DISTRICTGENERATOR: A NOVEL OPEN-SOURCE WEBTOOL TO GENERATE BUILDING-SPECIFIC LOAD PROFILES AND EVALUATE ENERGY SYSTEMS OF RESIDENTIAL DISTRICTS

Joel David Schölzel[1]*, Tobias Beckhölter[1], Sarah Henn[1], Carla Wüller[1], Rita Streblow[1], Dirk Müller[1]

[1]Institute for Energy Efficient Buildings and Indoor Climate, Aachen, Germany

*Corresponding Author: joel.schoelzel@eonerc.rwth-aachen.de

ABSTRACT

In the early stages of neighborhood planning, crucial data such as demand profiles of electricity, heating, cooling, domestic hot water, and occupancy profiles are often not available. The absence of this data hampers accurate evaluations of energy systems in districts. To address this, the proposed *DistrictGenerator* (https://github.com/RWTH-EBC/districtgenerator) offers a pioneering approach by mapping entire urban building stocks in neighborhood models, enabling comprehensive evaluations of diverse neighborhood concepts. This paper introduces the *DistrictGenerator* workflow, demonstrating the aggregation of various data sources for the automated compilation of building component areas and U-values. This forms the basis for automated load profile calculations and dimensioning of distributed energy resources. The paper outlines the user interface parameters and explains underlying assumptions necessary for neighborhood model creation, including load profile generation. Furthermore, the paper describes the evaluation method via Mixed Integer Linear Programming (MILP), which maps energy systems, encompassing all energy flows, generators, and consumers. A comparative assessment of different districts is presented, defining various typical districts. Diverse technology scenarios are analyzed and evaluated, exploring varied systems, component dimensioning, and operational modes. This analysis encompasses factors like different storage types, heating systems or the impact of objective functions such as maximizing self-sufficiency, minimizing CO_2 emissions, or reducing peak loads. With the results we can examine and compare different technology and flexibility scenarios, determine the sensitivity of individual parameters and finally emphasize the influence of different operating objectives with regard to district planning.

1 INTRODUCTION

The transition towards sustainable energy systems is a pivotal agenda for the global community, aiming to achieve carbon neutrality. For example, the building sector in Germany consumes approximately 35 % of total end energy primarily for heating and hot water. With the ambitious goal to become climate-neutral by 2045, Germany embarks on a significant overhaul, replacing fossil fuel-based heating systems with climate-friendly alternatives, notably heat pumps (HPs), supported by governmental incentives. However, the shift towards sustainability in the building sector is not limited to HP installation but encompasses a broader integration of renewable energy technologies, such as solar photovoltaics (PV) and wind turbines. Additionally, the rapid adoption of electric vehicles (EVs) is set to significantly increase electricity consumption in neighborhoods. These developments introduce new challenges and opportunities for the power distribution grid, necessitating innovative approaches to manage the increased complexity and ensure reliability and efficiency. (Becker et al., 2023; Agora (Hrsg.), 2020; Wagner et al., 2021)

The energy transition in neighborhoods and their electricity distribution networks encounters two major challenges: managing peak loads due to high renewable energy feed-in from solar and wind sources,

https://doi.org/10.52202/077185-0106

and increased demand from HPs and EVs, potentially leading to power purchases with high simultaneity and necessitating network expansion. The integration of these renewable energy technologies further complicates energy management due to their variable nature. On the other hand, studies highlight the potential of demand-side management, such as smart charging of EVs and operational adjustments of HPs, to mitigate peak loads and reduce infrastructure investment needs. Digital building technologies have demonstrated significant potential to optimize energy use of these technologies and their possible combinations in various building types through operational optimization, suggesting considerable savings in energy consumption and emissions. (Beucker and Hinterholzer, 2022; Agora (Hrsg.), 2020)

Furthermore, the concept of energy-efficient neighborhoods emerged as a key to unlocking synergies among buildings sharing energy through their joint grid structure, offering new efficiency potentials and action options at local and regional levels. Studies examined the benefits of integrated optimization of energy systems at the district level compared to individual building optimization. In summary, it was found that optimizing energy systems for both electricity and heating at the district level leads to significant cost and self-sufficiency advantages over building-specific optimization. (Triebel et al., 2022)

The neighborhood thus offers a variety of possible energy measures to improve and systematically utilize energy storage management, generation, consumption, and energy balance. To successfully implement the energy transition in the neighborhood, it is crucial to identify suitable generation technologies tailored to the structural conditions and (seasonal) energy demands. Therefore, the successful realization of energy-efficient supply concepts for neighborhoods requires a holistic planning approach that includes an analysis and evaluation of various technological systems. Planning tools can support this process by assessing the various measures in their interaction and enabling decisions based on a scientific foundation. The experiences from research projects of the scientific accompanying research ENERGIEWENDEBAUEN show that at the beginning of neighborhood projects, data of varying quality are available, often making it difficult to evaluate and compare conceptual solutions early on. To address this issue and enable a comparison of different neighborhood concepts, a model-based approach is suggested. The representation of complete urban structures in neighborhood models and their subsequent analysis, therefore, require user-friendly tools that can be used by different stakeholders involved in neighborhood planning.

1.1 Development Process of Energy Systems in Neighborhoods

The development process of energy systems in neighborhoods encompasses several distinct phases, each crucial for achieving sustainable and efficient energy systems. The key phases of this development process are strategic planning, preliminary planning, detailed planning, implementation, and monitoring. A variety of stakeholders play integral roles in the development process, including investors, implementers, property owners, users, operators, and ideologically involved parties.

