Transformation to Sustainable Building Energy Systems: A Decision Support System

Completed Research Paper

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Abstract

The sustainable transformation of the building sector is one of the biggest levers to achieve global climate protection agreements. Therefore, individual decisions regarding building energy systems (BESs) become more important and building stakeholders require tangible options to create an energy-efficient and renewable-energy-based building stock. Our research aims to address this problem and presents a decision support system based on a software engineering approach that follows the guidelines of the design science research methodology and seeks to provide guidance for investment decisions in BESs by highlighting technical, economical, and ecological performance indicators. The computational study evaluates the performance of various scenarios regarding costs and CO_2 *emissions for different buildings. Our results contribute insights for the design of future BESs and provide building stakeholders with a holistic view to tackle conflicting objectives and to follow a sustainable transformation path.*

Keywords: Transformation of Building Energy Systems, Decision Support System, Design Science, Green IS, Energy Informatics

Introduction

The United Nations (UN) lists 17 sustainability development goals that should be pursued globally at political, economic, and social levels. Among these goals are calls for increased awareness of climate change mitigation, the use of affordable and clean energy resources, and sustainable urban and community development. Furthermore, the achievement of sustainability development goals is linked to a time horizon. The share of renewable energy in the global energy mix should be drastically increased, and investments in energy infrastructure and clean energy technology are to be stimulated until 2030. Adherence to these targets represents a demanding challenge. To this end, the goals formulated by the UN go conjointly with the Paris Agreement of 2015 (United Nations, 2020; European Commission, 2020). As climate change still represents one of the most significant challenges that society must face, it is essential to address the sectors that potentially have the greatest leverage for CO_2 mitigation. According to the International Energy Agency (IEA), the building and construction sector accounted for 36% of global final energy use and emitted 39% of energy and process-related CO_2 emissions in 2018 (International Energy Agency, 2020). Thus, the sustainable transformation of the building sector is one of the biggest levers for reducing energy consumption as well as CO_2 emissions; therefore, it is necessary to achieve climate goals that have been set both nationally and internationally. Unsurprisingly, policy measures and regulations have targeted the stimulation of renewable distributed energy resources in buildings. The most prominent support scheme is feed-in tariffs, which stimulate the dissemination of photovoltaic (PV) systems on residential rooftops. These tariffs allow remuneration for each kilowatt hour (kWh) of electricity fed into the grid. Current developments reveal that feed-in tariffs have been decreased or even abolished, e.g., in Germany (Federal Grid Agency, 2017) or in the United Kingdom (Strielkowski et al., 2017). The decline, as well as the abolition, of the feed-in tariffs weakens the economic efficiency of PV systems and slows down the widespread distribution. However, PV systems are not the only promising technology for the energy supply of buildings. Heat pumps, thermal and electrical storage units, small cogeneration plants (CHPs), local heating networks, or solar thermal (ST) energy must be considered and, if suitable, integrated into the transformation of buildings. In addition, battery electric vehicles (BEVs) can efficiently supplement the energy system infrastructure of a building.

As the UN has noted, the transformation from fossil to renewable energy-supplied buildings is proceeding slowly across the world. However, in the electricity sector, the share of renewables is steadily increasing; comparable progress in the heating and transport sector is not observable (United Nations, 2020). Although there are strict guidelines for the implementation of renewable energies in new buildings, it is more challenging to apply them to the building stock. This is where our problem formulation comes in. Local renewable energy resources, as well as high CO_2 saving potentials, are not adequately used and pursued at the building level. The technical complexity, as well as the dynamic regulations and incentive programs, impede the investment decisions of building owners. To achieve the UN sustainability development goals, these stakeholders require tangible options to reduce their CO_2 emissions. For this purpose, it is necessary to first map a status quo that sensitizes them to the effects that their consumption has on emissions and then point out transformation paths to reduce them holistically and achieve financial savings. Consequently, information systems (IS) need to play a crucial role in supporting this transformation. Since 2010, the Green IS community has sought to address these postulated substantial challenges. Watson et al. (2010) state that "we need to show leadership in applying the transformative power of IS to create an environmentally sustainable society."

With this background, we have developed a user-centric and problem-oriented decision support system (DSS), the **N**ano **E**nergy **S**ystem **SI**mulator *(NESSI*), based on a software engineering approach, which is supported by design science research (DSR) guidelines. Our DSS *NESSI* enables multifaceted analyses of building stock, as well as new building energy systems (BESs). It incorporates various state-of-the-art energy technologies controlled by an energy management system (EMS). By taking economic and ecological parameters into account, it provides in-depth analyses of various BESs. The user receives information about the economic feasibility as well as the ecological footprint. We investigate the following research question (RQ):

RQ: "How can a DSS be developed to visualize and simulate the environmental and financial impact of different building energy systems configurations to raise awareness and encourage actions by stakeholders?"

Our research aims to support the transformation toward energy-efficient and renewable-energy-based buildings in order to use the biggest lever for CO_2 mitigation. Since we follow the DSR guidelines in our DSS development process, we structure the paper according to the publication schema for a DSR study by Gregor and Hevner (2013). First, the theoretical background, research methodology, and prior work are presented. Then, to provide a concise artifact description, the functionality and fundamental premises of *NESSI* are formulated. Subsequently, we evaluate *NESSI*'s application regarding utility and efficacy in our computational study. The results are highlighted and discussed afterwards, followed by recommendations. Finally, limitations, an outlook to further research, and conclusions are provided.

Theoretical Background and Related Research

Green IS and Energy Informatics

Our work ties in with the call of Watson et al. (2010), which emphasizes the importance and relevance of Green IS and Energy Informatics. They define Green IS as "an integrated and cooperating set of people, processes, software, and information technologies to support individual, organizational, or societal goals." Among other aspects, they refer to Green IS initiatives as key drivers for improving poor environmental practices such as unused resources, energy inefficiency, and emissions. We establish this call as the anchor of our DSS and address the following topics: efficient use of energy resources, renewable energy supply, and CO_2 emission mitigation. These priorities are also aligned with Butler's work, which highlights the application of Green IS for the control and monitoring of greenhouse gases and the management of energy-consuming facilities (Butler, 2011). Since 2010, numerous IS researchers have dedicated their work to the Green IS field and, in recent years, both theoretical foundations and research agendas, including those by Watson et al. (2010), Elliot (2011), vom Brocke et al. (2013), El Idrissi et al. (2016), Gholami et al. (2016), and Seidel et al. (2017), have been published in highly respected journals and conferences. Others encourage the use of the transformative power of Green IS by conducting solution-focused research for solving environmental problems (Gholami et al., 2016). Furthermore, IS researchers have presented the multifaceted application of Green IS. Loock et al. (2013) conducted a study investigating the role of IS in stimulating energy-efficient behavior in households. In their study, they created a web portal, to motivate customers of a utility company to reduce their electricity consumption and modify their energy conservation behavior. To expand this concept, Henkel and Kranz (2018) have provided an overview of studies that investigate the influence of Green IS on pro-environmental behavior at both macro and micro levels. Goebel et al. (2014) defined the scope of Energy Informatics research, as well as energy efficiency and renewable energy supply, as the overarching objectives that future research should tackle. This involves residential buildings, commercial properties, and factories. Watson et al. (2010) emphasized the scientific enrichment and supplementation of classical IS research through Energy Informatics. To show the entanglement of Green IS and Energy Informatics, we outline the work of various IS researchers. Brandt et al. (2014) and Valogianni et al. (2014) are prominent examples. Brandt et al. (2014) developed an IS artifact that ensures a sustainable and reliable energy supply in a microgrid. For this purpose, predictions that relate to the electrical yield of the PV system and the electrical load are processed and optimized. Valogianni et al. (2014) developed a Green IS-based artifact for owners of smart homes that supports decisions on device usage and charging of BEVs, considering future energy consumption. More recent research has dealt with local energy markets and the integration of machine learning algorithms to predict redispatch measures. Wörner et al. (2019) designed and implemented the first real-world peer-to-peer energy market in a local community. The field experiment yields meaningful insights into the appropriate design of local energy markets by establishing a trading platform and energy auction mechanisms. Staudt et al. (2018) analyzed the German energy market and energy redispatch with the support of machine learning algorithms. Within their work, they developed and compared tools to predict redispatch measures of utility companies. Despite extensive and insightful research into Green IS and Energy Informatics, to the best of our knowledge a similar DSS that addresses our research problem does not exist.

