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Open access decision support for sustainable buildings and neighborhoods: The nano energy system simulator NESSI

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ABSTRACT

The urgency of climate change mitigation, rising energy prices and geopolitical crises make a quick and efficient energy transition in the building sector imperative. Building owners, housing associations, and local governments need support in the complex task to build sustainable energy systems. Motivated by the calls for more solution-oriented, practice-focused research regarding climate change and guided by design science research principles, we address this need and design, develop, and evaluate the web-based decision support system *NESSI*. *NESSI* is an open-access energy system simulator with an intuitive user flow to facilitate multi-energy planning for buildings and neighborhoods. It calculates the technical, environmental, and economic effects of 14 energy-producing, consuming, and storing components of the electric and thermal infrastructure, considers time-dependent effects, and accounts for geographic as well as sectoral circumstances. Its applicability is demonstrated with the case of a single-family home in Hannover, Germany, and evaluated through twelve expert interviews.

1. Introduction

To mitigate the effects of climate change, global greenhouse gas (GHG) emissions must be substantially reduced. The building sector is considered one of the most emission-intensive, as building operations account for 27% of total energy sector emissions. In addition, the energy supply of buildings accounts for 30% of global energy consumption [1]. Based on these statistics, it is evident that the sustainable transformation of residential and commercial buildings is critical to achieve international climate (e.g., Paris Agreement) and development goals (e.g., United Nations Sustainable Development Goals). Recent political-economic developments such as Russia's invasion of Ukraine, persistent supply chain bottlenecks due to the Covid-19 pandemic, and rising inflation, significantly affected energy markets resulting in sharply rising energy prices [2]. As a result, emission-intensive countries (e.g., Germany and the United Kingdom) have defined goals and supporting measures for achieving energy transitions more quickly and efficiently. They set laws and policies toward fostering supply security, environmental as well as climate protection, and high efficiency in the energy sector [2]. The current developments and rising government support have additionally raised awareness of alternative energy supply among the general population and led to an upswing in the implementation of renewable energy systems in residential buildings, companies, and communities [2].

Thus, building owners, housing associations, and local governments are faced with the complex task of accommodating the often conflicting goals of cost-effectiveness, energy resilience, and environmental friendliness while transforming their building or neighborhood energy system. In particular, inexperienced stakeholders require intuitive and easily accessible decision support that is both accurate and reliable. Energy consultants are in higher demand than ever and equally need adequate tools to support their clients' decisions.

The Information Systems (IS) Research community has acknowledged this need and has been calling to use the transformative power of IS to provide solution-oriented, relevant studies that address climate change [3,4]. Moreover, Lehnhoff et al. [5] encourage solutions that reduce carbon emissions and explicitly state the value of decision support systems (DSS) that promote sustainable energy systems. Mathematical models, particularly multi-criteria DSS, have proven to reduce real-world complexities in decision problems [6]. Therefore, various energy models and software tools have been developed to reflect and combine the conflicting environmental, economic, and technological goals of sustainable energy transitions. However, based on

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various literature reviews, software evaluations, and open-source model analyses, we have found that tools are often too specific in terms of accessibility, standard functionality, purpose and/or structure of the model, geographic and/or sectoral coverage, time horizon, and temporal resolution. Groissböck [7] and Chang et al. [8] additionally state that most tools lack "out-of-the-box" functionality, which decreases their usability. Mavromatidis et al. [9] further criticize the missing connection and dissemination of academic energy models to practitioners. They urge closing that gap, as these tools solve real-world energy problems by enhancing and facilitating energy system planning and energy policy design. They particularly stress the importance of user-friendly, accessible models that satisfy industry needs.

Therefore, we introduce the design science research (DSR) based DSS *NESSI* (Nano Energy System Simulator) that provides the above-mentioned stakeholders with a scientifically rigorous energy system analysis tool, enables economically and environmentally sound decision support, and meets literature-, stakeholder-, and evaluation-based requirements. The article is structured along Gregor and Hevner [10]'s DSR publication schema. First, we elaborate on related DSS and energy system analysis tools in the literature review in Section 2 and derive requirements for our DSS. We then describe the employed DSR approach of Peffers et al. [11] in Section 3. In Section 4, we describe the DSS artifact thoroughly and demonstrate its applicability. Then, we present the evaluation results in Section 5. Finally, in Sections 6 and 7, we discuss implications for practice, limitations, and outline our conclusions.

2. Literature review, objectives, and requirement definition

According to Gregor and Hevner [10], the literature review section must include existing descriptive theory, prescriptive knowledge or artifacts with similar aims and scope. In the following, we consider energy system analysis-related models and software tools in academic literature as related artifacts. Due to the various dimensions regarding energy system planning and analysis, comprehensive tools are required for an informed and structured decision-making process. For this reason, various energy models and software tools have been developed that address and combine the conflicting goals by considering various pre-selected environmental, economic, and technological criteria. Comprehensive literature reviews (e.g., [6,7,12–16]) prove the wide range of energy models, each specialized in addressing particular problem classes or statements. Chang et al. [8] recently provided a summary of energy system modeling review articles. They classified 42 review articles from the last 20 years, underlining the extent of this research field.

The conceptualization of *NESSI* began in 2018 with the objective to address the formulated problem in Section 1 with a DSR-based DSS. Based on a literature review at that time, we have not identified any energy model or software tool that provides a sufficient solution. We have analyzed a variety of established software tools (e.g., *RETScreen* [17], *HOMER* [18], *iHoga* [19], *Hybrid2* [20], etc.) which we briefly summarize in the following.

RETScreen (link) was developed by Natural Resources Canada's CEDRL and its first version released in 1988. The software was specifically developed to assist in the preliminary assessment of potential renewable energy projects by evaluating the energy production, life-cycle costs, and GHG emission reductions for different types of renewable energy technologies using various Excel spreadsheets [17]. *RETScreen* is a desktop tool only available for Windows. It has comprehensive functionality but lacks an intuitive user flow for inexperienced users.

HOMER (link) and *iHoga* (link) are widely-known tools that conduct comprehensive techno-economic optimizations determining optimal sizing of components while minimizing net cost [18,19]. Developed by National Renewable Energy Laboratory of the United States of America and copyrighted by the Midwest Research Institute, the user can choose between *HOMER Pro* and *HOMER Grid*. The tools simulate the operation of hybrid microgrids and grid-connected systems by performing energy balance calculations at each time step (minute-by-minute to hour-by-hour) of a year. *HOMER* compares the electrical and thermal demand with the generated or supplied energy, calculates the energy flows, and then determines both the feasibility and the cost of the configuration. The software either uses a grid search algorithm to simulate all possible system configurations defined by the search space or a proprietary derivative-free optimization logic to find the most cost-effective system [18]. *iHOGA* and *MHOGA* are two versions of the *HOGA* software, developed at the University of Zaragoza (Spain) for the simulation and optimization of power generation systems based on renewable energies. *iHOGA* is designed for power systems up to 5 MW and *MHOGA* power systems without limit. As with *HOMER*, different traditional and renewable systems isolated from the grid or connected to the grid can be considered, and their optimization (based on genetic algorithms) is performed by minimizing the net present cost, maximizing the total net present value, or minimizing the electricity production cost. Particularly, this software includes control strategies for stand-alone systems and for grid-connected systems, which can be optimized [19]. Similarly to *RETScreen*, *HOMER* and *iHOGA* are desktop tools and have no easy-to-understand user flow. In addition, they are commercial tools and use lengthy optimization algorithms.