While the creation of a climate protection concept is not inherently part of the phases of energetic neighborhood development, it serves as a vital foundation. Such a concept builds upon existing data, establishing overarching goals and measures that provide a reliable framework for subsequent considerations. (Wrobel et al., 2016)

Strategic planning initiates the development process, adapting overarching goals to the neighborhood level and setting the course for further progress. This phase establishes initial conditions, identifies necessary existing data, conducts an analysis of the current state of the neighborhood, and considers forecasts for future development.

Preliminary planning, the subsequent phase, begins with technological research to determine the current state of available technology. Based on this research, a concrete implementation concept is devised, often involving the comparison of various alternatives. Financial assessments and sensitivity analyses are conducted to evaluate risks associated with different scenarios, considering the relatively uncertain nature of data and assumptions at this stage.

Detailed planning involves the creation of comprehensive plans required for implementation and the selection of companies to carry out the necessary work. Concurrently, a monitoring concept is

https://doi.org/10.52202/077185-0106

developed to assess the effectiveness of measures during and after implementation. **Implementation** involves the physical realization of planned measures, culminating in their handover to end-users. Subsequently, **monitoring** ensures smooth operation, evaluates the effectiveness of planned measures, and identifies opportunities for further optimization. (Wrobel et al., 2016)

Given the complexity of integrating various energy-efficient measures distributed over the different phases, planning tools play a pivotal role in facilitating decision-making based on scientific principles. These tools enable the evaluation of complex measures and combinations, aiding in the selection of optimal solutions for sustainable energy utilization in neighborhoods. Model-based planning tools allow for the depiction and analysis of the initial state as a reference scenario, followed by a comparison with alternative scenarios incorporating diverse measures and constraints. Such comparisons support decision-makers in identifying the most effective strategies for energy system development within neighborhoods. In conclusion, the development process of energy systems in neighborhoods entails a systematic approach involving strategic planning, detailed analysis, and continuous monitoring. Utilizing planning tools ensures informed decision-making, facilitating the creation of sustainable and energy-efficient urban environments. (Wrobel et al., 2016)

1.2 Existing Planning Tools for the Design of Energy Systems in Neighborhoods

It should be mentioned that only a national overview is given below, as the tool is being developed on the basis of the aforementioned national scientific accompanying research *ENERGIEWENDEBAUEN* and is being used specifically for German building types and neighborhood structures.

Within the *EG2050:E4Q* project, the *E^4Q* tool has been developed to create and analyze urban districts. This tool, operated through an Excel file interface, constructs the target neighborhood by selecting predefined archetype quarters. Subsequently, up to four supply and renovation concepts are chosen for comparative analysis. Each concept allows for adjustments to the renovation level or building envelope, as well as the provision of individual building services. Additionally, underlying conditions such as energy prices, interest rates, or cost functions of individual elements can be modified. However, it is important to note that altering these parameters may lead to erroneous inputs and tool malfunctions, as the corresponding scenarios may not be adequately represented in the underlying database. Ultimately, the tool yields seven assessment indicators, including but not limited to, final energy demand, greenhouse gas potential, total investment, and the self-consumption ratio of renewable electricity generated. (Koert and Müller, 2022)

Within the project *EnEff:Stadt* the Tool *District Energy Concept Adviser* was developed which aims at supporting the actors in the field of urban planning. It enables the user to identify the energy saving potential of various strategies in the areas of building construction, technical building systems, and centralized energy supply systems The tool can be installed locally on a computer. A graphical user interface allows the user to add buildings to a neighborhood using drag and drop. Building parameters can be adjusted in detailed menu fields. In addition, technology packages or individual technologies can be selected for the central supply and the supply of the individual buildings. Instead of simple benchmarks like average energy uses of building archetypes a calculation core is used for the energy performance assessment for single buildings in combination with various pre-configurations (as described above). The German standard DIN V 18599 (DIN 2009) is adopted for calculating the energy performance of individual residential and non-residential buildings. Based on ISO 13790 a monthly calculation procides. The calculation results are presented as delivered energy and primary energy, divided into energy carriers, CO_2 emissions and the renewable energy ratio. (Erhorn-Kluttig et al., 2013)

The *QuaSi* tool is freely available as a repository on *GitHub* and serves as a simulation software designed to address the energy supply and demand dynamics of buildings at the scale of city districts, particularly during the early stages of planning. *QuaSi* comprises three distinct simulation tools. The core component, *ReSiE*, is written in Julia and is dedicated to simulating the energy systems of urban neighborhoods. This simulation engine operates based on the principle of energy balances at the level

https://doi.org/10.52202/077185-0106

of individual technical equipment units, rather than providing a closed calculation of the entire system. Instead, it computes the operation of individual components based on the selected operating strategy and their interconnection in a predefined sequence. *GenSim*, another component of *QuaSi*, is utilized for generating high-resolution profiles of heating and cooling demands, as well as electricity consumption, for buildings with diverse usage types. The user interface of *GenSim* is built upon an Excel-based platform, facilitating user interaction and data input. Lastly, the *SoDeLe* tool is responsible for the calculation of photovoltaic systems, considering various orientations and types of PV modules. (Ott et al., 2023)

The tool developed within the research project *UrbanReNet* serves the purpose of balancing integrated energy supply concepts at the neighborhood level. By utilizing energetic urban space types, urban neighborhoods can be depicted and balanced both energetically and morphologically, with the tool allowing for the adaptation of typical building types. It assesses CO_2 emission reduction potentials and generates outputs such as end and primary energy consumption, as well as CO_2 emissions. Scenarios can be computed by varying different parameters, with a notable feature being the application of an optimization model to calculate peak load balancing between urban space types. To the best of the authors' knowledge, this tool is no longer open source. (v. Malottki and Koch, 2016)