Related Energy System Analysis Tools

As our research addresses energy systems' simulation, design, and transformation, we draw a comparison between established software tools and *NESSI*. A wide range of literature emphasizes numerous software tools affiliated with the field of renewable energy systems' simulation and optimization (e.g., Trillat-Berdal et al., 2007; Bernal-Agustín and Dufo-López, 2009; Zhou et al., 2010; Sinha and Chandel, 2014; Bahramara et al., 2016). Bahramara et al. (2016) and Sinha and Chandel (2014) highlighted the hybrid optimization model for electric renewables (HOMER) software. Hybrid energy systems use more than one renewable energy resource and include fossil energy consumption. By applying techno-economic analyses through several input parameters such as energy demand, component details, component costs, and emission data, HOMER can determine the optimal configuration and sizing of components and can minimize net costs. It utilizes mainly technical input parameters for techno-economic analyses. Bernal-Agustín and Dufo-López (2009) and Sinha and Chandel (2014) emphasize the hybrid system simulation software HYBRID, which uses precise time series and statistical methods to predict the performance of hybrid energy systems. Both tools are powerful and facilitate comprehensive techno-economic analyses. As HOMER and HYBRID enables researchers and engineers to plan and design microgrids, the usability for building owners is challenging. In contrast, *NESSI* addresses building stakeholders and therefore provides a graphical user interface (GUI) that facilitates comprehensive analyses for BESs. HOMER, HYBRID, and *NESSI* differ in terms of user target groups and analyses' objectives. Starting from the analysis of an existing energy system, *NESSI* can highlight the impact of investments on BESs' performance. The effects of changing scenario parameters of various BESs are quantified technically, economically, and ecologically and enable comparability.

Research Design

The objectives of Green IS research and Energy Informatics underpin the motivational background of our work. *NESSI* addresses the research priorities of Energy Informatics by integrating renewable energy technology and simultaneously supporting high resource efficiency through the EMS. Furthermore, the Green IS research links our DSS to general IS research and, thus, to the DSR methodology. Initially, Hevner et al. (2004) defined the fundamental principles of DSR as the creation of knowledge and understanding of a design problem and its solution by the application of an artifact. Our research question frames a complex decision problem that justifies a problem-oriented approach. Following the three cycle view of DSR outlined by Hevner (2007), Figure 1 presents how we embed relevance, design, and rigor into our development process. To underpin the importance of these three cycles in design research projects, we refer to Hevner and Chatterjee (2010).

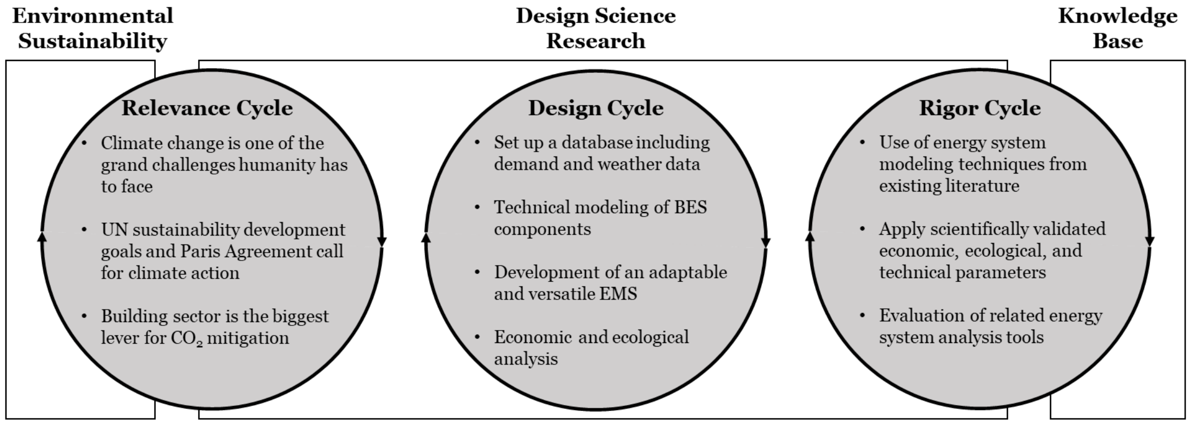


Figure 1. Three cycle view of DSR as applied in our approach based on Hevner (2007)

We draw the relevance of our research from the UN sustainability development goals as well as the Paris Agreement, as both call for climate actions and CO_2 mitigation. In particular, the building sector has a high CO_2 savings potential. In our design cycle, we follow a software engineering approach, which initially includes a requirements analysis. Despite the technical and economic complexity of BESs, we aim to make *NESSI* accessible to decision makers with limited previous knowledge and provide an artifact that supports their decision-making. Thus, comprehensibility, accessibility and usability are key aspects in the design process. Beyond that, customizability is essential to satisfy the individual requirements of users' problem domain.

