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The Need for Accelerating the Transformation Process Towards a Defossilized Building Sector: Introduction of Building Energy, Material, and Social Systems Engineering (BEMSSE)

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ABSTRACT

Building sector defossilization is key to achieving significant emission reductions in our society by 2045. Reducing emissions across the sector within a very limited timeframe requires executing complex transformation processes that depend on numerous options to take and multiple stakeholders. However, conventional methods make selecting the right option while integrating all stakeholders into the transformation process complex. In other research fields, integrated methods have already been established. In this work, we introduce process systems engineering and living laboratories and propose building energy, material, and social systems engineering (BEMSSE) as a powerful tool to accelerate the transformation process in the building sector.

Keywords: integrated design, sustainable design, process intensification, stakeholder dependency

NOMENCLATURE

Abbreviations	
A	Area
Amb	Ambient
BS	Buffer storage
BEMSSE	Building energy, materials, and social systems engineering
c	Heat capacity
DHW(S)	Domestic hot water (storage)
HP	Heat pump
HR	Heating rod
Int	Internal
PSE	Process Systems Engineering
$\dot{Q}$	Heat flow
Rad	Radiator
Sol	Solar
t	Time
Tra	Transmission
v	Volumetric
Ven	Ventilation

1. INTRODUCTION

On an average day, a person in Germany spends 90% of the time indoors, referred to as "Generation Inside" in a survey commissioned by the European Commission (European Commission, 2003). Van Treeck and Müller (2014) reinforce this aspect, as the building is indispensable in everyday life and will assume an increasingly important role as a living and working space in the future. However, to be comfortable in a building and to make changes to the indoor environment requires heating, ventilation, and air conditioning systems (Chenari et al., 2016). Furthermore, the system's operation relies on energy conversion processes that can cause direct and indirect CO2 emissions depending on their manufacture, operation, and disposal (Sharma et al., 2011).

Currently, up to 40 % of total European emissions are attributable to the building sector (UNEP, 2020). Thus, emission reductions in the building sector represent a promising lever in the context of the Paris Climate Agreement. Emission reductions in the building sector through further development of building supply are called defossilization of the building sector. In summary, the defossilization of the building sector is crucial for achieving the set climate targets. However, the building sector is also the subject of everyday life, so changes in this sector must be supported by all stakeholders involved. Consequently, far-reaching emission reductions can only be achieved through a holistic, societal transformation process (Honegger et al., 2020).

The goal of the transformation process is to reduce greenhouse gas emissions to mitigate the mean increase in the Earth's temperature to below 1.5 °C, which is also a common goal of the parties to the Paris Climate Agreement (Schleussner et al., 2016). In ratifying the agreement, the German Government adopted and revised the Climate Protection Plan 2045. The climate protection plan provides sector-specific measures to reduce greenhouse gas emissions (Pittel, 2021). All

