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Paving the way to carbon neutrality: Energy transition roadmaps for transforming Technical Building Services in factories

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Abstract

The efficient re-design of technical building services (TBS) remains a pivotal challenge in the pursuit of carbon neutrality within factories. Current energy solutions often fail to meet sustainability targets, hindered by complex interactions between technological and economic factors. An approach for guiding factory managers in selecting and implementing effective energy systems for carbon-neutral production is proposed. The approach utilizes a simulation tool coupled with an evaluation software to model various transformation paths and the associated configurations of TBS. By simulating multiple scenarios, the approach identifies the best order of technology deployment, accounting for economic feasibility, peak load management, and carbon emission reduction. The analysis highlights critical interactions between different energy flows inside a factory and identifies potential conflicts that could impact overall efficiency. Based on these results the best transformation path is selected. The approach was validated through a detailed case study on an electronic manufacturer, yielding valuable insights and practical recommendations for TBS transformation. Results demonstrate significant potential for carbon emission reduction and more efficient energy management. Thus, this approach empowers factory managers to make informed decisions towards achieving environmentally and economically sustainable production.

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Keywords: Energy System, Sustainability, Factory Planning, Transformation Paths, Energy Management, Energy Flexibility, Decarbonization

1. Introduction

The transition to carbon neutrality represents a significant challenge for manufacturing industries. Given their status as significant contributors to global carbon emissions, strategies are needed to transform factories and their energy system in order to facilitate sustainable operations [1]. One of the pivotal aspects of this transformation is the redesign of technical building services (TBS), which consist of the infrastructure responsible for maintaining the needed production conditions. However, current approaches to design TBS for carbon-neutral production are considered inadequate due to constraints posed by complex technological interdependencies and economic uncertainties [2]. Therefore, the existing gap to develop a comprehensive approach to guide factory managers in selecting and to implement effective energy systems for sustainable production is addressed. The proposed approach is able to derive transition roadmaps for the TBS of factories, enabling them to reach a defined goal for the energy transition. Furthermore, this study aims to highlight the critical

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interactions between different energy flows within a factory, and identify potential conflicts that may affect overall efficiency. The findings are validated through a case study conducted at an electronics manufacturing plant in Germany. The focus was on economic feasibility, peak load management, and carbon emission reduction capabilities. By developing a clear and adaptable roadmap, this research offers valuable guidance for factory managers and policymakers in the pursuit of carbon-neutral production. The results of this study demonstrate significant potential for carbon emission reduction and enhanced energy management, paving the way for sustainable and economically viable energy transition roadmaps for the manufacturing sector.

2. Background

2.1. Existing approaches for energy transition roadmaps

The term transition roadmap is not consistently defined in the literature but is widely discussed. Generally, it refers to a strategic plan outlining steps on a timeline to shift from a current system to a more desirable one. Often focused on national or broader scales, these roadmaps typically incorporate technological innovations, policy changes and social and economic adaptions. The goal is to transform energy systems in line with sustainability targets derived from an absolute sustainability framework [3, 4]. This work focuses on decarbonization targets aligned with the science based target initiative [5], emphasizing environmental sustainability. The scope and depth of such roadmaps might vary significantly, often distinguished between technological, social and political aspects [6–9]. For example, Cherp et al. identify three perspectives: techno-economic, socio-technical and political [10]. Roadmaps for energy transitions commonly address national-level goals. This includes achieving carbon neutrality [7] or transitioning to fully renewable energy mix [11, 12], outlining adaptive actions over several years or decades. While the considered aspects of the energy grid transition might differ between different studies, following aspects are typically considered:

Business-as-usual: Refers to the system's state before initiating the transformation process, serving as the baseline and starting point for the transition roadmap.

Change in energy demand: Over the long-term planning horizon of the energy grid, energy demand is expected to fluctuate. These changes are typically estimated using projections from various studies.