Hybrid2 (link) is a software package developed by the Renewable Energy Research Laboratory of the University of Massachusetts. It is a probabilistic computer model that uses time series data for loads, wind speed, solar radiation, temperature, and the user-designed or selected energy system to predict hybrid system performance. Variations are incorporated into the performance predictions at each time step using statistical models. This tool package, however, is currently not further maintained, leading to decreased usability over time through operating system restrictions [20]. The deterministic model *EnergyPLAN* (link) has been developed and extended by the Department of Development and Planning at Aalborg University since 1999. Its main purpose is to assist in the design of national or regional energy planning strategies covering the entire national or regional energy systems, including heat and power supply, as well as the transport and industrial sectors. The focus is on the future energy system, so *EnergyPLAN* includes future technologies such as biomass gasification and synthetic fuels [21]. Due to its scope, it is not suitable for individual buildings and neighborhoods.

To evaluate existing open license and open source energy models, we have analyzed more than 80 listed models by the *openmod* initiative (link). We investigated the models based on sector coverage, model class, type, geographic resolution, and scenario calculation to determine their applicability to the problem. We have adopted the *pvlib* model (e.g., [22]) and the *LoadProfileGenerator* model (e.g., [23]) from the *openmod* initiative. Those models are used to calculate the performance of photovoltaic systems and generate load profiles of households. However, the vast majority of models had weaknesses in one or more of our criteria. Models that met all criteria were still inadequate in their accessibility, usability, and installation requirements.

Based on the analysis of previous literature reviews and *openmod* models, we identified various software tools. However, each has shortcomings regarding our research goal: They are overly specific in terms of accessibility, out-of-the-box functionality, purpose of the model, structure of the model, geographical and/or sectoral coverage, time horizon, and temporal resolution. Recent literature reviews confirm that especially property rights and lack of out-of-the-box functionality impede the application of energy models and tools for users [7,8]. To ensure that our DSS meets the above-mentioned criteria, we determine objectives for a rigorous software development. We follow Walling and Vaneeckhaute [24]'s criteria for environmental DSS and differentiate between stakeholder-, model-, and system-oriented requirements.

Stakeholder-oriented objectives

Regarding the first category, we define stakeholders as citizens that own/manage residential or commercial buildings, energy consultants,

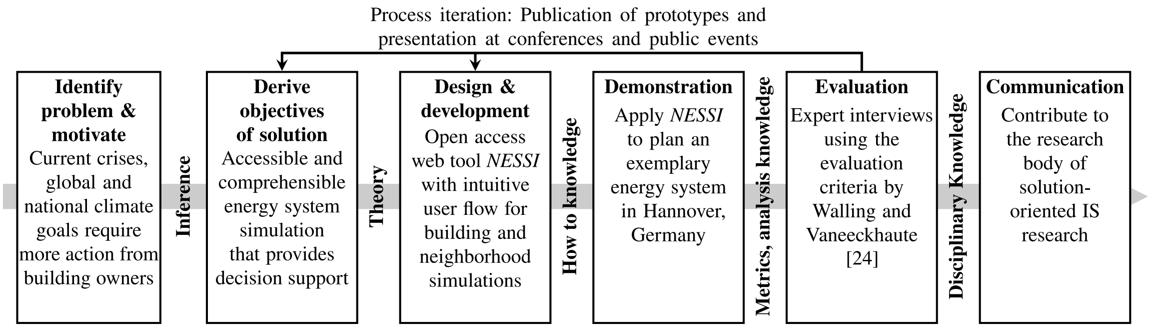


Fig. 1. Design science research methodology.
Source: Adapted from [11].

housing associations, and municipal administrations. Our overarching goal is to support the international goals of an energy transition that is characterized by supply security, environmental as well as climate protection, and high efficiency. We aim at empowering stakeholders to design the energy system that meets their particular needs in the most cost-effective way. We further aim at fostering communication between stakeholders and stakeholder groups by easily sharing energy system scenarios and results. Additionally, we support a faster energy transition by improving awareness of renewable energy technologies and their interrelation within a system.

Model-oriented objectives

Regarding model-oriented requirements, the design process of energy systems must consider and balance technical, economic, and environmental perspectives [25]. Mathematical models, specifically multi-criteria DSS, are often highlighted in the literature [6]. We must enable high adaptability to meet stakeholder-oriented requirements and to allow the consideration of uncertainties [24]. Thus, we choose simulation models to design different energy system scenarios with varying inputs. We consider a semi-structured decision process in which the decision solution depends on the subjective preferences of the stakeholder [24]. Various energy-producing, consuming, and storing components of the thermal and electrical infrastructure that are common around the globe must be available. To meet the above-mentioned perspectives of an energy system sufficiently, technical (e.g., size, efficiency), economic (e.g., purchase price, operation and management (O&M) cost), and environmental (e.g., GHG emissions) details of each energy technology must be considered by the model and adjustable by the user. Further inclusions should be location-specific characteristics (e.g., hourly weather data, geographic coordinates), stakeholder-specific circumstances (e.g., neighborhood or building simulation, housing size, load profiles), governmental policies (e.g., interest rates, feed-in tariffs), and variations over time (e.g., load and price developments, deterioration of components). Overall, the software must be able to consider the energy technologies' interrelations, calculate their energy yield, cost as well as environmental impacts, and compare different scenarios. To reduce complexities, the efficiency, and quality of the model must be carefully balanced.

System-oriented objectives

With regard to system-oriented requirements, high usability and easy comprehensibility must be ensured. The design of the software must be modern, appealing, and interactive. Thus, a graphical user interface must be provided to avoid the need of programming languages. An intuitive, stream-lined user flow must guide the stakeholders through the simulations. To enable collaboration and further analyses, the user must be able to share and download results. To increase the probability of use and satisfaction, the software must be easily accessible via a free web tool on various devices, such as computers, smartphones, and tablets. Additionally, the familiarization time must be low, with the target of five minutes to the first result. This includes the focus on low computational times. To achieve this goal, pre-defined templates and a wide range of buttons with explanatory and background information text must be provided. To continuously improve the software, a feedback form must be available. Additionally, to be of practical and theoretical value to academia, the software development must strictly follow scientific methods.

3. Research design and methodology

Our research goal addresses the implementation of an artifact which justifies the use of DSR [10]. DSR is a popular problem-solving paradigm in the IS community that aims to improve technical and scientific knowledge through the development of innovative artifacts. In this regard, scientific rigor and relevance are central aspects [26]. DSR's potential to contribute to society's critically needed sustainability transformation is explicitly highlighted [27]. Research outcomes of DSR can be design artifacts or design theories [28]. Multiple research processes exist in DSR, most prominently by Hevner [26] and Peffers et al. [11]. This work uses the latter consisting of the six steps (1) identify problem and motivate, (2) derive objectives of solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication. The process is iterative, feeding back lessons learned into earlier steps. We adapted the DSR approach for our needs (see Fig. 1) and follow the DSR publication schema proposed by Gregor and Hevner [10].