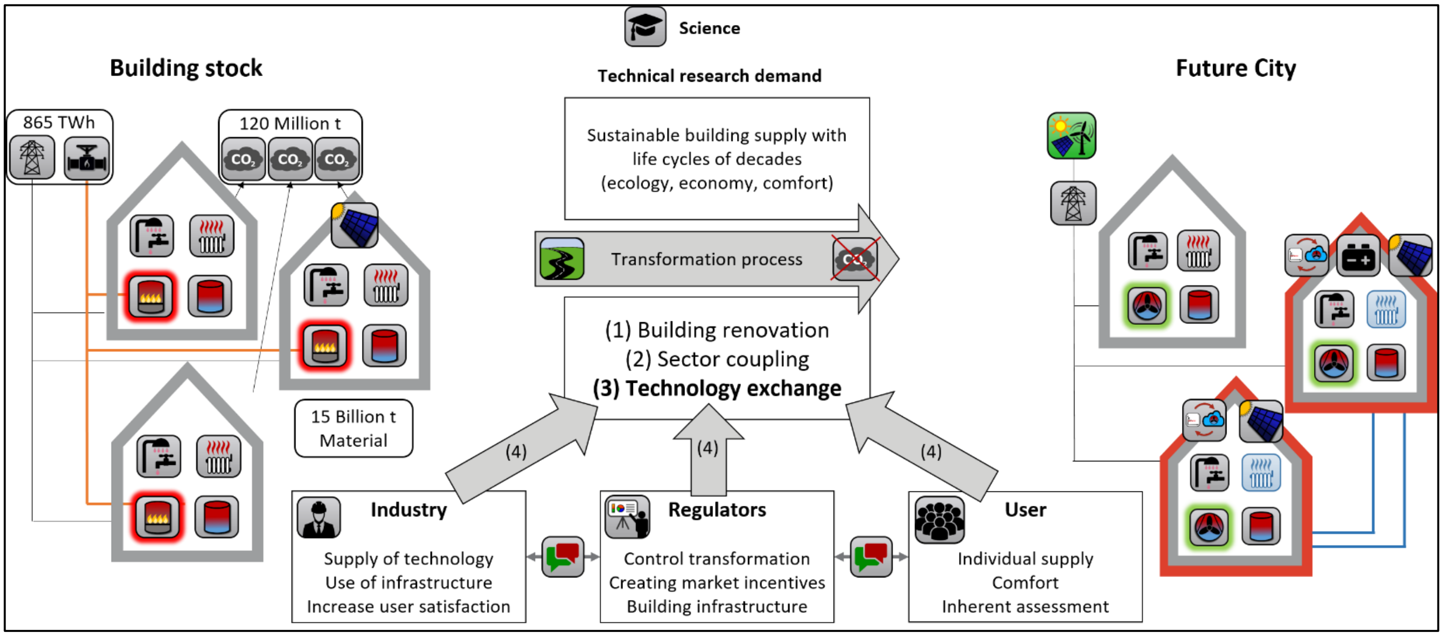

Fig. 1: The transformation process in the building sector with necessary measures for a successful transformation: (1) building renovation, (2) coupling sectors, and (3) technology exchange, which (4) all stakeholders must understand and support.

emission-reducing measures are evaluated in the context of a comprehensive sustainability strategy, in which "all three dimensions of sustainability (economic, ecological and social)" must be taken into account (Tremmel, 2003).

Specifically for the building sector in Germany, with about 19 million existing buildings, a "nearly climate-neutral building stock by 2045" is called for. With an average annual final energy consumption of about 865 TWh, CO2 emissions of about 120 million tons, estimated use of 15 billion tons of material (Müller et al., 2017), and prolonged decades of operation, the strict requirements imply a multi-layered transformation process of the building stock towards the city of the future (see Figure 1.1). Key components of this transformation process are (1) building renovation, (2) coupling of the heat and power sectors, and (3) replacement of conventional technologies with (4) input from external stakeholders. (Honegger et al., 2020)

Since the technology exchange (3) implicitly takes into account building renovation (1) and sector coupling (2) and can be considered under the influence of relevant stakeholders (4), the aspect of technology exchange from conventional heating systems to alternative technologies is focused on in this work.

For a sustainable technology exchange, exchange technology in the future must be optimally designed and operated. However, design and operation are inherently interdependent. Thus, a particular design may prevent optimal operation if design and operation decisions are not made simultaneously (Klein et al., 2014). Similarly, the optimal operation cannot be achieved with any designed plant and control technology if, for example, plants cannot achieve the required temperature levels. In this context, the technology exchange covers two domains: The design domain and the control domain. Furthermore, since the design and control domains have multiple layers, building energy systems also directly implies multi-scale systems, further complicating the considerations. Therefore, it takes many decisions to identify optimal exchange technology.

The ambitious technology exchange in a relatively short period increases the pressure on optimal decisions, which implicitly accelerates the transformation process. Taking many decisions in shorter time scales increases the overall complexity of identifying optimal pathways for sustainable building systems. To capture the complexity of tailor-made decision processes, a holistic view of the overall system is required (Fumo, 2014). Liu et al., 2010 already used an energy engineering approach to the optimal design of commercial buildings.