First, we set up a database including demand and weather data and defined its processing into *NESSI*. Second, we selected the BES components that were modeled technically using validated methods from the energy system modeling literature. Third, owing to the number of BES components, high requirements are imposed on the EMS. The technically possible BES compositions must be computable by the EMS; therefore, it must be highly adaptable and versatile. Fourth, we developed economic and ecological analyses based on technical simulations. To ensure reasonable accuracy of the simulations, validated input parameters that are derived from recognized energy research literature are necessary. The listed aspects were gradually implemented in a prototype. We then compared the results with the requirements several times to eliminate the weaknesses of our DSS, thus ensuring a cyclical improvement of the prototype. Finally, we ensured that *NESSI* provides an answer to our RQ. Since our artifact *NESSI* provides decision support, it refers to the IS discipline of DSS dating back to the 1960s. We use the definition of Power (2008), who declared a DSS as an “interactive computer-based system or subsystem intended to help decision makers use communication technologies, data, documents, knowledge, and/or models to identify and solve problems, complete decision process tasks, and make decisions.” Our artifact *NESSI* is a user-centric and problem-oriented DSS that includes simulation and optimization models according to the categorization of Arnott and Pervan (2005). Many researchers claim that design science is a major DSS research category, displaying the field’s heritage of the innovative application of IT (Arnott and Pervan, 2005). Within the concept of DSS, the lack of use and user involvement and improper implementation have been determined as key reasons for failure, thereby resulting in poor outcomes (Arnott et al., 2008; Hosack et al., 2012). Arnott and Pervan (2005) criticized the inaccurate identification of principal clients, as well as insufficient case studies and real-world applicability checks. Besides the three DSR cycles encompassing relevance, design, and rigor, the evaluation stage of artifacts remains an essential aspect in DSR processes (Gregor and Hevner, 2013). Because we developed a design science-based DSS, our work merges with artifact evaluation in general DSR processes and in particular DSS evaluation methods. Peffers et al. (2012) reviewed 148 DSR related articles in well-regarded computer science and engineering outlets and IS journals. From this, the authors derive distinctive artifact types and examined the frequency with which certain evaluation methods were applied to the artifact types. The distribution of evaluation methods by artifact type show that technical experiments, illustrative scenarios, prototype presentation, and case studies are by far the most frequently used methods. Brendel et al. (2018) analyzed DSR articles in Green IS and found similar results. Furthermore, Arnott and Pervan (2012) conducted an analysis of evaluation methods used in DSS design science research. According to their results, 42.3% of these articles have not applied any evaluation method, which weakens artifacts’ worth, effectiveness, or usefulness. Case study, simulation, and descriptive scenario evaluation have been identified as the most common evaluation methods in all articles. These studies show which evaluation methods are acknowledged and outline the shortcomings of evaluation in design science processes. Therefore, we consider IS literature that provides improvement to the evaluation stage in DSR. Instead of conducting artifacts’ evaluation after the design and development stage, Sonnenberg and vom Brocke (2012) emphasize four evaluation steps within DSR processes. They present two ex ante, and two ex post evaluation steps to validate the relevance, design, and application of artifacts earlier than in conventional approaches.

In line with Sonnenberg and vom Brocke (2012), we conducted evaluation activities between several steps in our design science research process. First, we presented the application and results of a DSS approach at the American Conference on Information Systems (AMCIS) in 2019 (Brauner and Kraschewski, 2019). Moreover, the AMCIS provided a platform to discuss the relevance and design validity of the artifact with the IS community. Following the evaluation activities, we presented a significantly enhanced version of *NESSI* at the Pre-ICIS Workshop of the Special Interest Group (SIG) Green 2019 in Munich. We submitted an extended abstract that introduces an advanced *NESSI* prototype to the workshop committee. After abstract acceptance, we incorporated the reviews of our submission in the artifact construction and design. Then, we presented the improved version of *NESSI* to the SIGGreen community in order to receive feedback and approval again. In this paper, we will conduct a computational study based on real-world data to evaluate the application of *NESSI* in terms of efficacy and utility. Through the evaluation steps during the design and development phase, we aim to achieve an improvement over conventional DSR processes.

Nano Energy System Simulator

Our DSS *NESSI* enables multifaceted analyses of building stock as well as new BESs with a user-centered GUI. It incorporates various state-of-the-art energy technologies controlled by an EMS. By taking economic and ecological parameters into account, it enables in-depth analyses of various BESs. *NESSI* is based on a comprehensive simulation of thermal and electrical energy flows using the numerical computing environment MATLAB R2019b.

System Architecture

Figure 2 presents the overall system architecture, including data processing, BES components, EMS, and analyses in MATLAB. Predefined load profiles are incorporated to support the user in applying the software. Demand data for households is modeled exogenously by a load profile generator (Pflugradt et al., 2013) while demand data for commercial buildings is derived from standardized load profiles provided for energy suppliers (BDEW, 2020; VDEW, 1999). Alternatively, self-generated load profiles can be imported into *NESSI* to facilitate customizability. The temperature and solar radiation time series stored in the database correspond to the location and year preferences entered by the user. In addition, the GUI provides input fields for the technical and economic parameters of the BES components. Among other parameters, capacities, efficiency rates, feed-in tariffs, component and fuel prices, CO_2 emission factors, and a potential CO_2 tax are included. The parameters are predefined based on verified literature, but can be adjusted to the users' needs. Thereby, *NESSI* monitors user inputs and checks for technical feasibility and plausibility. In preprocessing, the database provides the foundation to compute solar yields that are used for the PV and ST systems as well as the coefficient of performance of the heat pump. In addition, the space heating load is derived from the building size, insulation, and air temperature. Subsequently, the simulation and economic analysis are conducted. The results are presented in the GUI and include key indicators as well as temporal graphs.