The *GemEB* tool, also known as *GemeindeEnergieBeratung*, was developed at the Technical University of Munich and serves as a tool for energy master planning within settlement structures. It facilitates the calculation of the heating demand of individual buildings through automated Excel workbooks and was developed as part of the research program *EnEff:Stadt*. The tool takes into account the renovation state of buildings and allows for the analysis of potential savings through various measures. To the best of the authors' knowledge, this tool is no longer open source. (v. Malottki and Koch, 2016)

In summary, these tools already facilitate during the strategic and preliminary planning phases the identification of measures that support the detailed planning and subsequent implementation of sustainable and sector-coupling energy systems in neighborhoods, enabling cities and municipalities to make well-informed decisions. However, the models and calculation methods of the time series are often not transparent. For stakeholders such as smaller municipalities with limited resources, the complexity of these tools can be a barrier. Their user-friendliness is low, leading to potentially time-intensive applications. Furthermore, utilizing them may require specialized knowledge in energy planning, modeling, and data analysis, thus restricting access for less experienced users.

1.3 Contributions

Through the *DistrictGenerator*, we introduce an open-source web tool aimed at urban planners, energy suppliers, housing associations, engineering firms, architectural professionals, as well as academic and research institutions. Its user-friendly interface facilitates swift and straightforward utilization. This tool furnishes crucial insights into energy demands and generation, pivotal for the effective design and operation of any energy system. Consequently, users can discern actionable measures to harmonize energy supply.

Our contributions seek to advance the applicability of sustainable, cross-sectoral energy systems in neighborhoods, with a specific emphasis on exploiting synergy potentials among buildings of diverse usage structures through integrated concepts. We summarize the key contributions of the *DistrictGenerator* as follows:

- An open-source web tool with an intuitive user interface and minimal input requirements. Leveraging pre-set elements and default values of temporally resolved demand profiles, as well as decentralized heat generator sizing conforming to DIN standards.
- The tool enables the bottom-up representation of entire urban structures through neighborhood models, affording a sufficiently detailed analysis foundation.
- Facilitation of central operational optimization and presentation of analytical results and key performance indicators. This supports the examination of various neighborhood types and supply scenarios concerning technology selection and penetrations. We thereby create a

 https://doi.org/10.52202/077185-0106

platform for early-stage comparison of neighborhood concepts with the flexibility of selecting different variants, given the tool's rapid recalculations.

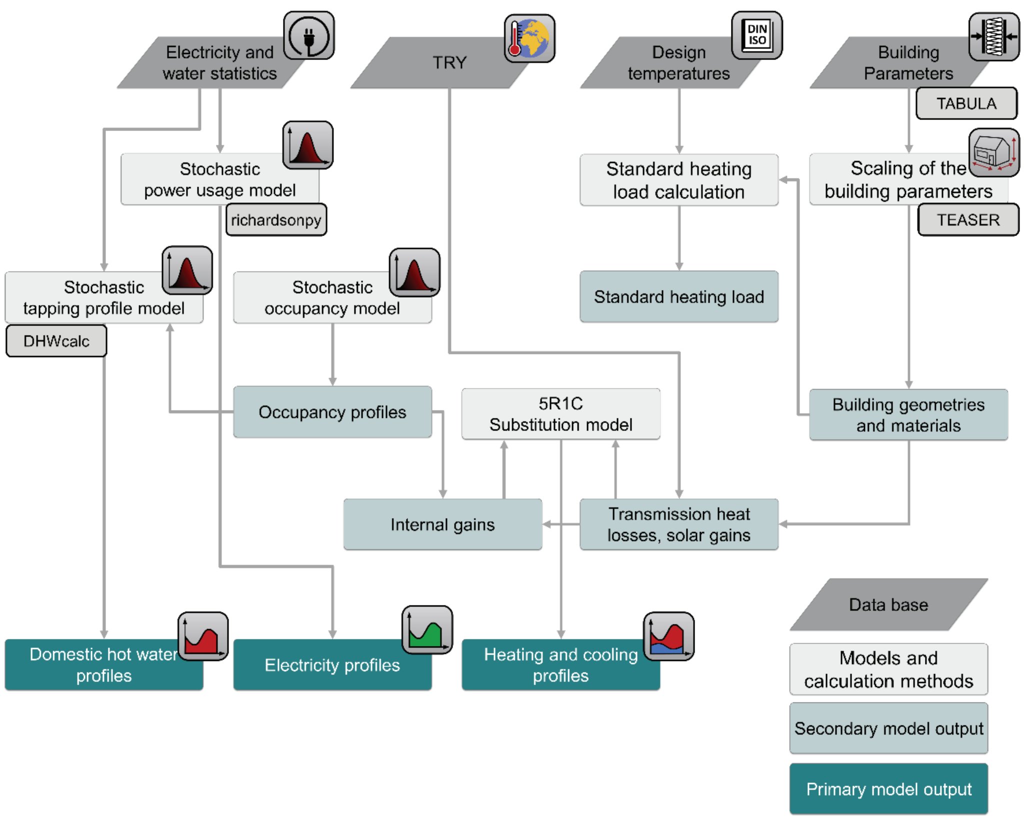
2 METHODOLOGY

In the first subchapter 2.1, we first explain the workflow of the *DistrictGenerator*, i.e. the use of external tools, models and data sources to obtain building-specific demand profiles. Then, in 2.2, we show the mathematical model on which the optimization calculations are based. In 2.3 we describe the scenarios examined and in 2.4 the Key Performance Indicators (KPIs) to evaluate the scenarios.