Process Systems Engineering (PSE) fulfills this requirement as it addresses the inherent complexity of systems (Klatt and Marquardt, 2009). Even though PSE is mainly used for chemical engineering on an industrial scale, its scope is also recommended for different fields, including energy systems or infrastructure systems (Demirhan et al., 2019; Stephanopoulos and Reklaitis, 2011; Klatt and Marquardt, 2009). However, a consequent application to the building sector and its materials is not stated in the literature so far. Furthermore, while PSE is interdisciplinary on an industrial level, it typically does not include stakeholders from different sectors or groups in society.

Living laboratories gained interest in the past years to include different stakeholders and societal groups in guided research processes. Living laboratories represent a research methodology for transformative and interdisciplinary research (Borner and Kraft, 2018). They help to gain knowledge about the system, the transformation process, and the aspired condition. Living laboratories include stakeholders from scientific, non-scientific (industry and private persons as users), and political sectors, which contribute to the innovation process (Seebacher et al., 2018).

The literature review shows that accelerating the building sector transformation process is crucial to mitigating climate impacts. However, solving problems in the building sector simultaneously requires holistic system approaches and the integration of different stakeholders. To capture systems on (1) multiple scales, (2) multiple domains, and (3) multiple stakeholders, new research methods are required.

In this work, we introduce building energy, material, and social systems engineering (BEMSSE) as a subfield of research in the field of PSE that covers (1) the scales from the environment and economy down to processes, materials, and molecules, (2) the domains of design and control, and (3) stakeholders for research, practice, regulators, and residents. Therefore, Section 2 presents the characteristic of building energy systems. Next, Section 3 introduces the definition of PSE, the design and the control domain, living laboratories and their application to BEMSSE. Finally, Section 4 concludes the findings and recommends future research perspectives.

2. CHARACTERISTICS OF BUILDING ENERGY SYSTEMS

According to DIN V 4701-10, a building energy system can be described by the subsystem's generation, distribution, and transfer (DIN V 4701, 2003). In addition, the system control can be considered a subsystem (Müller et al., 2016). These subsystems are shown for a bivalent monoenergetic heat pump system in Figure 2.

The heat pump and the auxiliary heating element provide heat in the generation subsystem. The distribution system ensures the transport and temporary storage of the heat. In the parallel connection shown, the storage tanks serve as hydraulic separators. For an overview, see the guide (BWP e.V., 2019) on hydraulic circuits of heat pump systems. Last, heat is transferred

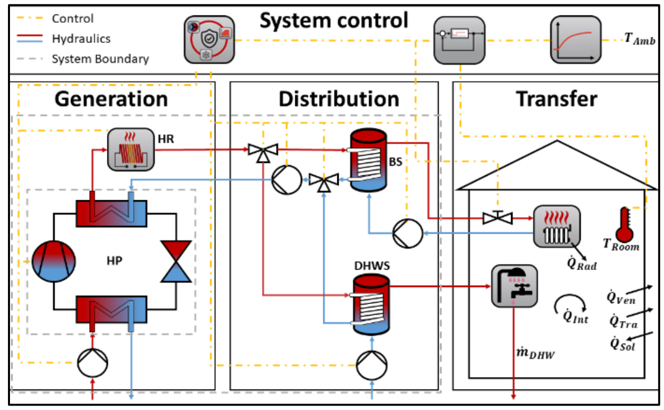

Fig. 2: Subsystems for a bivalent monoenergetic heat pump system.

through domestic hot water taps and heating surfaces. (Huchtemann, 2015)