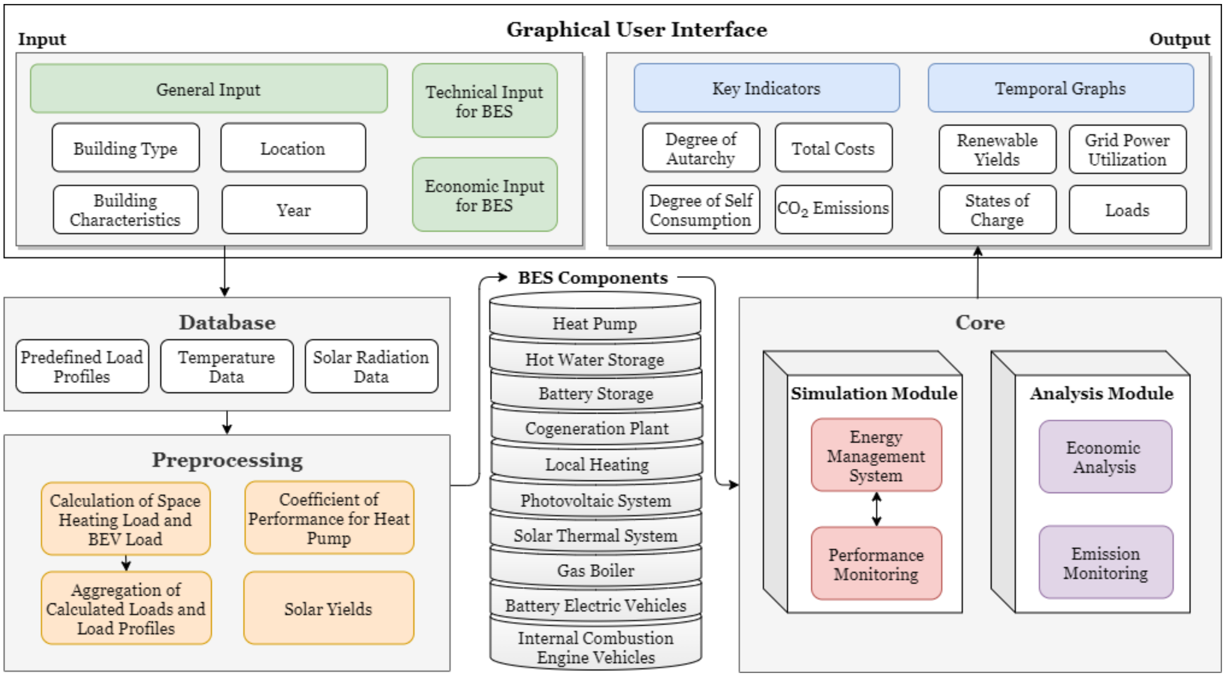
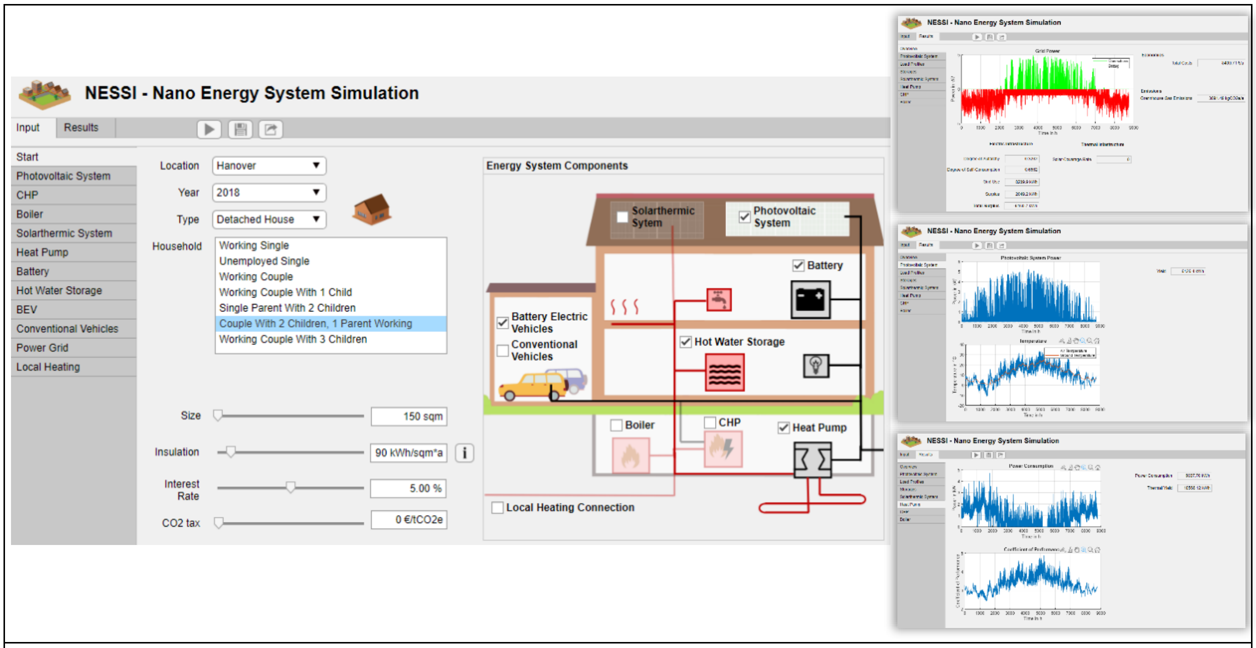


Figure 2. *NESSI* system architecture

Figure 3 provides an overview of the GUI and exemplary results. The start screen enables users to select BES components to set a scenario that is representative of their needs. The provided BES components include PV systems, ST systems, heat pumps, hot water storage (HWS), battery storage (BS), CHPs, gas boilers, connections to local heating, BEVs, and internal combustion engine vehicles (ICEVs). After running *NESSI* with respective settings, it produces temporal graphs regarding the thermal and electrical load, charge levels of storage, and power grid utilization, as well as technical, environmental, and economic key indicators. The visualization is structured in two layers, consisting of an overview and detailed component information to ensure comprehensibility. Another feature of *NESSI* is the saving of the scenario settings and their respective results. This allows users to easily compare certain scenarios with each other. Accordingly, past scenario data can be retrieved anytime so that in-depth analyses can be conducted more quickly. We performed numerous tests and found that one simulation run takes between 0.35 and 0.5 seconds depending on the number of BES components considered.



Location: Hanover
Year: 2018
Type: Detached House
Household:
- Working Single
- Unemployed Single
- Working Couple
- Working Couple With 1 Child
- Single Parent With 2 Children
- Couple With 2 Children, 1 Parent Working
- Working Couple With 3 Children

Size: 150 sqm
Insulation: 90 kWh/sqm*a
Interest Rate: 5.00 %
CO2 tax: 0 €/tCO2e

☐ Solarthermic Sytem
☑ Photovoltaic System
☑ Battery
☑ Battery Electric Vehicles
☐ Conventional Vehicles
☑ Hot Water Storage
☐ Boiler
☐ CHP
☑ Heat Pump
☐ Local Heating Connection

Figure 3. ***NESSI*** **GUI with output of results**

Energy Management System

To ensure reasonable precision, the time resolution of the BES simulation is set to one hour. Consequently, the EMS computes several performance indicators hourly in 8,760 iterations over one year. This comprehensive calculation is necessary to provide valid statements with regard to the overall performance of the BES and to evaluate the investments. Instead of formulating the EMS as an optimization problem, we decided to develop it based on a reliable ranking method. As energy surpluses or deficits occur, the EMS queries the BES components in a predetermined order. This realistically displays the way a BES operates because it has to react to the current demand. The query order is determined to make optimal use of renewable energy and efficient technologies. We claim that an optimization approach is not a fitting methodology for our DSS based on information from related literature. Off-line optimal energy management implies knowledge of future load demand profiles and future renewable energy generation. Thus, this optimization neglects the volatile and stochastic nature of these variables. In contrast, on-line optimization approaches consider the uncertainty of demand loads and renewable energy generation. According to Terlouw et al. (2019), the implementation of on-line optimization frameworks, including stochastic parameters, significantly increases the problem complexity and thereby extends the computation time. Shekari et al. (2019) implemented a mixed-integer linear problem to optimally schedule generation plants, converters, and storage options in microgrids. In their case study, which includes two BS, three HWS, three CHPs, and three wind turbines, the authors mention that the associated optimization problems take less than 5 minutes to solve. These frameworks are valuable analysis tools for research, but they have not been developed to be user-centered. Since *NESSI* also integrates a similar number of components, the EMS focuses on real-world applicability and fast computation.