After formulating the problem (see Section 1), we derived objectives and requirements for our DSS from literature (see Section 2). The iterative design process started in 2018 and included several presentations at international conferences [29–32], special interest groups in the research community, six public events, and intensive feedback from individual users. The informal interactions with about 200 participants enabled early and continuous feedback loops and were highly valuable to adjust the design to our stakeholders. In addition to the formally derived objectives from Section 2, that were validated during the interactions, these major additional requirements were acquired:

- Enable upload of load profiles
- Add air conditioner to list of components
- Enable the configuration of mixed-use (residential and commercial) buildings
- Depict PV systems with multiple orientations
- Make *NESSI* also usable from a script for scientific use rather than just via the user interface

In line with Sonnenberg and vom Brocke [33], who characterize four evaluation steps, two ex ante and two ex post steps, to validate the artifact earlier than conventional approaches, our informal interactions can also be considered part of the evaluation process. We report on the final artifact in Section 4 that also includes improvements made after the final evaluation. We demonstrate a user's interaction with the DSS with an exemplary case study set in Germany. The subsequent formal evaluation through expert interviews follows Walling and Vaneeckhaute [24].

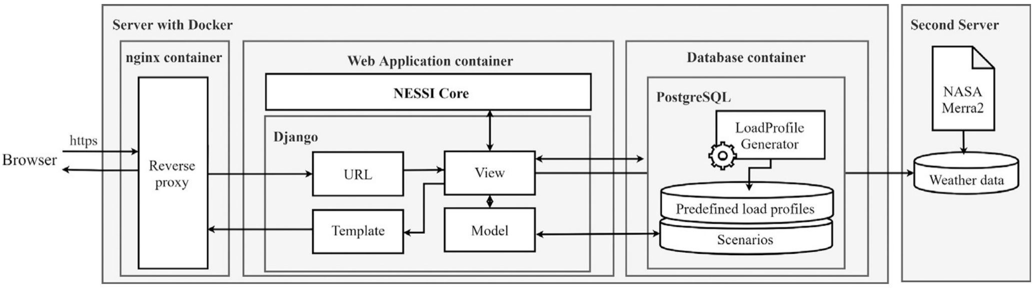
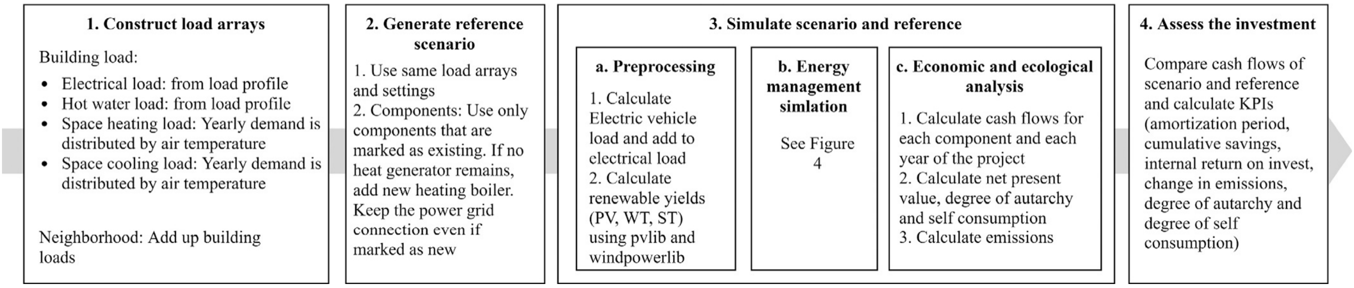


Fig. 2. Software architecture.


1. Construct load arrays

Building load:

- Electrical load: from load profile
- Hot water load: from load profile
- Space heating load: Yearly demand is distributed by air temperature
- Space cooling load: Yearly demand is distributed by air temperature

Neighborhood: Add up building loads

2. Generate reference scenario

1. Use same load arrays and settings
2. Components: Use only components that are marked as existing. If no heat generator remains, add new heating boiler. Keep the power grid connection even if marked as new

3. Simulate scenario and reference

a. Preprocessing

1. Calculate Electric vehicle load and add to electrical load
2. Calculate renewable yields (PV, WT, ST) using pvlib and windpowerlib

b. Energy management simlation

See Figure 4

c. Economic and ecological analysis

1. Calculate cash flows for each component and each year of the project
2. Calculate net present value, degree of autarchy and self consumption
3. Calculate emissions

4. Assess the investment

Compare cash flows of scenario and reference and calculate KPIs (amortization period, cumulative savings, internal return on invest, change in emissions, degree of autarchy and degree of self consumption)

Fig. 3. Four-stage simulation procedure.

4. Artifact description

The final artifact *NESSI* is designed as an open-access, free web tool available at https://nessi.iwi.uni-hannover.de/en/home. The user flow from a user's perspective is described in Section 4.3 whereas the following two sections focus on the underlying architecture and algorithms.

4.1. Architecture

To account for various types of stakeholders and respective energy system sizes, our DSS analyzes the energy supply for buildings (i.e., single family homes, multiple family homes, and commercial buildings) and neighborhoods. We applied an hourly resolution as a compromise between simulation duration and accuracy. The DSS comprises fourteen common renewable and non-renewable components: a connection to an external power grid, multiple photovoltaic (PV) systems, a wind turbine, solar thermal system, heat pump, boiler, cogeneration plant (produces both heat and electricity), a connection to an external heating grid, diesel generator, battery, hot drinking water storage, space heating water storage, air conditioner, and vehicles (conventional and electric). The simulation can either be conducted for one year or the project length for more accurate results (*multi-year simulation mode*). The latter comprises more input fields such as changes in load, cost, and states of health. Depending on the number of included components, a simulation takes less than 5 s. The programming language Python 3.10 was chosen for its dissemination in the scientific community. We further chose the Python-based full stack state-of-the-art web framework Django 3.1.6 for designing the web service. Dockerization of the back end enables easy portability and future development across all platforms (see Fig. 2). Weather data necessary for the simulation is obtained from NASA Merra-2 for the past year, as NASA provides world-wide data in the needed resolution. For ease of use, household load profiles for electricity and hot water demands are pre-generated using the science-based LoadProfileGenerator [23]. Commercial load profiles are derived from standardized load profiles provided for German energy suppliers [34]. For users that aim to generate their own load profiles from appliance usage information, we built a graphical user interface for the software RAMP by Lombardi et al. [35] and integrated it into the artifact [29]. The graphical user interface is designed mobile first, to be adaptable to any screen size. For a broader audience, the interface is available in German and English. Optionally, an account can be created to save scenarios.

4.2. Simulation procedure

The simulation flow is shown in Fig. 3. As described above, *NESSI* supports the analysis of both buildings and neighborhoods, which are simulated similarly. While the building simulation includes one building object, the neighborhood simulation model contains multiple building objects. First, four load arrays are constructed: electricity, hot domestic water, space heating, and space cooling. The values for electricity and hot water demand are taken from load profiles based on user input, while the space heating and cooling load are constructed from yearly demands guided by the Association of German Engineers (VDI) guideline 2067/DIN 4108 T6. If the daily mean air temperature falls below 15 °C, the difference between the hourly temperature and 20 °C is used as a measure to apportion the yearly space heating load to that hour. An adapted method is used for space cooling as well. The lowest daily mean temperature at which a cooling demand is assumed can be set by the user.