Technological Advancements: As the energy grid evolves over time, new technologies emerge and existing ones improve in efficiency or decrease in cost. Anticipating these developments is essential when designing a transition roadmap.

Additional factors considered in individual methods may include sociological aspects, such as population behavior and willingness to change, or logistical aspects like spatial availability of energy sources and transport options. On a single factory site, spatial availability and transportation costs are typically negligible. The three perspectives outlined by Cherp et al. – techno-economic, socio-technical, and political – are relevant not only on a national scale but also at the factory level. For instance, the social and socio-technical perspective impacts factory energy transitions through public acceptance or resistance to technologies, such as wind energy. The political perspective influences the economic viability of technologies via subsidies. Transition roadmap development relies on projections of future trends. Incorporating socio-technical and political perspectives introduces significant uncertainty. Consequently, the proposed approach focuses on the techno-economic perspective.

2.2. Drivers for energy transition of factories

Adapting the concept of an energy transition roadmap to the manufacturing industry requires defining a clear goal, addressing the business-as-usual state, and estimating changes in energy demand and available technologies over the transition period. Capozza et al. identified key motivations for the energy transition of European manufacturing companies [13]. The following push- and pull-drivers can be identified:

Policies: Regulations and taxes act as push-drivers, while subsidies and public procurement serve as pull-drivers, all stemming from external policies enforced on companies.

Environmental Responsibility: Market demand, corporate reputation, and self-commitment drive sustainability efforts, such as reducing carbon emissions.

Economic success: Maintaining a positive financial balance is essential for operation. High energy costs in Europe, particularly in Germany, make energy system transitions a potential source of significant cost savings.

Resilience: Although less emphasized, the ability to manage risks and disruptions is gaining importance in manufacturing [14]. Different approaches how to transform towards a more resilient manufacturing system are present in literature [15–17].

When developing energy transition roadmaps for factories, these main motivations should be kept in consideration. The TBS, which encompass the infrastructure required to maintain production conditions, account for a significant share of manufacturing energy demand. In 2019, HVAC systems were responsible for nearly 10% of useful energy consumption in the German industry, with process heat and cooling accounting for an additional 68% [18]. Industries with specific indoor climate requirements, such as battery manufacturing, see even higher shares, with HVAC systems contributing up to 60% of energy consumption [2]. Additionally, the TBS facilitates the conversion of final energy to useful energy and the on-site generation of renewable electricity. Therefore, the TBS should be central to the energy transition roadmap.

2.3. Drives and targets for TBS transformation

Technical building systems (TBS) are integral to every manufacturing industry and often contribute significantly to a factory's energy-related carbon emissions. Transforming TBS toward more economic and environmentally sustainable operation is a crucial part for achieving sustainable manufacturing. A factory must first ensure its financial viability to maintain production. Environmental sustainability can indirectly impact cash flow by meeting customer demands or avoiding emission-related charges. More influencing factors

from an energy system perspective are the cost of energy consumption, regional charges such as peak power surcharges and energy supply security. These factors must all be carefully considered when designing a transition pathway for a factories TBS.

3. Approach

As with transition roadmaps for the national energy grid, developing a transition roadmap for a company requires first defining a concrete goal and timeframe. For example, reaching carbon neutrality by 2035 or to reduce energy cost by 50 % over the course of 10 years. Strategies are derived from goals and serve as interim targets and for deriving suitable KPIs. Possible strategies are e.g.: increasing on site generated energy, reducing peak loads or increasing the energy efficiency. This selection of strategies can be extended as required. For implementation, different measures must be considered. Possible measures include technologies to be implemented in a factory, such as more efficient pumps, battery storages or a photovoltaic plant. The organizational measures like the adaption of operational parameters (e.g., the reduction of the temperature of the heating network) are also included. Based on the defined goal relevant strategies are defined. It is possible that all strategies can be pursued simultaneously or that individual strategies are mutually exclusive. Based on these strategies valid measures are derived. These measures might be relevant for only a share of all strategies. For example, a heat storage increases the utilization of on-site generated energy while reducing the overall energy efficiency of a factory, due to increased heat losses. In such cases the positive and negative effects must be weighed against each other. Even if the implementation of such measures is still beneficial, the order in which these measures are implemented is directly influenced by these positive and negative effects.