Figure 4 shows the BES components and their links to the infrastructure of electricity, heat, and fuels. All BES components that are connected to an infrastructure can exchange energy without distribution losses. The arrows indicate the direction in which energy flow is possible. Components that are only linked to one type of infrastructure (generators, storage, demands) are displayed in the color of that particular infrastructure. Converters that connect infrastructures are marked in green. Fuels are shown simplified as one infrastructure despite representing various fuels such as natural gas, heating oil, biogas, gasoline, diesel, and biofuels. As an EMS represents the key element of the BES, it controls the interaction of all energy system components. We summarize the underlying assumptions of the EMS:

- Demand must be met each hour.
- BES components are subject to maximum capacities and efficiencies; both storage types are also subject to maximum (dis)charging rates.
- PV and ST system yields depend on module orientation and inclination angle as well as cell type.
- ST system yield can be wasted if necessary; PV system yield, however, cannot because the grid can be used as a sink.
- CHP's output depends on heat demand and it interacts closely with HWS to ensure high full load hours.
- Electric surplus can be stored in HWS via a heat pump.
- BEVs are treated as additional time-discrete electric demand.
- ICEVs are not connected to the BES, but are considered with regard to total costs and CO_2 emissions to provide a comparison to BEVs.

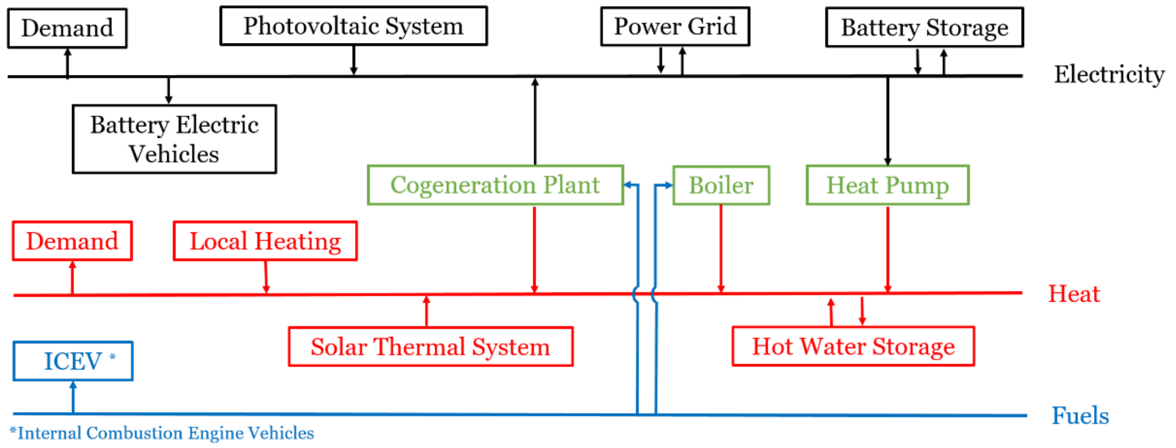


Figure 4. Available BES components and associated infrastructure

Techno-economic Analysis and Ecological Footprint

Based on the hourly simulation of the BES, key technical and economic indicators are computed. Two highly used indicators to describe renewable-energy-based BES are the degree of autarchy (DoA) and the degree of self-consumption (DSC). The DoA describes the proportion of electricity that can be covered by electricity generation plants in the building. The DSC describes the proportion of the electricity demand that is covered by these generation plants. It can only be defined if electrical generation plants are installed in the building. These indicators can be used to monitor and compare the BESs. High degrees are favorable but come at high economic costs. Therefore, an economic analysis is also included. We conduct our economic analysis using the net present value (NPV) because it is a widespread method in the field of energy systems and a thoroughly intuitive approach to evaluate an investment based on future cash flows and discount rates (Strantzali and Aravossis, 2016). By doing this and providing the selection of a risk equivalent interest rate, we consider investment in a diversified capital market portfolio. In general, the NPV of an investment in energy systems is defined as (Talavera et al., 2010; Nofuentes et al., 2003):

$$NPV = -C + \sum_{t=1}^{T} \frac{R_t - E_t}{q^t} \qquad with\ q = 1 + i \tag{1}$$

The NPV represents the sum of investments C, revenues R, and expenditures E discounted by an interest rate i. Period T represents the planned lifetime of the technical components. *NESSI* includes fixed and capacity-dependent investment costs (CAPEX) to account for economies of scale. The expenditures consist of operation and maintenance costs (OPEX), and fuel and electricity costs. For reasons of comparability with current systems, we calculate the annual total costs and hereby use the annuity approach, which spreads NPV evenly over the observation period.

$$Total\ Costs = NPV * \frac{q^T(q-1)}{q^T - 1} \tag{2}$$

In addition, aggregated CO_2 emissions are shown to provide a perspective on the use of fossil and renewable energy resources and climate impact. The CO_2 emissions are calculated by using the emission factors for each fuel that are obtained in the input GUI and multiplying them by the fuel consumption. The same applies for the electricity used from the external power grid. Emissions from ICEVs are also considered to provide a comparison for BEVs. With these technical, economic, and ecological key indicators, users can gain in-depth analyses of simulated BESs and can compare these in terms of environmental impact, costs, and grid dependency.

Computational Study

This section applies the DSS *NESSI* to evaluate its utility and efficacy. First, two buildings are defined, which are then simulated as part of various BES combinations and discussed from both economic and ecological perspectives. Table 1 provides an overview of predetermined settings for a detached family house and an office building both located in Hannover, Germany.

The assumptions for the detached family house correspond to an average family home in Germany with four occupants, while the parameters for the office building are chosen so that they result in the measured consumption of a real office building in Hannover. Due to instantaneous water heaters, the energy demand for hot water supply is included in the electricity consumption of the office building. To enable economic analyses, we assume an interest rate of 5% and a period of 20 years. Technical parameters are not explicitly shown but are chosen carefully to reflect reality as far as possible. The selection for these cases is based on the following reasons:

- The different sizes of buildings and numbers of people involved lead to significantly different thermal and electrical consumptions, both in terms of amount and temporal characteristics of the consumption profiles.
- It enables the investigation of economies of scale in investments in the BES and the effects of different energy prices.

The results of the simulations are presented in Figures 5 and 6 considering CO_2 emissions and total costs. This enables the evaluation of different configurations with regard to their economic and ecological implications and ensures comparability. The electrical and thermal requirements of a BES must be continually met. In all analyses, both fossil and renewable resources are used by the components to meet the required load. In general, the electrical load is secured by the power grid in all scenarios. In the first scenario, a gas boiler is used for thermal supply. Consequently, the supply is based on fossil energy resources, which is why this is used as the reference scenario. Other scenarios use a heat pump, CHP, or a combination of these for their heat supply. Moreover, the electrical infrastructure of some systems is enhanced by a PV system. In general, we compute a baseline scenario (filled circles) as well as additional scenarios that comprise various storage options. The baseline scenarios are extended with BS (square), HWS (hexagon), or both (triangle). We introduce clusters to underline the coherence of the scenarios; the size has no additional meaning.