The heat provision depends on the duration and number of residents' taps of the domestic hot water (DHW) $\dot{Q}_{\mathrm{DHW}}$ and the radiator output $\dot{Q}_{\mathrm{Rad}}$. This results from an energy balance of the building. Transmission heat losses $\dot{Q}_{\mathrm{Tra}}$, internal gains $\dot{Q}_{\mathrm{Int}}$, solar gains $\dot{Q}_{\mathrm{Sol}}$, and ventilation heat losses $\dot{Q}_{\mathrm{Ven}}$ influence the energy balance. In a simplified building consideration for a single thermal zone with room temperature T_{Room}, ambient temperature T_{Amb}, air mass m_{Air}, and specific heat capacity $c_{\mathrm{v,Air}}$ holds:

$$m_{\mathrm{Air}} \cdot c_{\mathrm{v,Air}} \cdot \frac{\partial T_{\mathrm{Room}}}{\partial t} = -\dot{Q}_{\mathrm{Tra}} - \dot{Q}_{\mathrm{Ven}} + \dot{Q}_{\mathrm{Int}} + \dot{Q}_{\mathrm{Sol}} + \dot{Q}_{\mathrm{Rad}}$$

$$\text{with} \quad \dot{Q}_{\mathrm{Tra}} = U \cdot A_{\mathrm{Building}} \cdot (T_{\mathrm{Room}} - T_{\mathrm{Amb}})$$

Where A_{Building} is the exterior building surface, U is the heat transfer coefficient of the building envelope, and t is the time. The parameters A_{Building} and U are defined here as concentrated parameters. In reality, detailed calculation rules have to be applied; see, for example, in DIN EN 12831 (2017). The task of the heat pump system is to provide a thermally comfortable room temperature and domestic hot water taps at all times.

Thermal comfort is a part of the overall comfort of users. Other aspects are air quality, lighting, and acoustic comfort. Thermal comfort is inherently subjective and depends on many factors. Fanger (1972) defines thermal comfort using the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). Furthermore, DIN 15251 defines comfort classes depending on the operative temperature. For cold outside temperatures, a tolerance band of 20 to 24 °C is defined. Comfort class II is considered to have been achieved if the deviation is 2 K in less than 1% of the use time. A deviation greater than

2 K automatically leads to the derecognition of class II (EN 15251, 2017).

The control of a heat pump system to adjust the thermal comfort is done with the help of the system controller. The core task of the system controller is the regulation and control of the components for the provision of thermal comfort and domestic hot water.

Both thermal comfort and domestic hot water demand are directly related to the user. Thus, users must be integrated into the transformation process as central stakeholders. In addition, the transformation process is even more complicated due to the enormous number of buildings in Germany. Therefore, to simultaneously capture both the entire building sector and different stakeholders requires holistic stakeholder-dependent consideration of energy, materials, social aspects and systems. Therefore, we combine PSE and living laboratories to ensure a holistic view of the building sector using the description of building energy, materials, and social systems engineering (BEMSSE).

3. BUILDING ENERGY, MATERIALS, AND SOCIAL SYSTEMS ENGINEERING (BEMSSE)

Applying PSE to the building sector requires the definition of PSE prior to the application (Section 3.1). Then, in Section 3.2, we also state the paradigms of PSE and deduce the two main domains in building energy systems: the design and the control domain. Finally, in Section 3.3, we introduce the living laboratory to integrate stakeholders into the method of PSE.

3.1 Process System Engineering (PSE)

PSE was defined by Takamatsu (1983) as the discipline of systematic planning, design, operation, and control of chemical processes. Single (chemical) processes should not be considered independent from their surroundings but from a holistic point of view in a more extensive system (Takamatsu, 1983). Grossmann and Westenberg (2000) try to close the gap between science-based and system-based research by broadening the scope of PSE with an even more holistic approach. They apply PSE to the concept of chemical supply chains and thus, interpret PSE as a tool of scientifical methods and tools to support systematic decision making. Hence, they stress the multi-scale perspective of PSE. However, PSE is recommended not only for chemical engineering processes but also for energy or infrastructural systems (Stephanopoulos and Reklaitis, 2011; Klatt and Marquardt, 2009).

In order to use technical (energy) systems, they must be designed and operated according to their purpose. Design processes can become arbitrarily complex depending on the application, cross-domain functionalities, and boundary conditions. An overview of process systems engineering is given to introduce the systems view of technical systems and subsystems.

