs	LCOE	Net present value	Internal rate of return	Discounted payback period
[–]	[°]	[°]	[m^2]	[W/m^2]	[kW$_p$]	[MWh/a]	[kWh/(kW$_{p*}$a)]	[€]	[€/a]	[c€/kWh]	[€]	[%]	[–]
A00033a9d	257	36	32.0	128	1	0.96	955	1600	16	11.9	418	4.5	15,2
A00033a9d	77	39	28.4	114	1	0.85	848	1600	16	13.4	164	3.0	17,8
A00014758	228	45	77.5	134	4	4.00	1000	5678	57	10.1	2943	6.8	12,3
A00014758	229	45	33.1	134	1	1.00	1000	1600	16	11.4	526	5.2	12,7
A00014758	138	46	37.8	139	2	2.07	1034	3019	30	10.4	1424	6.4	14,3

This procedure is applicable to hundreds of buildings in a CityGML file simultaneously, making it easy to find, for example, buildings with the highest potential or the best financial feasibility. The quarter-related but building-specific approach allows the German building stock to be assessed in this respect very time-efficiently and with a high level of detail. The flexible scalability of the application based on the 3D city model is seen as a major advantage, enabling any project scope from a single house view to the simulation of entire districts or cities, without having to sacrifice a huge part of calculation accuracy. In this context, the presented work can also serve as an instrument for urban planning, e.g. by investigating how urban structures influence PV yield/development.

Though, the electricity demand represents by no means the actual load profile or represent a forecast possibility it still shows the typical behavior and volatility of residential load profiles, considering simultaneities especially for multi-family houses and seasonal effects. The hourly PV yield is highly dependable on the input weather data. Since 20-year average data was used for this simulation it can also be said, that the result does not give an exact image of reality but they still help to evaluate PV systems on roof tops and give a helpful insight when conducting an economic analysis.

Since weather and cost factors are highly volatile, the presented approach offers the possibility to simulate different scenarios and conduct parameter studies, which can be adapted by various levers, a high degree of automation and reasonable computing times.

5 Conclusions

By developing a method for generating household electricity demands, which is applicable to all types of residential buildings and the analysis possible PV yield as well as economic parameters, SimStadt opens to a broader group of users and makes a more details analysis possible. This tool can be an innovative, integral instrument for the planning of energy concepts at city and neighborhood level for various stakeholders. For example, it offers municipalities and urban planners the possibility to model the economic impact of energy concepts with a consistent set of input data and the possibility of setting the system boundary from a few buildings up to a whole city quarter. For energy suppliers, it provides the opportunity to estimate the current and future energy demand of a neighborhood already connected to the grid and shows what potential exists for photovoltaics. For municipal authorities, it also enables the creation of installation plans that prioritize buildings based on payback periods or effects on grid stability. Though the idea of planning (urban) building structures in an environmentally friendly way is very laudable, amortization periods or internal rates of return are key criteria for most decisions towards or against implementing a higher share of renewable generation technologies. A technology- and manufacturer-independent evaluation creates the necessary transparency for municipalities to invest in the most effective and efficient measures to achieve a specific goal in sustainability. This provides a better assessment of energy options, minimizing the risk of additional expenditure, i.e. through constant review and, where appropriate, correction of adapted paths and strategies. Furthermore, the development, implementation and review of energy concepts can be made more consistent, cost-effective and efficient through partial automation.

The simulation results illustrate under which framework conditions the installation of PV systems pays off and whether and where, for example, storage systems should be considered. Although the case study represents a typical inner-city neighborhood in Germany, further studies seem appropriate to firstly assess the influence of different quarter structures and secondly to draw conclusions on the optimal orientation and structure of urban quarters.

All this requires a solid understanding of the associated potentials at a detailed, sub-urban level. To gain widespread support and acceptance, measures to reduce greenhouse gas emissions should be financially attractive and increase the quality of living. Climate protection measures should therefore meet multiple claims in order to provide attractive incentives for implementation. This approach is taking a step forward in achieving a transformation of city quarters into more sustainable ones. The tool and methods presented in this paper take a holistic approach for contributing to the transformation towards a sustainable building stock.

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