2.1 Workflow of the *DistrictGenerator* for the Generation of Building Specific Load Profiles

The district generator integrates multiple open-source tools and databases. Figure 1 visualizes the dependencies of external tools and data with internal functions. The user input for the parameterization of a neighborhood consists of a minimum of data. First, the user enters the number of buildings and basic information about each building, namely the building type, year of construction, retrofit level, and net floor area. The number of buildings to be calculated is not limited by the program. Optionally, the site of the district, the time resolution of the profiles and the test reference year (TRY) for weather data can be modified. All inputs are done via an user interface and directly forwarded to the Python model.

Figure 1: *Usage of external tools and data sources to generate results with the*



To obtain a fully parameterized building model, the TEASER tool performs a data enrichment with data from the TABULA WebTool and uses statistical and normative information about the building stock (Loga et al., 2015; Remmen et al., 2018). Finally, the TEASER python package determines the geometry and material properties of the buildings. As the TABULA WebTool defines archetypal building properties for type, age class and retrofit level, the generated districts are composed of representative buildings, making them ideal for representative analyses or scalability studies. The DIN

https://doi.org/10.52202/077185-0106

EN 12831-1:2017-09 (DIN EN 12831-1: Energetische Bewertung von Gebäuden - Verfahren zur Berechnung der Norm-Heizlast, 2017) provides standard design temperatures for various locations. Utilizing this standard, a heating load calculation is conducted. To ascertain the standard load for domestic hot water demand, the unit dwelling method outlined in DIN 4708-1:1994-04 (DIN 4708: Zentrale Wassererwärmungsanlagen - Begriffe und Berechnungsgrundlagen, 1994) is employed. Based on this, the tool calculates stochastic profiles. The richardsonpy tool generates occupancy profiles that fluctuates pseudo-randomly throughout the day, mirroring the natural behavior of individuals in their daily routines (Richardson et al., 2010). Based on this, the tool stochastically creates synthetic profiles of the electricity demand. With the DHWcalc tool the domestic hot water demand is calculated (Jordan et al., 2005). Therefore, it considers various factors such as the number of occupants, building characteristics and climate data to stochastically estimate the hot water usage patterns in a residential setting. Including all these tools the *DistrictGenerator* gives as output hourly demand profiles as csv. file for each building in the neighborhood.

An expansion stage of the *DistrictGenerator* includes technologies that can be assigned to each building. Based on that, firstly, the user will be given access to renewable energy generation data, like PV generation and solar thermal heat generation. Secondly, with a module for operation optimization the energy system of the district can be simulated and evaluated. The mathematical model and the key performance indicators will be explained in the following.

2.2 District Energy Model for the Operational Optimization

Model inputs consist of the hourly resolution building-specific demand profiles described above, as well as weather data (temperature profile, solar radiation profile). Additionally, emission factors, energy prices, etc. can be input. Further inputs include information about the energy system per building as well as the sizing of the devices. Additional details such as physical and technical parameters are to be specified. **Model outputs** are the results of operational optimization. These include, for example, the power output of each system at each time step during the analysis period. Furthermore, the model outputs aggregated values for neighborhood energy demand and local emissions during the analysis period. Operational optimization is performed independently for representative weeks. Representative weeks are identified by clustering the time series obtained for a year using time-series aggregation methodology, such as k-medoids. The frequency of occurrence of each type of week within a year is known. Based on this information, the optimization results can be extrapolated to a year in post-processing.

For each type of week, the following objective function is solved within the mixed-integer linear program. This function aims to minimize the total energy costs of the neighborhood $\boldsymbol{Cost_{NH}}$ while penalizing the peak power $\boldsymbol{P_{\mathrm{Peak}}}$ at the local grid transformer with a penalty factor. The variables of the optimization problem are represented in bold in the following equations, while the parameters are in normal font.

$$\min \quad \boldsymbol{Cost}_{\mathbf{NH}} = \boldsymbol{W}_{\mathbf{imp,elec}} * c_{imp,elec} - \boldsymbol{W}_{\boldsymbol{exp},\mathbf{elec}} * c_{imp,elec} + \boldsymbol{W}_{\mathbf{imp,gas}} * c_{gas} + pen \cdot \boldsymbol{P}_{\mathbf{peak}}$$

The emissions for the neighborhood's energy consumption are calculated as the sum product of the imported energy quantity $\boldsymbol{W}_{\mathbf{imp}}$ of an energy carrier and its cost factor c.
The peak power at the grid connection point corresponds to the maximum electricity demand occurring over the analysis period.

$$\boldsymbol{P}_{\mathbf{peak}} \geq \boldsymbol{P}_{\mathbf{imp,elec},\boldsymbol{t}} \quad \forall\, t \in T$$

The energy carriers considered in this study are electricity and gas. The imported energy quantity for both energy carriers is calculated as the integral of the power over all time steps t within the one-week analysis period.

$$\boldsymbol{W}_{\mathbf{imp,Elec}} = \sum_{t \in T} \Delta t \cdot \boldsymbol{P}_{\mathbf{imp,Elec},\boldsymbol{t}}$$

https://doi.org/10.52202/077185-0106

$$\boldsymbol{W}_{\mathbf{imp,Gas}} = \sum_{n\in N}\sum_{t\in T}\Delta t \cdot (\boldsymbol{P}_{\mathbf{imp,Gas,CP},\boldsymbol{n},\boldsymbol{t}} + \boldsymbol{P}_{\mathbf{imp,Gas,Boiler},\boldsymbol{n},\boldsymbol{t}})$$

However, electricity can be both consumed by and supplied to the low-voltage grid by buildings, allowing for exchange between buildings.

$$\boldsymbol{P}_{\mathbf{imp,Strom},\boldsymbol{t}} + \sum_{n\in N}\boldsymbol{P}_{\mathbf{exp,Elec},\boldsymbol{n},\boldsymbol{t}} = \boldsymbol{P}_{\mathbf{exp,Elec},\boldsymbol{t}} + \sum_{n\in N}\boldsymbol{P}_{\mathbf{imp,Elec},\boldsymbol{n},\boldsymbol{t}} \quad \forall n,t$$