Next, a reference scenario is defined. The reference scenario is used to assess the investment in components that are marked as newly purchased. Scenarios can also be compared individually, but the implicit definition of a reference scenario speeds up the process. The reference scenario encompasses all components marked pre-existing by the user. If no component is marked as newly purchased, the reference scenario generation is skipped. If no heat generator is marked pre-existing, a new boiler is added to the reference scenario to ensure thermal load coverage. The simulation of the defined scenario and its accompanying reference scenario consists of pre-processing, energy management simulation, and economic and ecological analysis. In the pre-processing phase, possible electric vehicle loads are calculated and added to the electrical load. Further pre-processing steps include the calculation of PV and solar thermal system yields with the library *pvlib* and wind turbine yields with *windpowerlib* (link).

The energy management simulation is described in detail in the next paragraph. Afterward, cash flows for every component and each

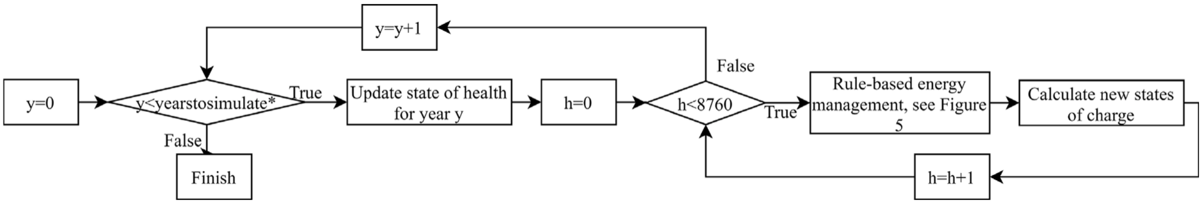


Fig. 4. Energy management simulation (*for default simulation: yearstosimulate = 1, for multi-year simulation: yearstosimulate = project length).

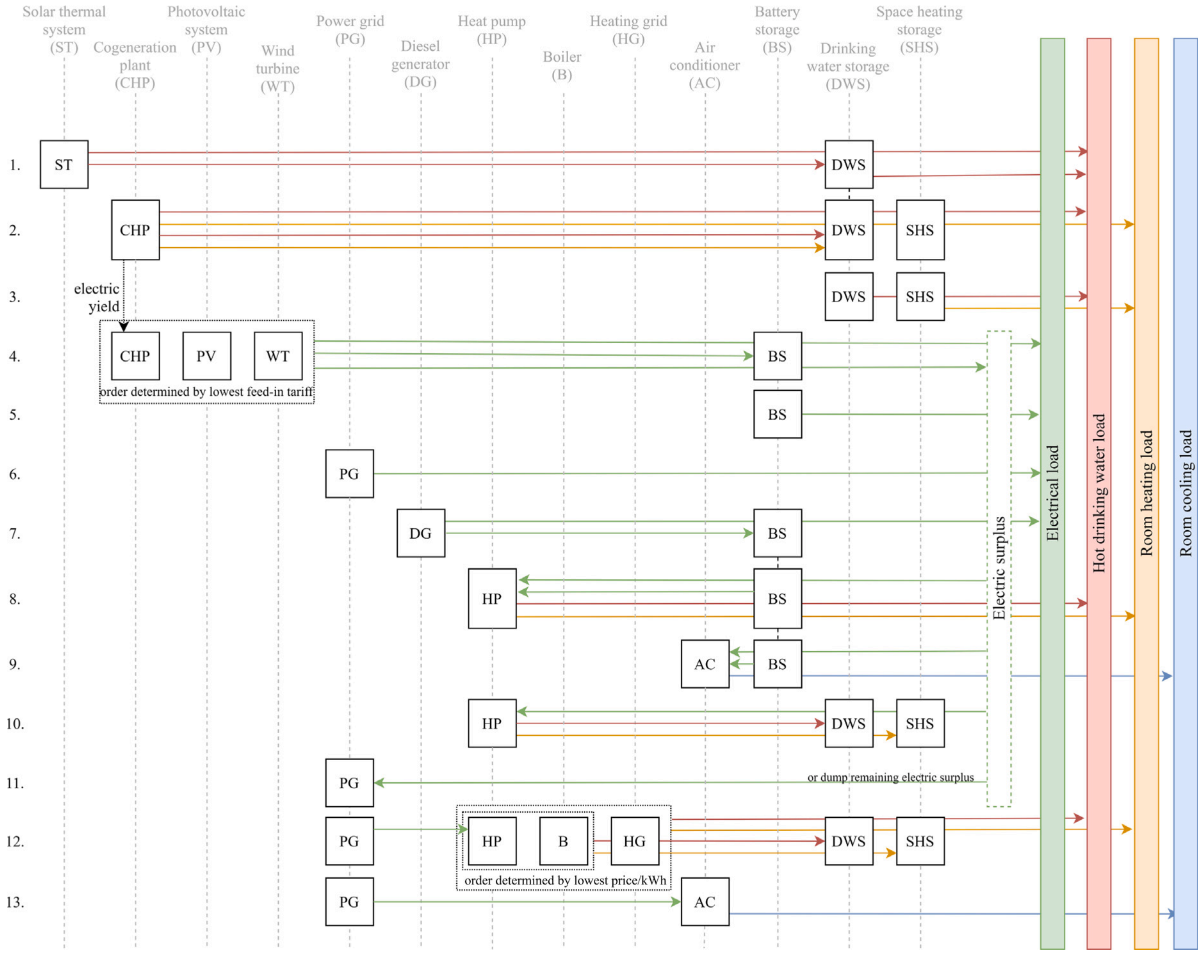


Fig. 5. Hourly rule-based energy management.

year of the project are calculated, taking into account residual values, re-invests, revenues from feeding-in power, and cost over the years. Further, key performance indicators (KPIs) such as net present value, degree of autarchy and self-consumption, and GHG emissions are calculated. Lastly, the investment is assessed by comparing cash flows of both scenarios and calculating the amortization period, cumulative savings, internal return on investment, changes in GHG emissions, degree of autarchy, and self-consumption.