			Detached family house	Office building	Based on
General parameters	Electrical demand [kWh/a]		2,930	220,000	Pflugradt et al., 2013 Energy Monitoring
	Space heating demand [kWh/a]		13,500	643,530	
	Water heating demand [kWh/a]		5,066	-	
	Electrical tariff [$€/kWh$]		0.300	0.180	Assumption
	Electrical tariff (heat pump) [$€/kWh$]		0.230	0.140	Assumption
	Gas tariff [$€/kWh$]		0.060	0.046	Assumption
	Revenue for fed-in electricity [$€/kWh$]		0.094	0.072	Federal Grid Agency, 2017
	Emission factor of natural gas [$kg\ CO_2/kWh$]		0.250		IINAS, 2019
	Emission factor of grid electricity [$kg\ CO_2/kWh$]		0.502		IINAS, 2019
BES components	Gas boiler	Capacity [kW]	10	200	
		CAPEX	€3,300 + €55/kW		McKenna et al., 2019
		OPEX [$€/kW$]	10		Assumption
	Photovoltaic system	Capacity [kW]	8	100	
		CAPEX	€3,000 + €700/kW		Datas et al., 2019 Fina et al., 2019
		OPEX [$€/kW$]	15		Huang et al., 2019
	Air-source heat pump	Capacity [kW]	4	80	
		CAPEX	€2,700 + €550/kW		Datas et al., 2019
		OPEX [$€/kW$]	5		Assumption
	Cogeneration plant	Capacity [kW]	1	25	
		CAPEX	€15,000 + €2,000/kW		McKenna et al., 2019
		OPEX [$€/kWh$]	0.036		Assumption
	Hot water storage	Capacity [kWh]	50	500	
		CAPEX	€25/kWh		Datas et al., 2019
		OPEX [$€/kWh$]	0		Assumption
	Battery storage	Capacity [kWh]	4	40	
		CAPEX	€670/kWh		Huang et al., 2019
		OPEX [$€/kWh$]	0		Assumption

Table 1. General parameters and techno-economic settings of BES components

Figure 5 shows the scenario clusters for the detached family house. Starting from the reference scenario (black filled circle) with annual total costs of 1,340 € and annual CO_2 emissions of 6,560 kg, the installation of a PV system reduces both emissions up to 19% and costs up to 18%. Instead, switching the heat supply to CHP with a peak load boiler (red cluster) leads to an increase in costs and emissions. A combination of CHP and a heat pump (violet cluster) mitigates emissions up to 25% by reducing gas consumption but increases the total annual costs by 87%. Adding a PV system (blue cluster) leads to a minimal cost reduction and a mitigation of emissions. The orange cluster includes the all-electric scenarios, as the thermal infrastructure is completely based on electrical energy. The heat pump and PV system offers the highest emission reduction of the scenarios considered, with a reduction of 50 (no storage) to 60% (both storage types).

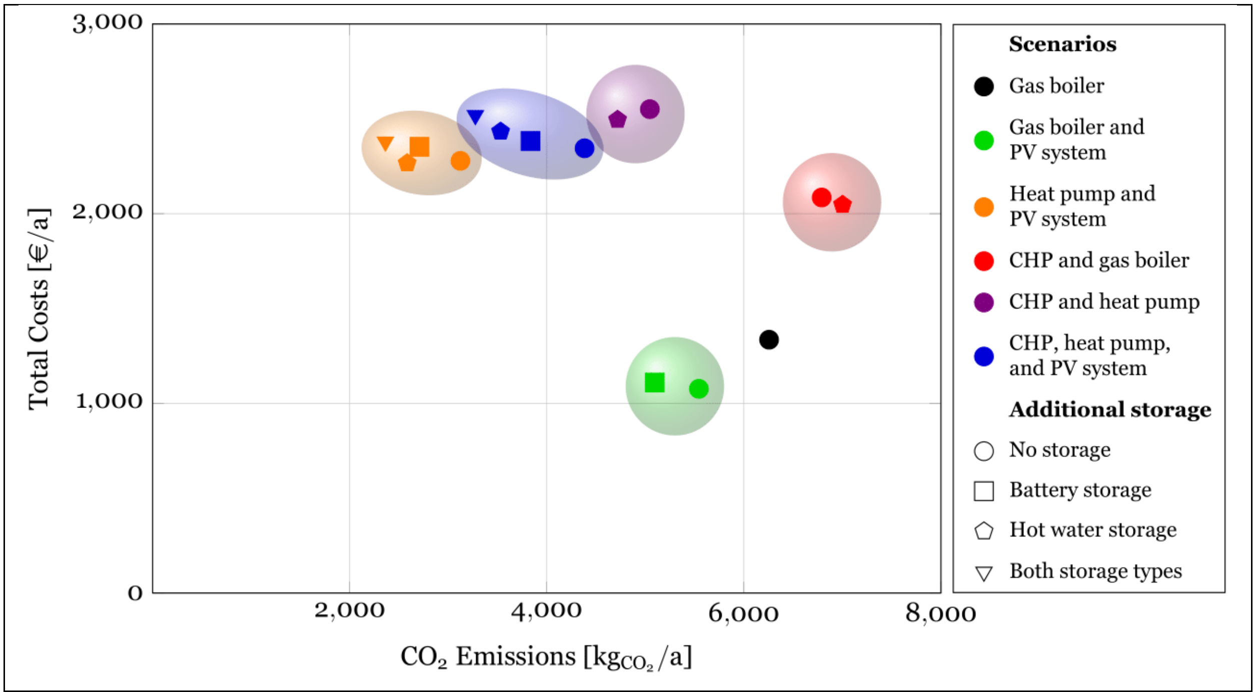


Figure 5. Economic and ecological performance of BES setups in the detached family house

In contrast, the total costs increase by about 70% in comparison to the reference scenario. Nevertheless, compared to the blue and violet clusters, the orange cluster is the most cost-effective option for CO_2 mitigation. It is noticeable that in general, storage systems reduce CO_2 emissions, but usually have a marginal effect on total costs. The only exception is the red cluster in which the HWS leads to an increase in emissions.

The analyses based on an office building in Figure 6 show different economic and ecological results in some scenarios in comparison with a detached family house. The reference scenario (black filled circle) accounts for annual total costs of 42,788 € and annual CO_2 emissions of 277,935 kg. The installation of a PV system (green cluster) leads to remarkable savings from both an ecological and economical perspective. It avoids 14% of the initial CO_2 emissions and enables cost savings of up to 19%. The CHP in the red cluster significantly reduces annual costs but slightly increases CO_2 emissions. There is a shift from previous analyses, where the scenario led to an increase in both parameters. The violet cluster for this office building shows a similar tendency analogous to that of the detached family house. It lowers emissions by 21% but leads to an increase by 18% in total costs. A noticeable effect can be observed by adding a PV system (blue cluster). This combination leads to high CO_2 savings of about 35% and is more cost-effective than the orange and violet clusters. The annual total costs increase slightly by about 5% compared to the reference scenario. The all-electric scenarios (orange cluster) lead to the most significant emission reduction up to 38%, but also cause the highest costs. Basically, the installation of a storage unit leads to a reduction in emissions. BS increases the annual costs in all cases. In scenarios containing CHP, the installation of HWS contributes to cost reduction but, except for the blue cluster, slightly increases emissions.