The following electricity balance of a building ensures that any electricity purchased by or generated in the building is used in the building or fed into the grid.

$$\boldsymbol{P}_{\mathbf{imp,elec},\boldsymbol{n},\boldsymbol{t}} + P_{\mathrm{PV},n,t} + \boldsymbol{P}_{\mathbf{elec,CHP},\boldsymbol{n},\boldsymbol{t}} + \boldsymbol{P}_{\mathbf{BAT,dch},\boldsymbol{n},\boldsymbol{t}} = \boldsymbol{P}_{\mathbf{exp,elec},\boldsymbol{n},\boldsymbol{t}} + P_{\mathrm{household},n,t} + \boldsymbol{P}_{\mathbf{BAT,ch},\boldsymbol{n},\boldsymbol{t}} + \boldsymbol{P}_{\mathbf{elec,HP},\boldsymbol{n},\boldsymbol{t}} + \boldsymbol{P}_{\mathbf{elec,EH},\boldsymbol{n},\boldsymbol{t}} \quad \forall n,t$$

The thermal energy storage (TES) can be charged by all gas-based and electrothermal heat generators and discharged to meet space heating (SH) and domestic hot water (DHW) demand. The latter can be partially met by an electric heater (EH) depending on the heating supply temperature.

$$\dot{\boldsymbol{Q}}_{\mathbf{TES,ch},\boldsymbol{n},\boldsymbol{t}} = \dot{\boldsymbol{Q}}_{\mathbf{CHP},\boldsymbol{n},\boldsymbol{t}} + \dot{\boldsymbol{Q}}_{\mathbf{Boiler},\boldsymbol{n},\boldsymbol{t}} + \dot{\boldsymbol{Q}}_{\mathbf{HP},\boldsymbol{n},\boldsymbol{t}} + \dot{\boldsymbol{Q}}_{\mathbf{EH},\boldsymbol{n},\boldsymbol{t}} \quad \forall n,t$$

$$\dot{\boldsymbol{Q}}_{\mathbf{TES,dch},\boldsymbol{n},\boldsymbol{t}} = \dot{Q}_{\mathrm{SH}n,t} + \dot{Q}_{\mathrm{DHW},n,t} - \dot{\boldsymbol{Q}}_{\mathbf{DHW,EH},\boldsymbol{n},\boldsymbol{t}} \quad \forall n,t$$

$$\dot{\boldsymbol{Q}}_{\mathbf{DHW,EH},\boldsymbol{n},\boldsymbol{t}} \geq \dot{Q}_{\mathrm{DHW},n,t} \cdot \sum_{\mathrm{w}\in\Omega}\frac{\theta_{\mathrm{DHW}}-\theta_{\mathrm{VL}}}{\theta_{\mathrm{DHW}}-\theta_{\mathrm{RL}}}\, x_w \quad \forall n,t$$

The coupling of thermal generation and electrical or gas consumption is provided for the individual generators via the efficiency.

$$\boldsymbol{P}_{\mathbf{EH},\boldsymbol{n},\boldsymbol{t}} = \eta_{EH}\left(\dot{\boldsymbol{Q}}_{\mathbf{EH},\boldsymbol{n},\boldsymbol{t}} + \dot{\boldsymbol{Q}}_{\mathbf{DHW,EH},\boldsymbol{n},\boldsymbol{t}}\right) \quad \forall n,t$$

$$\dot{\boldsymbol{Q}}_{\boldsymbol{HP},\boldsymbol{n},\boldsymbol{t}} = COP_{HP,t} \cdot \boldsymbol{P}_{\boldsymbol{HP},\boldsymbol{n},\boldsymbol{t}} \quad \forall w,n,t$$

$$\dot{\boldsymbol{Q}}_{\mathbf{Boiler},\boldsymbol{n},\boldsymbol{t}} = \eta_{\mathrm{Boiler}} \cdot \boldsymbol{P}_{\mathbf{imp,Gas,Boiler},\boldsymbol{n},\boldsymbol{t}} \quad \forall n,t$$

$$\boldsymbol{P}_{\mathbf{CHP},\boldsymbol{n},\boldsymbol{t}} = \eta_{\mathrm{CHP,el}} \cdot \boldsymbol{P}_{\mathbf{imp,Gas,CHP},\boldsymbol{n},\boldsymbol{t}} \quad \forall n,t$$

$$\dot{\boldsymbol{Q}}_{\mathbf{CHP},\boldsymbol{n},\boldsymbol{t}} = \eta_{\mathrm{CHP,th}} \cdot \boldsymbol{P}_{\mathbf{imp,Gas,CHP},\boldsymbol{n},\boldsymbol{t}} \quad \forall n,t$$

The state-of-charge (SOC) of the thermal and battery energy storage at each time point is determined by the following energy balance. The coupling of thermal and electric or gas power consumption is provided for individual generators via the efficiency factor

$$\boldsymbol{SOC}_{\mathbf{TES},\boldsymbol{n},\boldsymbol{t}} = \phi_{\mathrm{TES}} \cdot \boldsymbol{SOC}_{\mathbf{TES},\boldsymbol{n},\boldsymbol{t-1}} + \Delta t \cdot \left(\dot{\boldsymbol{Q}}_{\mathbf{TES,ch},\boldsymbol{n},\boldsymbol{t}} - \dot{\boldsymbol{Q}}_{\mathbf{TES,d\,ch},\boldsymbol{n},\boldsymbol{t}}\right) \quad \forall n,t$$

$$\boldsymbol{SOC}_{\mathbf{BAT},\boldsymbol{n},\boldsymbol{t}} = \boldsymbol{SOC}_{\mathbf{BAT},\boldsymbol{n},\boldsymbol{t-1}} + \Delta t \cdot \left(\eta_{\mathrm{BAT,ch}}\,\boldsymbol{P}_{\mathbf{BAT,ch},\boldsymbol{n},\boldsymbol{t}} - \frac{\boldsymbol{P}_{\mathbf{BAT,d\,ch},\boldsymbol{n},\boldsymbol{t}}}{\eta_{\mathrm{BAT,dch}}}\right) \quad \forall n,t$$