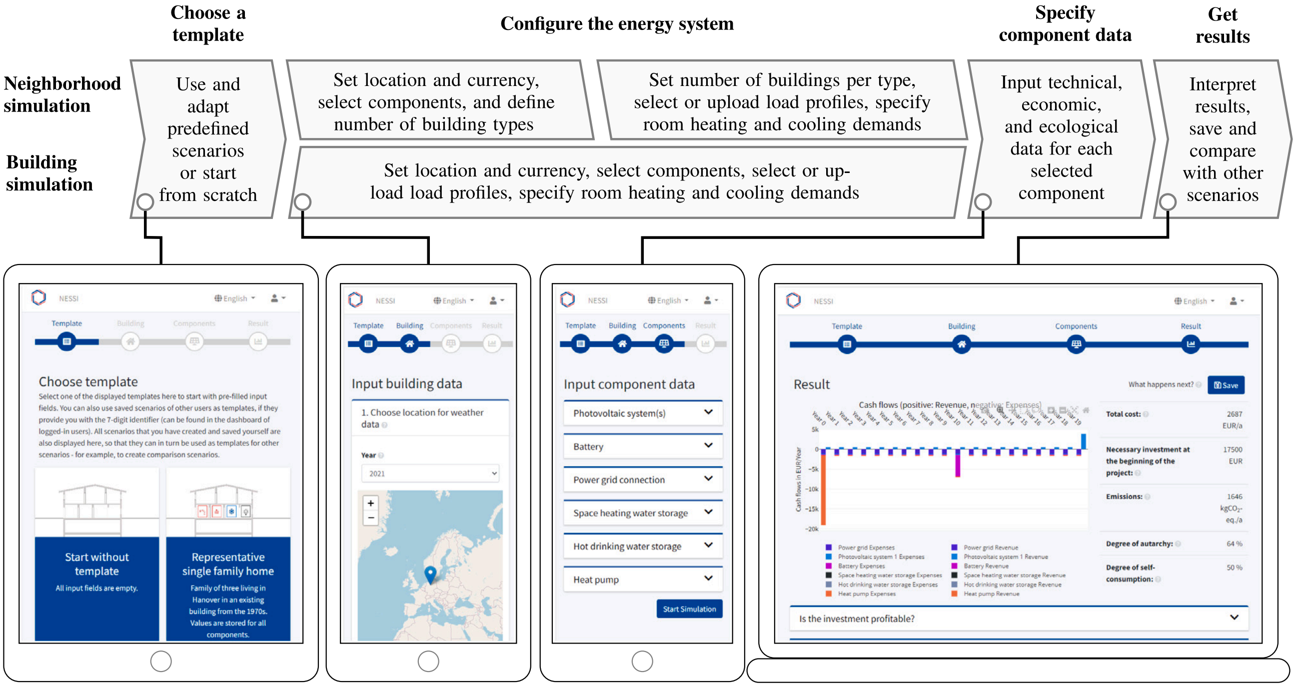
Rule-based energy management

Fig. 4 summarizes the energy management simulation logic. In the case of a multi-year simulation, states of health are calculated for each component and each simulated year. The hourly simulation of energy flows is based on a pre-determined ranking of all available components. This ranking is designed to make optimal use of generated renewable energy yields. The order and simulation sequence are shown in Fig. 5. In each step, the model checks whether the individual components are present and skips their consideration otherwise. The generation of hot drinking water is prioritized over space heating in every component's management. At the end of each hour, the state of charge is calculated for each storage type. The ranking is as follows:

1. The solar thermal plant is used for generating only hot drinking water, not heat for space heating purposes. As the cost per generated kWh is zero after the plant is installed, it is located at the top of the ranking. Its yield is used toward covering the hot drinking water load, excess is stored if possible or dumped.

2. As cogeneration plants (also known as combined heat and power (CHP) plants) should have as many operating hours as possible to be efficient, it is used directly after the solar thermal yield. As common for building and quarter purposes, the plant is managed heat-controlled, which means that its operation is determined by heat, not electricity demands. The generated electricity is considered the by-product. The plant is only turned off if possible excess heat cannot be stored in the hot water tanks.

3. The water tanks are discharged, if necessary, to cover remaining thermal loads.



Choose template

Select one of the displayed templates here to start with pre-filled input fields. You can also use saved scenarios of other users as templates, if they provide you with the 7-digit identifier (can be found in the dashboard of logged-in users). All scenarios that you have created and saved yourself are also displayed here, so that they can in turn be used as templates for other scenarios - for example, to create comparison scenarios.

Start without template: All input fields are empty.

Representative single family home: Family of three living in Hanover in an existing building from the 1970s. Values are stored for all components.

1. Choose location for weather data

Year: 2021

Result

Total cost: 2687 EUR/a

Necessary investment at the beginning of the project: 17500 EUR

Emissions: 1646 $kgCO_2$-eq./a

Degree of autarchy: 64 %

Degree of self-consumption: 50 %

Fig. 6. User flow of neighborhood and building simulation with exemplary screenshots on various devices.

4. After the determination of the cogeneration plant's heat yield, its corresponding electric yield is utilized in the electric infrastructure subsequently. The order in which the cogeneration plants', wind turbines', and PV's electrical yields are used to cover the electric load is determined by descending feed-in remuneration to ensure the highest revenue from surplus feed-ins. Possible surplus is stored in the battery if possible or cached in a variable for use in later steps.

5. If uncovered electrical load remains, the battery is discharged.

6. The external power grid is simulated as an unlimited energy source, but periodic outage windows can be imputed. Thus, the model checks its availability at the given time step. If the power grid connection exists and is available, the remaining electrical load in the particular hour is covered in this step.

7. Therefore, this step is only relevant, if the power grid is non-existent or not available. In that case, a diesel generator is used to cover the remaining load. Operation at rated power is prioritized. Excess electricity is stored in the battery. If that is not possible, the diesel generator is operated at partial load.

8. Back to the thermal infrastructures, the electric surplus and stored electricity from the battery are used in the heat pump to generate heat and cover thermal loads.

9. Remaining surplus electricity is used in the air conditioner to cover the cooling load.

10. If there is still surplus electricity and a heat pump is present, it is used to fill the hot water tanks.

11. The external power grid is used as a sink for the remaining surplus electricity. If no connection to an external power grid is present, the remaining surplus electricity is fictively converted to hot water via a heating rod. The amount of generated hot water is saved as a separate variable (separate to the thermal infrastructures).

12. In the case of remaining uncovered thermal loads, external energy is used — using the boiler, external heating grid connection or heat pump (the latter supplied by electricity from the external power grid connection). If more than one of those components is present, their order is determined by lowest price per kWh. For heat pump and boiler, operation at rated power with excess heat stored in the hot water tanks is prioritized. The heating grid is simulated as unlimited and therefore does not interact with the hot water tanks.

13. At last, the air conditioner is operated with electricity from the external power grid, if needed.

4.3. *Demonstration: User flow*

We describe a potential use case from the perspective of a single family homeowner in Hannover, Germany. The exemplary user has already invested in a PV system with a battery, but is uncertain, if they should invest in a heat pump as well. On the homepage, they find general explanations of the tool, the user manual, a list of related research publications, and two buttons leading to the building and neighborhood simulations. Via the language options on the top of the homepage, they switch to English. Next to it, a menu button offers a log-in and sign-up option. The homepage also provides two buttons to either start a building or neighborhood simulation. The respective user flows and exemplary screenshots of the graphical user interface are displayed in Fig. 6.

The user chooses the building simulation and is guided through the steps *Templates*, *Building*, and *Components* toward the simulation's *Results*. On the first page, *Templates*, several pre-generated templates are shown that contain input variables for representative cases. If the user is logged in, their previously saved scenarios are depicted. The user chooses to start with the template "Representative single family home". The user is then led to the subsequent page, *Building*, where they choose the location of their building via a graphical map, and the currency Euro. Subsequently, they select a PV system, battery, heat pump, thermal storage for space heating and for hot drinking water, and power grid connection from the list of potential components. Next, *NESSI* queries the building's loads. For electricity and hot water demands, representative load profiles for households and commercial activities are selectable. Alternatively, own load profiles can be uploaded. As they do not have hourly load profiles for their household's electricity and hot drinking water consumption, the user indicates a residential building use and selects the load profile "three persons, thereof two adults with predominantly non-domestic activities (e.g., work), and one child" from the drop-down menu with pre-defined household profiles and leaves the proposed annual electricity consumption of 3,000 kWh/a for that household profile unchanged. Subsequently, they impute information about the space heat demand and select to not include space cooling demands. Further, the user decides to leave the pre-filled expert settings, e.g., project length, interest rate, automatic reference scenario

Table 1
Input data for the demonstration.