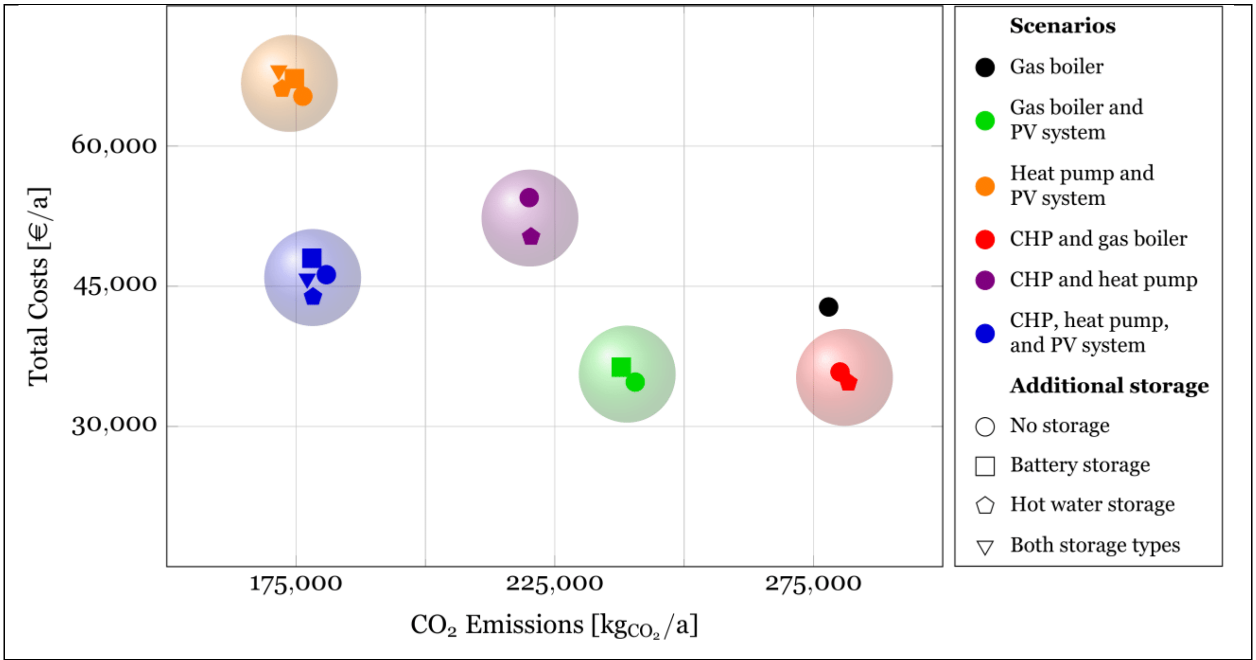


Figure 6. Economic and ecological performance of BES setups in the office building

Discussion and Recommendations

With reference to our research question, we computed and graphically evaluated a range of scenarios for a detached family house and an office building in a computational study. In Figures 5 and 6, trends and correlations can be identified, which will be discussed in the following section under technical, economic, and ecological aspects. Comparing both building types, PV systems (green clusters) lower CO_2 emissions due to the reduction of grid power utilization. Furthermore, total costs decrease because the income from the sold surplus electricity and the saved expenditure from grid usage exceed the annual costs of the PV system. The installation of BS increases the degree of self-consumed energy, thereby mitigating indirect emissions of grid power utilization. However, the total costs significantly increase due to the high specific investment in BS. While CHP (red clusters) leads to higher total costs and emissions in a detached family house, it results in lower total costs in an office building. This difference is due to the high initial investment and operation costs of CHP. CHP covers the heat demand and thereby generates electrical energy that cannot be sufficiently consumed in residential buildings. In contrast, CHP in the office building is used more efficiently due to a higher base load, which explains the positive effect. Furthermore, the CHP is larger in capacity, which reduces the specific investments. In addition, a HWS enables more flexible operation and improved utilization of the CHP and hereby raises the number of full load hours, thus further reducing costs but slightly increases CO_2 emissions. This performance can be observed in almost all scenarios involving CHP. We conclude that CHP are only suitable for larger buildings with a high base load and should be considered within a BES design process. In contrast, the low base load in detached family houses impedes the economic efficiency of CHP and no positive environmental effects are visible. With regard to a heat pump (violet clusters) instead of the peak load gas boiler installed, a similar effect can be observed in both cases. While the increase in total costs is due to the high investment in the heat pump, CO_2 emissions are reduced because of the efficient power-to-heat conversion. By adding a PV system (blue cluster) to the previously examined scenario, emissions and costs are reduced, comparable to the green scenario. Due to the extensive power consumption of the heat pump and the associated high investment, the total costs reach the maximum in the orange cluster, compared to all other scenarios, in the office building. This development is also driven by the high electricity price for heating compared to the gas tariff. Nevertheless, the orange cluster has the largest potential to reduce the CO_2 emissions of the building, since the specific emissions of the electricity mix are decisive and no local emissions occur. The analyses assume the current CO_2 emission factor of the German energy mix. With the transformation to a renewable-based energy supply mix, this share of CO_2 emissions will continue to decrease and consequently reduce the emissions from the building. Assuming an emission-free power supply, this scenario has the potential to completely avoid emissions. In summary, the violet, orange, and blue clusters show that the heat pump has an immense leverage effect for CO_2 reduction, but at the same time requires high investments. Especially for residential buildings, the all-electric scenario achieves a better performance both ecologically and economically compared to the blue cluster, which integrates CHP. This result is consistent with our conclusion on the economic feasibility of CHPs in detached family houses.

Within the EU, the sectors of energy supply and emission-intensive industries regulate their total CO_2 output through the Emission Trading System (ETS). Additional emission-intensive sectors such as transport, agriculture, and buildings are not targeted by the ETS in most parts of Europe. Therefore, countries such as Sweden, Finland, and Denmark introduced CO_2 taxes for non-ETS sectors to enhance emission reduction as one of the most critical societal challenges and reach national climate targets (Kirchner et al., 2018). Flues and Thomas (2015), Kirchner et al. (2018), and Kemfert et al. (2019) analyzed the long-term economic value effects of CO_2 taxes for citizens, companies, and society and claim the implementation of reasonable taxes. Using *NESSI*, the economic influence of such a tax can be made visible to stakeholders and efficient recommendations for action can be developed. In Figure 7, we highlight two baseline scenarios and summarize the resulting total costs with and without a taxation of €50/t CO_2. The comparison proves that the blue scenario is economically more advantageous compared to the black reference scenario with high CO_2 emissions, which previously generated lower costs. *NESSI* enables users to include potential CO_2 taxations within their economic and ecological analyses. It reinforces the effect of taxation and the importance of considering it in future studies. A further aspect is the economic and ecological evaluation of electricity fed into the power grid. According to our computational study, surplus electricity is remunerated by a feed-in tariff. However, extensive analyses require the consideration of additional options for action. Instead of feeding the surplus electricity into the power grid, it can be used to charge BEVs. In the case of an office building, it could also be used to charge a company's or employees' vehicles during office hours, especially to take advantage of the PV noon power peak. The electricity surplus accounts for 27,600 kWh (green scenario) and corresponds to a range of about 140,000 km and an emission reduction of about 13 t CO_2 in comparison to an ICEV fleet.