According to Arthur, technical systems encapsulate reliably controlled causal action mechanisms (Arthur, 2011) and are characterized by a function that processes substance, energy, and/or information (Ropohl, 2009). Processing can be divided into three types: Conversion, Transport, and Storage. In combination with process systems engineering (Pistikopoulos et al., 2021), a technical system considers the associated life cycle. According to NASA, the life cycle includes design, implementation, technical management, operation, and decommissioning (NASA, 2008).

Within the system and life cycle considerations, two major paradigms exist in PSE for system design: Analysis and Synthesis, which are illustrated in Figure 3. Both paradigms predominantly rely on computer-based methods: modeling, simulation, and optimization (MSO) (Klatt and Marquardt, 2009).

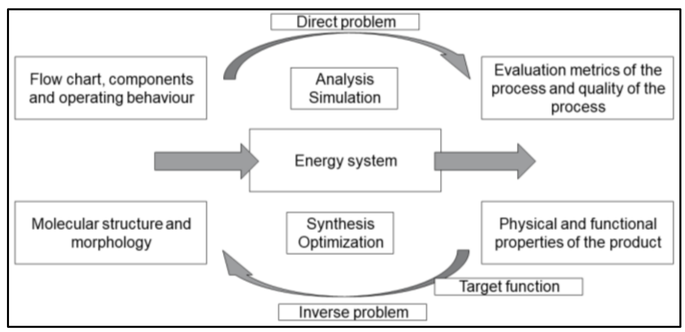

Fig. 3: Analysis and Synthesis in PSE.

Based on simulations for circuits, components, and operating boundary conditions, the analysis paradigm solves direct problem formulations, for example, through parameter variations. This can be used to determine indicators of performance or product quality. In contrast, synthesis solves the inverse problem by searching for the optimal structure for the desired function. Depending on the task and the use case (complexity), choosing an associated paradigm is appropriate (Klatt and Marquardt, 2009).

With steadily increasing computational power, increasingly complex tasks and case studies can be investigated in a sufficient time using MSO methods. For this purpose, models of processes have to be structured and developed. According to Marquardt and following the systems theory, complexity can be transferred into two independent coordinates for orientation in model structuring: Substantive complexity and phenomenological complexity (Marquardt, 1992).