Category	Input	Value	Based on
Building	Location	Hannover	–
	Currency	Euro	–
	Load profile	Pre-defined load profile for three persons, thereof one child	Pflugradt et al. [23]
	Electricity consumption	3000 kWh/a	Pflugradt et al. [23]
	Specific space heating demand	110 kWh/m^2a	dena [36]
	Living area	120 m^2	dena [36]
	Space cooling demand	None	Assumption
	Project length	20 a	Assumption
	Interest rate	5%	Assumption
	Hot water temperature	60 °C	Assumption
	Flow temperature in heating circuit	50 °C	Assumption
Power grid	Electricity price	0.364 €/kWh	Federal Statistical Office [37]
	Emission factor	0.485 $\text{kg}_{\text{CO}_2 eq.}$/kWh	Federal Energy Agency [38]
Photovoltaic system	Capacity	12 kW_p	Assumption
	Efficiency	20 %	Mittelviefhaus et al. [39]
	Performance factor	75 %	Assumption
	Orientation	South	Jacobson and Jadhav [40]
	Tilt angle	30°	Jacobson and Jadhav [40]
	Investment	1400 €/kW_p	Market research
	O&M costs	14 €/kW_pa	Market research
	Feed in tariff	0.086 €/kWh	Willuhn [41]
	Lifetime	25 a	Fitó et al. [42]
Battery storage	Capacity	6 kWh	Assumption
	(Dis-)Charging power	3 kW	Assumption
	Efficiency	93 %	Rikkas and Lahdelma [43]
	Investment	900 €/kWh	Market research
	O&M costs	9 €/kWha	Market research
	Lifetime	10 a	Rikkas and Lahdelma [43]
Heat pump	Rated power	7 kW_el	Assumption
	Investment	2500 €/kW_el	Market research
	O&M costs	10 €/kW_{el}a	Assumption
	Lifetime	20 a	Mittelviefhaus et al. [39]
Space heating storage	Rated power	30 kWh (= 860 L at 50 °C)	Assumption
	Investment	15 €/kWh	Market research
	O&M costs	0 €/kWha	Assumption
	Efficiency	95 %	Rikkas and Lahdelma [43]
	Lifetime	20 a	Zhang et al. [44]
Hot drinking water storage	Rated power	10 kWh (= 215 L at 60 °C)	Assumption
	Investment	100 €/kWh	Market research
	O&M costs	0 €/kWha	Assumption
	Efficiency	95 %	Rikkas and Lahdelma [43]
	Lifetime	20 a	Zhang et al. [44]

generation, and no multi-year simulation, unchanged. By clicking the *Next* button, the user is led to the *Components* page. The forms for each selected technology are displayed to impute their specific entries for yield, cost, and GHG emission calculations. The user leaves the pre-filled inputs that are summarized in Table 1 unchanged. Additionally, the user marks the PV system, battery, and thermal storage tanks as stock components (with ages 0) and the heat pump as a new purchase.

Clicking "Start Simulation", *NESSI* simulates the configured scenario and the automatically generated reference scenario and gives the user a graphical presentation of the annual cash flows, including expenses and revenues on the "Results" page, see Fig. 6, right screenshot. Several KPIs, such as total yearly costs and GHG emissions, are presented. Further sections on the page for each simulated component give more detailed results of yields, costs, GHG emissions in graphs and numbers. These sections are collapsed when the page is loaded to avoid overwhelming the user and can be expanded by clicking on the heading (similar to the third screenshot in Fig. 6). Another section offers a profitability check which displays the amortization rate, cumulative savings, net present value of the investment, and internal rate of return (see Fig. 7). Further variables show the difference in costs, GHG emissions, and yields to the respective reference scenario.

Based on these results, the user can make a more informed decision toward the investment. They note the necessary investment of 17,500 € at the beginning of the project and a second investment of 5400 € after 10 years to replace the battery and the residual value of the PV system after 20 years due to its lifetime of 25 years (Fig. 6, right screenshot). The user expands the "Is the investment profitable?" section (Fig. 7) and clicks on "Info on the underlying reference scenario" to learn that the reference scenario consists of the existing power grid connection, PV system, battery, and thermal storage tanks. In addition, a newly purchased boiler was assumed. Its input parameters are also displayed with capacity: 11 kW, efficiency: 97 %, purchase price: 500 €/kW, O&M costs: 10 €/kWa, fuel costs: 0.13 €/kWh, emission factor: 0.247 $\text{kg}_{\text{CO}_2 eq.}$/kWh, and lifetime: 20 a. In comparison to the reference scenario, cumulative savings of more than 10,000 € are achievable. The investment will be amortized in 10 years. Next to economic figures, the user is also interested in the ecological impact and considers the GHG emission reduction of 3,400 $\text{kg}_{\text{CO}_2 eq.}$/a. A higher degree of self-consumption is achievable (+25 percentage points), but the degree of autarchy decreases by 29 percentage points.

If the created reference scenario does not correspond to the expectations, the user can save both scenarios to the *Dashboard* by creating an account and edit it to their liking. For this purpose, we provide the function "Scenario comparison" to generate the KPIs and graphic of the "Is the investment profitable?" section for any scenario combinations with same project length and currency. Users can also share the scenarios' results by going to the dashboard, permitting its further use, and copying the automatically created link. For further analyses, the users can also download the simulation results in Excel format.

A reference scenario has been created based on your entries. The reference scenario is also saved when you click on 'Save' and can then be adjusted. To compare, you can use the 'Scenario comparison' function.

Cumulative savings:	10910 EUR
Amortization time:	10 a
Net present value of the investment (at 5.0 % interest rate):	2989 EUR
Internal rate of return (IRR):	8.19 %
Emission change:	-3394 $kgCO_2$-eq./a
Change in degree of autarchy:	-29 %P
Change in degree of self-consumption:	+25 %P

Fig. 7. NESSI's simulation result: Single family home with newly purchased heat pump and existing PV system and battery.

5. Evaluation

According to Gregor and Hevner [10], an evaluation must address the criteria validity, utility, quality, and efficacy to highlight the value of an artifact. With our demonstration in Section 4.3, we pointed out its validity. Specifically, Gregor and Hevner [10] suggest expert reviews and evidence of impact in the field. Regarding the latter, we adduce that to this date, over 600 scenarios have been saved in *NESSI* - not including unsaved scenarios by unregistered users. Further, we have received positive feedback specifically in regard to its accessibility, design (incl. user flow), comprehensiveness, comprehensibility, and speed during public events from participants and were able to see a rise in traffic and simulated scenarios on the website. A head of a software engineering firm approved of our initial broad stakeholder definition and stated it is best to postpone narrowing the stakeholder group to a later stage.