2.3 Investigated scenarios with technology penetrations

In the following, we examine a typical German settlement structure in a rural area with 27 single-family houses and (SFH) 13 multi-family houses (MFH). The year of construction is 1984.The building energy systems of the SFH and MFH within the neighborhood are equipped either with heat pumps or gas boilers. Electricity generation is achieved by PV systems in selected scenarios. Thermal storage and electrical battery storage systems are also taken into account. The technology penetrations vary across the studied scenarios and are presented in table 1.

In this study, we size thermal energy storages with the given amount of liters per kW thermal power of the respective heat generator. In the scenarios with PV systems, 40 % and 80 % of the SFH and MFH

https://doi.org/10.52202/077185-0106

roof areas are covered by PV modules, whereby the peak power is about 5 kW and 27 kW. Furthermore, we use the battery storage capacity of 5 kWh for SFH and 30 kWh for MFH.

Table 1*: Technology penetrations of the investigated scenarios within the neighborhood*

Scenario	HP	Boiler	PV	BAT	TES
1	0 %	100 %	-	-	~ 70 l/kW
2	40 %	60 %	-	-	~ 70 l/kW
3	80 %	20 %	-	-	~ 70 l/kW
4	40 %	60 %	40 %	-	~ 70 l/kW
5	40 %	60 %	80 %	-	~ 70 l/kW
6	40 %	60 %	80 %	-	~ 140 l/kW
7	40 %	60 %	80 %	40%	~ 70 l/kW

We analyze the results based on the optimization of four typical weeks of the time series, determined using the k-medoids clustering method. The electricity price for the electricity purchase is the average electricity price in Germany, 46,91 ct/kWh, in 2023 (BDEW, 2023) and 8,11 ct/kWh is the price for PV-generated electricity when sold to the higher grid level. The gas price is 10,8 ct/kWh. Regarding the CO_2-equivalent emission factors, we have assumed that electricity purchased from the higher-level grid causes 0,434 kg/Wh and gas consumption 0,202 kg/Wh.

2.4 Key Performance Indicators for the Evaluation of the District Energy System

The different scenarios described in subsection 2.3 and their operation are analyzed and evaluated with the following KPIs. The accounting applies to all KPIs for the entire quarter. The results of the type weeks were extrapolated to a full year using the weighting factors.

- Energy costs: summed energy costs of the neighborhood.
- Demand-Cover-Factor (DCF) and Supply-Cover-Factor (SCF): two energetic indicators that are calculated based on load and feed-in profiles of the building energy system. With them the coverage of the local electrical load by the local electrical generation and the share of self-used generation within the neighborhood are calculated. (Müller et al., 2017)
- Peak load: incurred during operation measured at the neighborhood's grid connection point.
- Emissions: caused by device operation in the neighborhood.

3 RESULTS AND DISCUSSION

The results for the described scenarios are analyzed below. First, the influence of the technology mix on the CO_2-equivalent emissions and the district energy costs is examined. Further analyses of the electricity supply based on the DCF and SCF as well as the grid load based on the peak loads for the scenarios with different flexibility potentials are described.

3.1 Impact of the heat pump penetration

In figure 2, the caused emissions and the energy costs for district operation are depicted. In scenario 1, a total of 393 tons per annum (t/a) are emitted, with 35 % resulting from electricity consumption and 65 % from gas consumption. With a heat pump share of 40 % in Scenario 2, emissions amount to 372 t/a, representing a reduction of 21 t/a. In this scenario, 58 % of the emissions are attributable to electricity consumption and 42 % to gas consumption. In Scenario 3, where 80 % of buildings are supplied with heat pumps, the emission volume is 351 t/a, with the majority, 84 %, caused by external electricity consumption and 14% by gas consumption. The gas consumption in Scenario 4 remains the

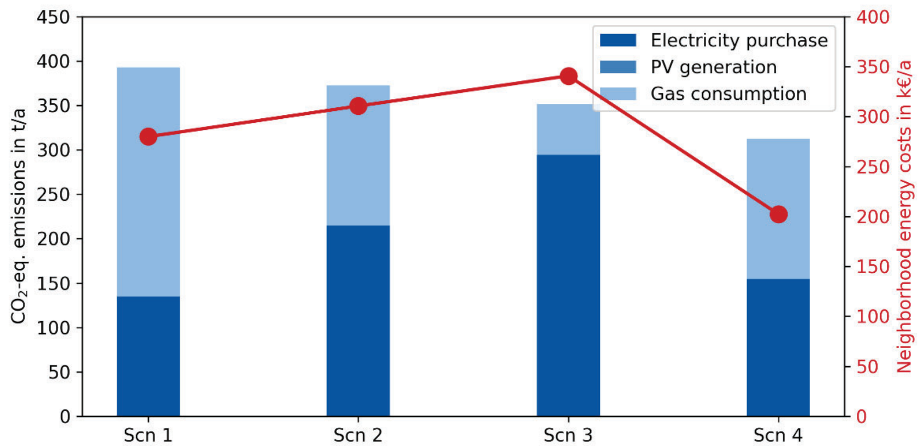
https://doi.org/10.52202/077185-0106

same as in Scenario 3 due to an equivalent proportion of gas boilers in the district. However, its share of the total emissions, 313 t/a, accounts for 50.5 %, because electricity procurement from the higher-level network layer is reduced due to PV electricity generation in the district. Consequently, external electricity procurement is responsible for 49.5 %.