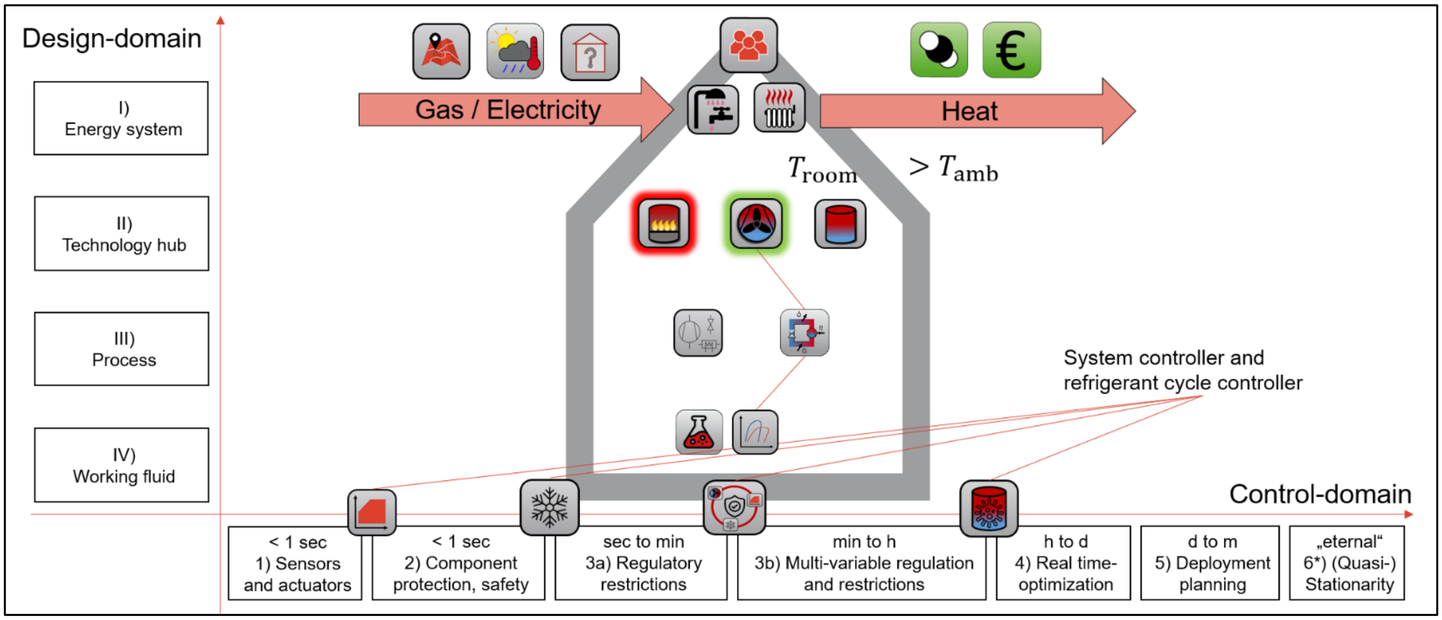

Fig. 4: Design domain and control domain in (building) energy systems.

Substantial complexity results from delineating material parts of a system or component. Phenomenological complexity is used to describe the behavior of components. The delineation of components and the description of component behavior transforms the technical system into a computer-based, manageable form of mathematical equations that can be implemented and solved efficiently in suitable software environments.

In addition to the interactions of the system, initial and boundary conditions must be implemented. Often, technical systems are subject to time-variant boundary conditions, which can increase the overall complexity since transient component behavior must be considered to represent the overall system reliably. Therefore, it requires a systematic approach to investigating and optimizing building energy systems.

3.2 Applying PSE to Building Energy Systems

In this work, process systems engineering as a process engineering discipline is applied to the building sector concerning energy and its materials. Compared to process engineering, the complexity in building energy systems results less from the complexity of the individual processes (e. g., distillation, material separation) but from the time variance of the processes (e. g., weather, users). Therefore, in this section, the design domain and control domain are merged following representations by Klatt and Marquardt (2009) and Seborg (2017) and applied to (building) energy systems (Figure 4).

In Klatt and Marquardt (2009), three levels are schematically introduced. On the level of the elementary systems (processes), however, the working fluid is not explicitly understood. On the other hand, the working group of Professor Bardow, Schilling et al. (2021), among others, show that the integrated consideration of working fluid and the process is essential for optimal design. Therefore, the working fluid added to the design domain's representation is supplemented.

The design domain consists of four levels: (I) energy system, (II) technology hub, (III) processes, and (IV) working fluid. At the top level (I), the energy system is a balanced space for mechanical, thermal, and chemical energy flows. In this context, the balance space is a technically equipped building that requires dedicated heat flows to set indoor temperatures and provides domestic hot water to maintain user comfort. The necessary energy flows are realized by technologies provided within the technology hub (II).

The technology hub includes technologies for energy conversion (e. g., boilers, heat pumps), energy storage (e. g. sensible thermal storage), and energy transport (e. g., hydraulic transmission systems). At the level of the technology hub, the optimal plant technology must be selected, and the optimal dimensioning of the plant technology must be carried out for the optimal supply of the building.

The optimal selection and dimensioning of the plant technology can only be made if on the III. design level, the process level, and suitable concepts exist to fulfill the desired function by the concatenation of phenomena. In this work, refrigerant cycles for heat supply are considered on this level. Due to the availability of different refrigeration cycle flow sheets with different refrigerants, the selection of the optimal interconnection is also complex. It can only succeed optimally if the working fluid level (IV: working fluid) is also considered (McLinden et al., 2017). Each working fluid has different equilibrium data and transport properties, which can strongly influence the efficiency of heat pumps (McLinden and Huber, 2020).