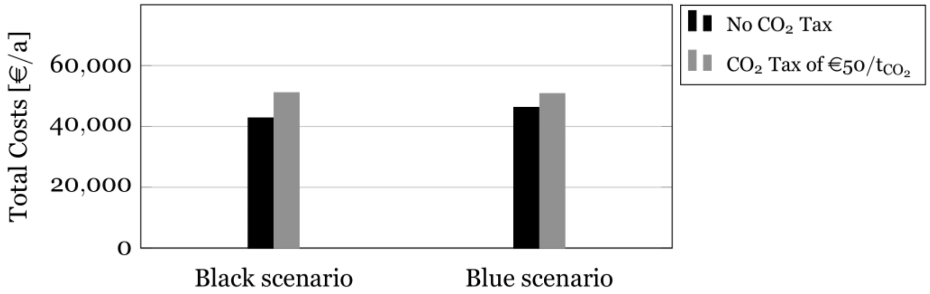


Figure 7. Comparison of black and blue scenarios for the office building including CO_2 taxation

The conducted analyses underpin *NESSI*'s practical applicability and contribution to the Green IS community by demonstrating exemplary use cases. We presented two cases with underlying assumptions in a transparent manner. Afterwards, we simulated 26 BES configurations and presented and discussed the results in an aggregated way. While the results depend on building location, size, and related load profiles, they are also influenced by the assumptions made with regard to the technical and economic parameters of the individual components or general assumptions on electricity and gas tariffs.

In summary, the computational study highlights the following aspects:

- The validity of the simulations is based on detailed information regarding technical and economic parameters of the considered components in the BES. These specifications are defined by default to support the user, but can be customized at any time.

- We emphasize that the results are strongly influenced by these specifications and that they determine which BES is most suitable depending on the user's goal. Therefore, some of the findings cannot be generalized, but refer to the two cases and the underlying assumptions.
- The cases show a proportion of *NESSI*'s features. Our DSS is capable of computing technical key indicators like DoA and DSC, as well as accurately mapping energy flows and displaying them as required; thus, the level of detail used for comparisons and analyses can be adjusted to the users' needs.
- Our results confirm that BESs' ecological and economic efficiency cannot be pursued equally. High ecological efficiency leads to high total costs and thus limited feasibility.
- To resolve this well-known imbalance, some countries have introduced taxes on fossil fuels or have targeted investment costs by subsidizing technologies such as heat pumps. This necessity is also evident in the scenarios considered, in which often those with the highest CO_2 reductions unfortunately also cause higher costs.
- For this reason, we have compared scenarios with regard to CO_2 taxation effects, showing both the efficacy of the taxation and the option of being able to consider it in *NESS*I and depict the associated effects. By adjusting the CAPEX of components, the impact of subsidies on BESs can be quantified in *NESSI*.

The computational study aims to give an understanding of the potential of *NESSI* as a DSS and to highlight the relevance of taking a holistic view (technical, economic, environmental) to ensure valid results that can support the stakeholders in designing their BES.

Limitations and Outlook

In this section, we distinguish between computational study-related and DSS-related limitations. Our results are influenced by location-based factors. This causes a conflict between the precision and generalizability of the obtained results. Local temperature and solar radiation profiles were used, and consumption profiles were represented by standard models. In contrast, no local support schemes were considered to increase comparability. Nevertheless, these additions can be integrated by modifying the cost assumptions. The scenarios shown are only a selection of possible configurations of the BES components. An adjustment of the component parameters can also lead to different results.

Regarding DSS-related limitations, *NESSI* is a compromise between complexity reduction and real-world applicability. As BESs include a large range of technologies, their simulation becomes highly complex. Consequently, certain technical parameters and processes must be simplified from a technical aspect. Our artifact presented is based on a time-discrete hourly resolution to reduce computing times, which is why short-term effects in the range of minutes or seconds cannot be simulated with *NESSI*. Further research can investigate whether these effects have an impact on the results. Our simulations use a reliable ranking-based method without an underlying optimization approach. Therefore, the EMS does not achieve full efficiency and cannot be compared with optimal operational management. Since optimization models require prediction of load and yield profiles, real-world applicability is weakened and therefore not suitable as part of *NESSI*. Nevertheless, further research can combine forecast applications and optimization in advanced EMS. Additionally, a future field study can complement the conducted evaluation steps and prove the applicability and efficacy of the DSS in an authentic problem context.

Although conventional discounted cash flow approaches are prominent and widely used in the current literature, there is a broad agreement about the possible drawbacks of these methods, as they do not consider uncertainties and changing capital and risk structures. A reasonable inducement is the execution of a real options valuation to account for environmental or endogenous uncertainty, whether it is regulatory uncertainty, or uncertainty of risks and costs. As explained by Trigeorgis (1993), the valuation of real options leads to more accurate results than traditional discounted cash flow methods such as the NPV. Another possible strategy regarding the lack of unconsidered uncertainties could be the coupling of NPV-based assessment with probability-weighted simulations such as Monte Carlo simulation with supplementary stochastic models (Barroso and Iniesta, 2014; Himpler and Madlener, 2014).

Conclusions

The UN postulates 17 sustainable development goals and thereby calls for climate change actions regarding the dissemination of renewable and clean energy resources globally, as well as the sustainable development of cities and communities (United Nations, 2020). Additionally, the IEA confirms that the building sector represents one of the biggest levers for reducing fossil energy consumption and emissions (International Energy Agency, 2020). However, the UN criticizes that the sustainable transformation of buildings progresses at a slow pace, and thus the large CO_2 reduction potential remains unused. Broad participation (companies, state organizations, and citizens) is crucial to create an energy-efficient and renewable-energy-based building stock to achieve climate goals. We have adopted this grand challenge to tackle it with the transformational power of IS research. More specifically, we acknowledge Green IS and Energy Informatics as suitable research fields that must address this global problem. We used this motivation and developed our DSS *NESSI* that is based on a user-centric software engineering approach and followed the guidelines of DSR methodology originally posed by Hevner et al. (2004).

We introduced the system architecture of *NESSI* and presented the underlying premises of our BES model. Additionally, we presented the functionality of our techno-economic analyses. In our computational study, we verified both practical applicability and efficacy of *NESSI*. The results indicate that building types, location-related parameters, and consumption characteristics strongly determine the suitable application of energy technologies. Regarding detached family houses, we identified CO_2 reduction potentials of up to 60% associated with an increase in costs that limits feasibility. With regard to an office building, we found reasonably-priced reduction potentials of up to 38%. Furthermore, we discussed the economic effect of CO_2 taxation and suggest that such a tax will elevate ecologically positive BES setups into an economic advantageous position. To conclude, we demonstrated *NESSI's* ability to highlight the financial and environmental impacts of investments in BESs and thus enhance stakeholders' awareness of transformation potentials. *NESSI's* holistic approach, considering taxation, incentives, and realistic assumptions, should encourage stakeholders to review their individual BES and find sustainable solutions.

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