Regarding the resulting energy costs of the district, figure 2 shows an increase from 280.000 euros per annum (k€/a) in Scenario 1 to 311 k€/a in scenario 2. The highest costs are incurred in scenario 3, amounting to 341 k€/a, which represents a relative increase of 22 % compared to scenario 1. The lowest energy costs for the district are 242 k€/a in scenario 4, which can be attributed to local PV electricity generation significantly reducing external electricity procurement.

The fact that emissions decrease with higher heat pump penetration while energy costs increase is justified by the CO_2-equivalent factors and the energy costs of the respective energy carriers. Considering the ratio of CO_2-equivalent factors and the specific energy costs of electricity to gas, which are 2,15 and 4,34, respectively, the different impacts on emissions and costs can be explained.

***Figure 2**: CO_2-equivalent emissions and the district energy costs*



3.2 Impact of the flexibility provision in energy supply and peak loads

Figure 3 illustrates the DCF and the SCF for scenarios 4 till 7. In scenario 4, the DCF amounts to 20 %, and the SCF to 69 %. The doubling of PV plant capacity in scenario 5 increases the DCF to 23 %. Conversely, the SCF decreases to 45 %. This reduction, larger than the increase in DCF, is attributed to the fact that a significant portion of the additional electricity generation is not consumed within the district due to lack of demand but is fed into the higher-level grid. Scenario 6 maintains the same penetrations of heat generators and PV plants as scenario 5. Additional flexibility in this scenario is provided by larger thermal energy storage systems, charged by the heat pumps. Despite this added flexibility, compared to scenario 5, the DCF remains at 23 %, and the SCF at 45 %. Therefore, the doubled capacity of thermal energy storage does not increase operational flexibility, as the operation of heat pumps, covering thermal demands, is already maximally flexible with the smaller TES. Scenario 7 also has the same equipment penetrations as Scenario 5. However, battery storage is integrated into the energy systems of 40 % of buildings with PV installations. Consequently, the DCF in scenario 7 is the highest among the scenarios at 39 %, with the SCF at 62 %. The findings thus indicate that battery storage is more suitable than larger TES for enhancing the local energy supply of districts with high penetrations of HPs and PV systems.

https://doi.org/10.52202/077185-0106

Figure 3: *DCF and SCF for the scenarios with different flexibility potential*

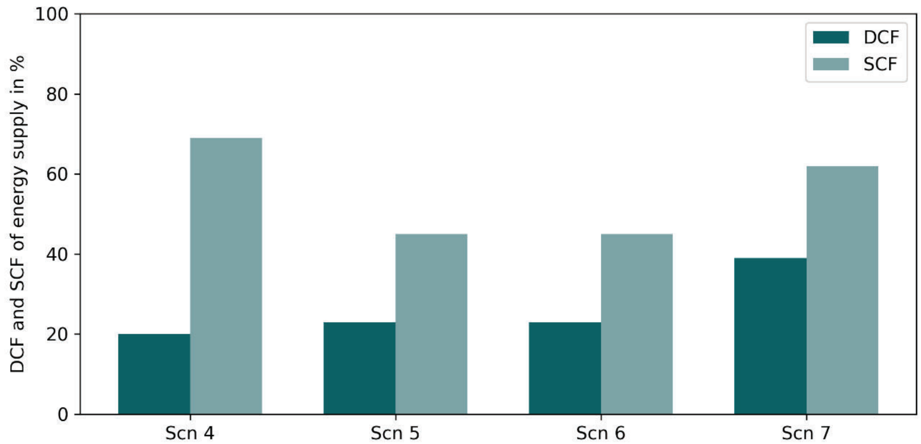
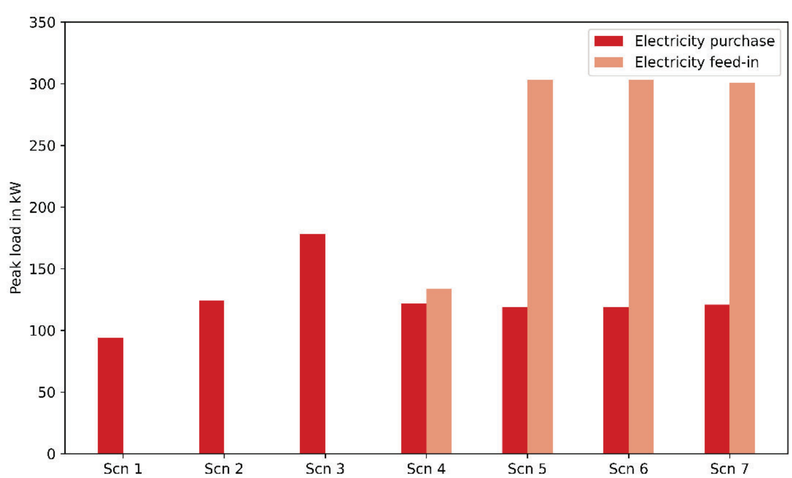


Figure 4 presents the peak loads in kW for various scenarios, divided into peak load due to electricity consumption and electricity feed-in. For scenarios 1 to 3, due to the absence of electricity generation facilities, only values for the peak load from electricity consumption are provided, which increases from 94 kW to 178 kW as the number of heat pumps increases. In scenario 4, the peak load decreases to 122 kW due to feed-ins from PV electricity generation. In scenario 5, it further decreases by only 3 kW to 119, indicating that with a 40 % share of PV systems, the electricity demand is almost entirely met during the times of electricity feed-in. In scenarios 6 and 7, the peak load is 119 kW and 120 kW, respectively. Despite additional flexibilities, the peak loads due to electricity consumption are not reduced. This demonstrates the extremely low simultaneity of electricity consumption and feed-in by the PV systems and heat pumps, accordingly offering little flexibility when PV-generated electricity is fed into the grid. Starting from scenario 4, peak loads due to electricity feed-in are also shown, amounting to 134 kW in scenario 4 and rising to over 300 kW in scenarios 5 to 7. These values further underscore the extremely low simultaneity of electricity consumption and feed-in during the periods studied.