In addition to the overlay of the four design levels, there are five control levels (1-5), according to Seborg (Seborg, 2017). The first control level 1) has a time constant smaller than one second and describes the field level with all sensors (including temperatures and pressures) and actuators (including valves and pumps) of a technical (energy) system. On the same order of magnitude as the time constant is also the second control level 2), which protects the components with all safety-relevant devices (among other things, high-pressure valves and safety relays).

In the case of time constants in the seconds to minutes range 3a) or minutes to hours range 3b), a distinction is made at control level 3 between two types: 3a) Regulatory restrictions and 3b) Multi-variable regulation and restrictions. At level 3a), for example, desired pressure or temperature levels and volume flows are set in a system.

Multi-variable control drives the system stably to the limited operation (for example, maximum efficiency) and remaining in this operation in a controlled manner. If forecast data can be integrated into the control at time constants from hours to days, the fourth control level, 4) is reached. This serves for the optimal adjustment of the system on a short forecast horizon. If the forecast horizons become even longer (days to months), Seborg suggests the fifth control level 5): Deployment Planning. This level is used to deploy the optimal system technology over extended periods. (Seborg, 2017; Rawlings and Maravelias, 2019).

In this paper, to these five levels of control, the sixth level added to Seborg's approach is the thermodynamic case of (quasi-) stationarity and can, in principle, be valid for processes with constant boundary conditions. However, as discussed at the beginning, building energy systems are generally subject to time-varying boundary conditions, so the remaining levels on the control domain are necessary. Thus, all control domain levels are described in addition to the design domain levels. However, no stakeholder-dependent interactions have been considered so far. To fulfill the specifications of BEMSSE, stakeholders need to get involved in the process by using living laboratories while still maintaining a systematic delineation according to PSE.

3.3 Living Laboratories

Beecroft et al. (2018) define the three aims of living laboratories, which meet the concerns of all stakeholders involved in the transformation process: Scientific, practical, and educational goals. Scientific goals include the gain of knowledge about the current state of a system, knowledge about the aspired state of the system, and knowledge about the transformation process. Practical goals include gaining knowledge about the realization of transformation processes and achieving acceptance of new technologies. Educational goals involve the shift to a more sustainable lifestyle for an individual. Stakeholders work together during Co-Design, Co-Production, Co-Evaluation, and Co-Interpretation to equally contribute to an optimal solution (Borner and Kraft, 2018; Wedell et al., 2018).

Identifying optimal solutions requires objective functions. In conventional solution approaches, single objectives are chosen to identify the best solution in one metric. However, using a single metric for assessment might yield misleading conclusions in other metrics and shift a problem from one to another (Reinert et al., 2021). Therefore, multi-objective assessment methods, including the entire life cycle from the cradle to the grave like life cycle assessment (LCA), are gaining interest, as well as circular carbon economies, which are already feasible, e.g., in the plastic industry heavily employing different recycling routes simultaneously (Meys et al., 2021).

In the context of living laboratories, integrating relevant stakeholders and multiple objective functions becomes even more important since the user as a stakeholder in the building sector plays a unique role by affecting metrics directly with his behavior. Thus, living laboratories are crucial for integrating the user into the transformation process of the building sector. In addition, considering planetary boundaries as a pre-condition for the entire development on Earth is essential to avoid overstepping certain boundaries that might have an irreversible impact on life (Rockström et al., 2009, Raworth, 2012).

One potential boundary condition, which is not often discussed in the literature on building energy systems, especially for the German building sector, is the demographic change in the population. While Germany has about 82 million people in 2022, this number might reduce to 67 Million (73 Million) based on the assumed immigration rates (Statistisches Bundesamt, 2015). This decrease should be considered in future calculations to find the optimal transformation process for Germany, which is only possible using multipronged approaches (Garimella et al., 2022).