For expert reviews, we conducted semi-structured interviews with twelve experts from different industries. We used the stakeholder-, model-, and system-oriented evaluation criteria for environmental DSS from Walling and Vaneeckhaute [24] as guidelines. Regarding stakeholder-oriented criteria, the emphasis is on whether and to what extent the objectives of the stakeholders are addressed by the DSS. Model-oriented criteria refer to the quality and validity of the computational and decision-making models used by the DSS. The system-oriented criteria encompass the construction and composition of the overall system, and the interaction with users [24]. The interviews took 60 to 90 min. Table 2 summarizes the most important information about the experts including job description, domain of operation, and field of expertise. We chose to interview experts with diverse academic backgrounds and expertise to evaluate *NESSI* from the perspective of different disciplines and to obtain versatile feedback. The experts had the opportunity to test *NESSI* before the interview. After an introduction to the DSS, one or more scenarios were reviewed in terms of the evaluation criteria by Gregor and Hevner [10] and Walling and Vaneeckhaute [24]. Then, a discussion was opened with the experts based on the following questions: (1) Do you have general questions about *NESSI*? (2) How do you rate *NESSI's* benefits for stakeholders? (3) Do you have any suggestions for improving *NESSI*? We had also prepared follow-up questions in case evaluation criteria were not addressed.

The experts evaluated an earlier version of *NESSI* than the one presented in Section 4 as we incorporated most of the feedback back into the artifact. We report on the most significant feedback received. In general, *NESSI* was perceived as a comprehensibly designed and structured tool. The participants' expectations were surpassed in terms of design, speed, and information provided. Expert 9 commended specifically the user flow and guidance through features such as the progress bar. Features unique to energy system simulators, such as the ability to calculate different module orientations for the PV systems, were also positively noted. To cover both inexperienced and experienced users, experts 6 to 9 supported the separation of standard and expert settings. Energy consultants specifically see potential in using *NESSI* as an aiding tool during consultations with building owners whose demand is increasing rapidly. They also used or offered to use their communication channels to colleagues (websites, nation-wide newsletters) to showcase the tool. Other participants indicated that *NESSI* could be used as an alternative to external energy consulting for a first assessment of alternatives. Participant 9 considered the level of detail sufficient for local governments generating neighborhood's energy supply plans. Some experts indicated that citizens are feasible addressees, while others are concerned that the DSS is too complex. The latter see usage in a commercial context, e.g., by architects, energy managers, and heating installers.

Most pressing suggestions for improvement were reducing the time needed to assess an investment and separating the thermal infrastructure into circuits for heating and domestic hot water. Regarding the former, the economic analysis method was critiqued by multiple experts. The presented version employed the net present value and annuity methods to calculate yearly costs. Expert 1 suggested using a cash flow analysis and amortization period for easier comprehensibility. This was also supported by experts 6 and 7. In addition, expert 2 highlighted the importance of reference scenarios and presented this as an essential function for users. Participant 12 noted that the time to assess the investment is too high. Based on this feedback, we reworked the economic analysis. To reduce the time needed to assess an investment, *NESSI* now defines a reference scenario. The previous user flow had preconditioned that users needed to configure two scenarios and compare them afterward to assess an investment. Investment-specific KPI's like the amortization period and internal return on invest were implemented. In addition, interactive cash flow graphs were included. Interview participants 4 to 7 addressed the energy management simulation. They specified the need for technical separation of the heating and domestic hot water circuits as temperatures can vary and especially

Table 2
Overview of evaluation interviews experts.

Participant	Job description	Domain of operation	Field of expertise
1	Sustainability lead	Consulting and service	Development of energy concepts for quarters
2	Project engineer	Climate protection agency	Neighborhood energy concepts, municipal heating planning
3	Program director	Climate protection agency	Climate protection education, renewable energies in buildings
4	Scientist	High voltage technology and power systems	Energy management and energy economics
5	Scientist	Supply engineering	Supply engineering and facility management
6	Electrical engineer	Climate protection agency	Renewable energies and energy systems
7	Civil engineer	Climate protection agency	Energy optimization of buildings
8	Branch manager	Software and service	Geo-informatics and facility management for public administrations
9	Project manager	Software and service	Heat demand analysis and heat planning
10	Financial manager	Distribution grid operator	Financial analysis
11	Financial manager	Distribution grid operator	Financial analysis
12	Quality manager	Transmission grid operator	Internal knowledge management

heat pumps' efficiencies depend heavily on the hot water temperature. We followed their advice and separated the infrastructures. In the input step, space heating and hot water demands were already queried separately, which was positively noted.

Experts 1, 2, 3, and 12 suggested expanding the scenario templates and implementing more representative examples. Concerns were raised that the provided load profiles are not intuitively named. We incorporated this feedback by renaming the pre-generated load profiles and providing more representative templates. Overall, the selection of renewable and non-renewable technologies was deemed sufficient. Nevertheless, expert 1 regarded wind turbines for small-scale energy systems dispensable. Due to our aim at addressing various energy system sizes, we kept this feature.

Several experts suggested integrating information about current funds, subsidies, and prices of specific components. As this feature would need continuous maintenance and is location-specific, we refrained from integrating it at this moment. Experts 6 and 7 suggested moving more input fields from standard to expert settings if we aim to focus on inexperienced stakeholders. Experts 8 and 9 addressed the operation and user flow. It was advised in several instances to provide easier operation using sliders or alternative input methods. This feedback is not yet implemented as simple sliders may not allow for a sufficient level of detail for all stakeholders, and sliders with adjustable number input fields would increase the amount of input fields significantly. Thus, the two key aspects complexity of the tool and the stakeholder definition remained controversial. We discuss these further in the next section.

6. Discussion

6.1. Interpretation, implications, and generalized recommendations

Our demonstration and evaluation highlighted our tool's validity, utility, quality, and efficacy. Additionally, the web tool fulfills our predefined stakeholder-, model-, and system-oriented requirements by supporting various stakeholders with different goals and needs in the decision process toward an efficient, sustainable energy transition. Through *NESSI*'s ability to quantify and illustrate the economic and ecological impacts of individual energy systems, the user is enabled to make informed decisions toward certain energy technologies. Next to our demonstration case, the vast amount of inputs and outputs invite for various analyses. In addition to the defined application, there are further possible areas of use in the fields of policy implications by testing the impacts of, e.g., subsidies (i.e., feed-in tariffs or CO_2 certificates), electric-mobility, or the comparison of technology types. Furthermore, the tool offers the option to analyze load shedding effects, changing prices, deterioration rates of technologies or changes in energy demand — circumstances particular for the Global South, see, e.g., [30,45–47]. Thus, *NESSI* is unique in this context as it is an open-access web tool that does not require local installation, is available free of charge and has been designed with a user-friendly, mobile-first user interface.

In the context of the data-information-knowledge-wisdom (DIKW) pyramid [48], our DSS provides the structure that transforms the observable economic, ecological, and technical data into information. However, the user (i.e., the decision-maker) themself is responsible for receiving this information, critically understanding its relations, patterns, and principles as well as the underlying analyzed issue (knowledge), and making a final decision toward their optimal energy system (wisdom) [48,49]. This is acknowledged by researchers as the programmability in the decision support process decreases and the need for the human factor increases, the higher the level of the DIKW pyramid is [50]. We have added features (e.g., alerts, error messages, help texts) to avoid incompatible inputs and provide templates for reference. Nevertheless, we urge users to critically assess and discuss the tool's inputs and outcomes. The tool's efficiency and effectiveness are and will remain highly dependent on the user's supervision.