Figure 4: *Peak load for electricity purchase and feed-in*



https://doi.org/10.52202/077185-0106

4 CONCLUSIONS

In this paper, we presented the functional principle of our open-source neighborhood generator tool, with which we can support the stakeholders involved in the early planning phases of neighborhoods with initial data and building-specific demand profiles of the neighborhood.

Using a district as an example, we demonstrated the evaluation function of the district generator, with which we can very quickly, less than 5 minutes calculation time per scenario, analyze various supply scenarios with different system technology. This gives the user a further opportunity to establish a decision basis based on various key performance indicators to determine the direction in which neighborhoods should be developed in terms of their energy supply structure.

In particular, the cost benefits and the selected objective function, which primarily minimizes the energy costs resulting from district operation, but also reduces the peak loads considered by a penalty meter, only arise in reality if appropriate management systems and (financial) incentives are implemented within the district during the operating phase. These incentives can be realized within the framework of energy communities, for example. Nonetheless, the results from the district generator are to be understood as an analysis of potential, which enables the comparison of different district concepts. In the further conception and implementation phases of the district, the objectives from the planning phase must be pursued accordingly in order to achieve similar results in real operation.

REFERENCES

Becker, S., Hagen, J., Saikiran, J., Krüger, R., De La Serna, S., 2023. Dena-Gebäudereport 2024 - Zahlen, Daten, Fakten zum Klimaschutz im Gebäudebestand.

Beucker, S., Hinterholzer, S., 2022. Einsparpotenziale aus der Optimierung von Heizungsanlagen in Wohngebäuden.

DIN 4708: Zentrale Wassererwärmungsanlagen - Begriffe und Berechnungsgrundlagen, 1994.

DIN EN 12831-1: Energetische Bewertung von Gebäuden - Verfahren zur Berechnung der Norm-Heizlast, 2017.

Erhorn-Kluttig, H., Erhorn, H., Weber, J., Wössner, S., Budde, E., 2013. The District Energy Concept Adviser: a software tool to support urban decision makers in planning district energy supply schemes.

Jordan, U., Vajen, K., Kassel, U., 2005. DHWcalc: PROGRAM TO GENERATE DOMESTIC HOT WATER PROFILES WITH STATISTICAL MEANS FOR USER DEFINED CONDITIONS.

Koert, J., Müller, A., 2022. E4Q - Einbindung erneuerbarer Energieträger in die Energieversorgung vernetzter Quartiere.

Loga, T., Stein, B., Diefenbach, N., Born, R., Institut Wohnen und Umwelt (Eds.), 2015. Deutsche Wohngebäudetypologie: beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden ; erarbeitet im Rahmen der EU-Projekte TABULA - "Typology approach for building stock energy assessment", EPISCOPE - "Energy performance indicator tracking schemes for the continous optimisation of refurbishment processes in European housing stocks," 2., erw. Aufl. ed. IWU, Darmstadt.

Müller, D., Monti, A., Stinner, S., Schlösser, T., 2017. Energieoptimiertes Bauen.

Ott, E., Steinacker, H., Stickel, M., Kley, C., Fisch, M.N., 2023. Dynamic open-source simulation engine for generic modeling of district-scale energy systems with focus on sector coupling and complex operational strategies. J. Phys.: Conf. Ser. 2600, 022009. https://doi.org/10.1088/1742-6596/2600/2/022009

Remmen, P., Lauster, M., Mans, M., Fuchs, M., Osterhage, T., Müller, D., 2018. TEASER: an open tool for urban energy modelling of building stocks. Journal of Building Performance Simulation 11, 84–98. https://doi.org/10.1080/19401493.2017.1283539

Richardson, I., Thomson, M., Infield, D., Clifford, C., 2010. Domestic electricity use: A high-resolution energy demand model. Energy and Buildings 42, 1878–1887. https://doi.org/10.1016/j.enbuild.2010.05.023

https://doi.org/10.52202/077185-0106

Triebel, M.-A., Steingrube, A., Stryi-Hipp, G., Reggentin, P., 2022. Modellierung Sektorintegrierter Energieversorgung im Quartier.

v. Malottki, C., Koch, T., 2016. Erweiterte Bilanzierung von Energieverbrauch und CO2 Emissionen auf Quartiersebene.

Verteilnetzausbau für die Energiewende – Elektromobilität im Fokus, 2020. . Agora Verkehrswende, Agora Energiewende.

Wagner, J., Namockel, N., Gruber, K., 2021. Ökonomische Bewertung des Nutzens lokaler Koordinationsmechanismen in der Stromversorgung.

Wrobel, P., Schnier, M., Schill, C., Kanngießer, A., Beier, C., 2016. Planungshilfsmittel: Praxiserfahrungen aus der energetischen Quartiersplanung.

ACKNOWLEDGEMENT

We gratefully acknowledge the financial support by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), promotional reference 03EWB003B.

https://doi.org/10.52202/077185-0106