Overall, the transformation process in the building sector is complex and requires innovative methods to reach climate goals and mitigate climate change. BEMSSE, a combination of PSE and living laboratories, is a promising method to capture the systems thinking and find optimal pathways for the transformation. Besides MSO methods, experiments are crucial, and multipronged approaches are necessary to accelerate the transformation process.

4. DISCUSSIONS

BEMSSE is a target-orientated approach to speed up the transformation process towards a defossilized future in the building sector. By including stakeholders from non-scientific sectors, users and industry feedback can influence the research fields. In this way, research is directed towards feasible and practicable research topics and does not lose time with approaches that will not be accepted by society or the industry. Also, the risk of publishing products, which may not break through the market, can be reduced.

The involvement of users into the research process may also raise the awareness in society building sector defossilization and thus enlarge the acceptance of new and innovative solutions. This can be defined as the educational goal of the living laboratory.

The holistic and systematic approach, which is implied in BEMSSE, enables the potential for optimal solutions. Integrally optimizing the system prevents problems between individual subsystems. Furthermore, subsystems, for example heat pumps, can be individually optimized to meet the system's requirements and user comfort most efficiently. High-efficiency systems can be found, and a generation of systems with lower efficiency can be skipped. Due to the longevity of heating systems in buildings, this might drastically speed up the transformation process in the building sector.

At the same time, integrating stakeholders may lead to early denial of ideas. Users may reject solutions due to missing maturity, not considering the full potential it may have. For this reason, it is important to involve stakeholders at the right time.

Furthermore, it is necessary to find many users who offer to participate in living laboratories. This way, many users' preferences can give researchers and the industry feedback.

There is also the risk of not mapping the average user and not mapping all aspects of a real-life application. Being in a laboratory may lead to the changed behavior of users. Some aspects, for example, vandalism, may not be considered.

Further challenges and limitations may arise from the existing building stock. Old buildings may not provide the possibility of integrating innovative technology or may lead to high costs. Historic orders may enlarge this problem. If these challenges can be tackled, BEMSSE promises to meet the needs for the following points:

- Accelerated development: Concerning the Paris Climate Agreement, the German Government concluded in January 2022 in an opening balance that current actions are not sufficient to achieve their own goals, in particular for the building sector (BMWK, 2022). Furthermore, they demand accelerated development.
- Systematic Approach: Departing from fossil fuels leads to various components in building energy systems. In order to maximize their efficiency, these components need to be designed together and adjusted for the specific application.
- Including stakeholders: Challenges in control of building energy systems arise party from the user. From a technological point of view, the user can be seen as a primarily unpredictable confounding variable, which makes it harder to control the whole system. However, building energy systems exist mainly to comfort the user, so this confounding variable should be included in the development.

5. CONCLUSION

This work summarizes the building sector transformation process challenges to mitigate climate change. The main findings of this paper are summarized below.

- We identified that the transformation process is complex due to simultaneous consideration of (1) multiple scales, (2) multiple domains, and (3) multiple stakeholders. Therefore, to capture inherent dependencies already in research, a uniform description is beneficial to bundle forces that draw up a successful transformation process.
- The combination of the two research focuses PSE and living laboratories appear to be a promising solution. While PSE is a standard approach in the chemical industry to capture different scales and domains, it has not yet been widely applied to building energy systems. In addition, living laboratories are

currently an emerging research direction that cover stakeholder integration into research. We call the merging of the favorable methods of building energy, materials, and social systems engineering (BEMSSE).

- BEMSSE aims to capture the two PSE paradigms analysis and synthesis with MSO methods and combine them efficiently with experiments to integrate different stakeholders already into the research process. While experiments are often more time-consuming than MSO methods, it is necessary to design experiments optimally, for instance, by applying OED methods. OED methods can reduce the number of experiments and accelerate the research process. In this context, optimal combinations of MSO and Experiments (MSO-E) are the key to archiving goals even faster.
- Especially the concepts of LCA and circular carbon economy, considering the demographic change and materials, are promising to avoid misleading conclusions in the transformation process. We need multipronged approaches to reach climate goals and mitigate climate change because the time for the transformation is relatively short.

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