During evaluation, we have earned positive feedback for the three evaluation criteria, i.e., stakeholder-oriented, model-oriented, and system-oriented. Particularly, the participants' expectations were exceeded in the latter category, which includes the design, speed, and information provided. However, two controversial and interdependent key aspects transpired, i.e., the complexity of the tool and the stakeholder definition. In any DSS development, considerations about the level of detail for the respective tool have to be addressed. This involves a trade-off between the needed level of detail to generate realistic results and the range of possible applications to meet stakeholder requirements, which both come at the expense of the ease of use. To accommodate the vast amount of application options, different input fields, technologies, expert settings, and templates are provided, which adds to input times, requires more user knowledge, and ultimately increases complexity. However, limiting the software's capabilities reduces its applicability for the defined stakeholders. Simultaneously, generalized inputs would lead to distorted results for certain users, which can only be detected with expert knowledge. Most prevalent in this regard and shown in the use case is the automatic creation of a reference scenario which is subject to various pre-defined assumptions and needs to be adjusted when necessary. As stated above, the user is responsible to obtain and critically assess these inputs. However, we aim to support the user to the maximum extent possible. Extensive help texts or individualized templates could be one part of the solution, and are provided in the software. However, collecting up-to-date data for different regions and their requirements is a challenge that increases the risk of biased results due to incorrect inputs. In this context, it is debatable whether the broad definition of stakeholders is appropriate for our defined problem. A one-size-fits-all approach, as presented with *NESSI*, may have the opposite effect in practice, as its complexities may discourage certain user groups. Nevertheless, as one expert has stated, this broad definition is needed in our software development, but refinement in the further research and development process must be prioritized. One option could be to split *NESSI* into several similar software tools, classified by user group (e.g., expert, layperson, policymaker), geographic region, electrical or thermal infrastructure, or population density. However, the disadvantage of this approach is yet again its inability to meet the requirement of cross-stakeholder communication. Furthermore, classifying stakeholders is difficult and users might miss certain functions in their selected application. Another option is modularizing the DSS for the respective user group or stakeholder in order to provide an appropriate user experience. However, this would again jeopardize a quick start to the actual simulation, may require preliminary discussions with developers, and thus entail a lengthy simulation phase. Thus, user feedback compilation and expert interviews need to be continued to further assess the trade-off of complexities to ensure application possibilities, realistic results, and usability. Another option for simplifications is the switch from a ranking-based method to an optimization tool, which would decrease the number of needed inputs. However, optimization tools often predetermine the user's perspectives on economic or environmentally optimal paths. They limit the user's ability to choose from a variety of possibilities with quantitative and qualitative distinctions [51]. Supported by Walling and Vaneeckhaute [24], we anticipate that different user challenges and needs will result in a number of suitable energy system combinations, whose selection will be dependent on the decision-maker's preferences. This is further highlighted by Awad and Ghaziri [50]'s as well as Rowley [49]'s statements about the importance of human assessment to create knowledge and wisdom — and in our case a user-specific optimal energy system. Therefore, we continue to avoid explicit recommendations by the software. Lund et al. [51] state that simulation tools have the advantage that make them suited for long-term decision-making in democratic societies. Moreover, the increased computational times of most optimization models would further contradict our system requirements and, ultimately, limit the software's applicability. Thus, *NESSI*'s energy management is focused on efficiency, but it does not have perfect foresight.

6.2. Limitations and future research

We enable the analysis of in total fourteen renewable and non-renewable energy generating, storing and consuming technologies in buildings and neighborhoods. We have included governmental incentives toward a sustainable energy transition through, e.g., feed-in tariffs, CO_2-taxes or interest rates that can also be analyzed. Time-varying factors, the comparison of different technologies of the same type, cross-sectoral or cross-location analyses can be conducted. Thus, we were only able to demonstrate a fraction of *NESSI's* functionality in this study. Although, we have shown that *NESSI* is a comprehensive software tool encompassing a multitude of functionalities, DSS are inherent to simplifications. *NESSI* is not able to reflect on political, economic, and environmental uncertainties. In its current version, we utilized hourly time steps and omitted line losses. More components such as small hydroelectric power plants, hydrogen, heating rod, and continuous-flow water heater will be implemented. To follow further expert recommendations, the options of including funds and subsidies as well as life-cycle emissions is subject for further developments. Distortions to the results must always be considered. We, therefore, regard our tool to be supportive for a general decision direction, but advise specialists for the implementation of the energy technologies. Further, the performance is dependent on the user's devices and literacy, as well as a reliable Internet connection. Future studies must include a validation with real measured values. Regarding our evaluation, we have interviewed twelve experts across various disciplines. However, although we were able to collect and incorporate citizen feedback at various public events, our evaluation is missing methodologically-conducted ex-post interviews with non-expert citizens, for example through surveys, focus group discussions or interviews. Further, as our experts and public events were situated solely in Germany, the geographic scope of the evaluations must be broadened as we strive toward global applicability of our tool. In addition, the cyclic design process will continue as we attend and organize further public events and interact with users. The implemented feedback form will also help us to incorporate users' requests.

7. Conclusions

The web-based DSS *NESSI* is developed to support a multitude of decision-makers (e.g., residential and commercial building owners, housing associations, and local governments) and energy consultants to analyze buildings and neighborhoods energetically and to pave the way to an emission-free energy supply. Our motivational background arose out of calls from the IS community for solution-oriented artifacts to tackle climate change. As an established research method in IS research, we have conducted a DSR process guided by Gregor and Hevner [10] and Peffers et al. [11].

From the literature review, investigation of established energy software tools, and continuous interactions with stakeholders, we derived goals and requirements for *NESSI*. We have subsequently shown the implementation of these requirements in the artifact description. This included a detailed presentation of the software architecture and simulation procedure. Then we elaborated in depth on the kernel of *NESSI*, that is, the hourly rule-based energy management simulation. We demonstrated a use case for a building owner in Hannover, Germany. The underlying technical and economic assumptions were mentioned. By presenting the result output, we showed how *NESSI* can support decisions toward an efficient and sustainable energy transition. Subsequently, we summarized evaluation steps including twelve interviews with experts from various disciplines, and statistics on *NESSI's* usage from real-world stakeholders.

With this DSR guided article, we aim to position *NESSI* within the research community and increase its visibility. We argue that *NESSI* separates itself from other energy models and energy-related software tools because of its open-access, out-of-the-box functionality while employing research-based, rigorous design cycles. *NESSI* can support decision-makers dealing with the complex task of transforming the building stock.

CRediT authorship contribution statement

Sarah Eckhoff: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria C.G. Hart:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Tim Brauner:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation. **Tobias Kraschewski:** Writing – review & editing, Visualization, Software, Investigation, Data curation. **Maximilian Heumann:** Writing – review & editing, Software, Investigation, Data curation. **Michael H. Breitner:** Writing – review & editing, Supervision.

Data availability

Data will be made available on request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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