3.1. Framework

The framework for the approach is structured in four steps, as shown in Fig. 1. The first step Foundation, comprises 1.1 system analysis, 1.2 strategies and 1.3 measures. The system analysis evaluates the factory's current energy system, focusing on final energy flows, useful energy demands, and existing energy conversion technologies. In 1.2 strategies, relevant strategies are identified to achieve the defined goals. Building on the system analysis and selected strategies, 1.3 defines suitable measures tailored specifically to the use case, ensuring their applicability and effectiveness within the factory's unique context. With this foundation, the next step, 2.1 definition focuses on scenarios, including individual measures in the factory and potential transformation paths. The inclusion of individual measures serves as a reference to identify positive and negative effects between measures when analyzing the transformation paths. In 2.2 Evaluation Criteria, key performance indicators (KPIs) are defined. These KPIs depend on the defined goal and strategies and should be appropriately chosen for each factory. Suitable KPIs might be of economic or ecologic nature or depict energetic information of the factory. The different scenarios are evaluated during 3.1 simulation, described in the following section. The result in 4.1 roadmap is the final transformation roadmap for the analyzed factory, which highlights the novelty of this approach and is described in section 3.3.

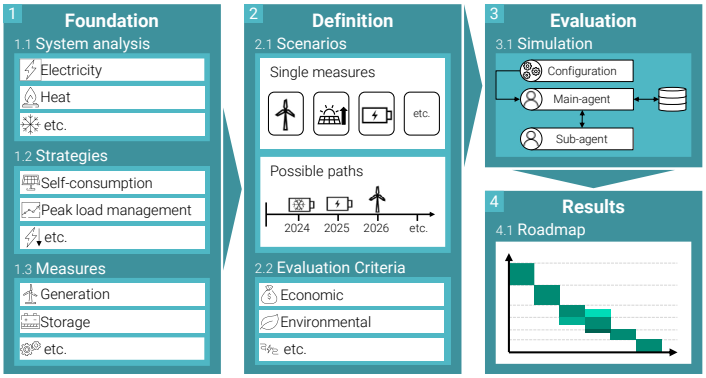


Fig. 1 Framework of the approach

3.2. Simulation

When modeling a factory's energy system, several factors must be considered. First, data from the existing system should be collected to develop a suitable simulation structure. To account for seasonal variations, energy data should be gathered for at least a year. Information on relevant TBS components, both current and planned, must be compiled, along with system requirements like minimum flow rates in heat distribution. All data should be standardized for easier handling. The simulation output should include aggregated KPIs and time series data to analyze system performance under various conditions.

The simulation structure must enable flexible parameterization of TBS components, constraint implementation, and decision-making on factory, energy system, and component levels. This work uses an agent-based system, where a main agent governs the energy system's behavior based on factors like energy demand, renewable production, and restrictions. The main agent communicates with sub-agents, each representing an energy system, which respond by producing, storing, or converting energy within their constraints. Information flows from the main agent to system and component agents. The main agent integrates data from all sub-agents, enabling evaluation of the entire system. Measures are assessed individually to rank their impact on KPIs, followed by an analysis of their interactions in the transformed system. Multiple parameters are tested to approach the optimal combination of measures in regards to KPIs and payback period.

3.3. Development of transition roadmap

The implementation sequence of different measures depends on their payback period as shown in Fig. 2. The values presented should help to clarify the example. Graph a) illustrates the initial invest (100 k€ and 150 k€) and annual savings (20 k€ each) for two measures. The total invest of 250 k€ reflects both measures combined. Complex interactions between different systems can affect annual savings, either positively or negatively. For example, a photovoltaic plant may

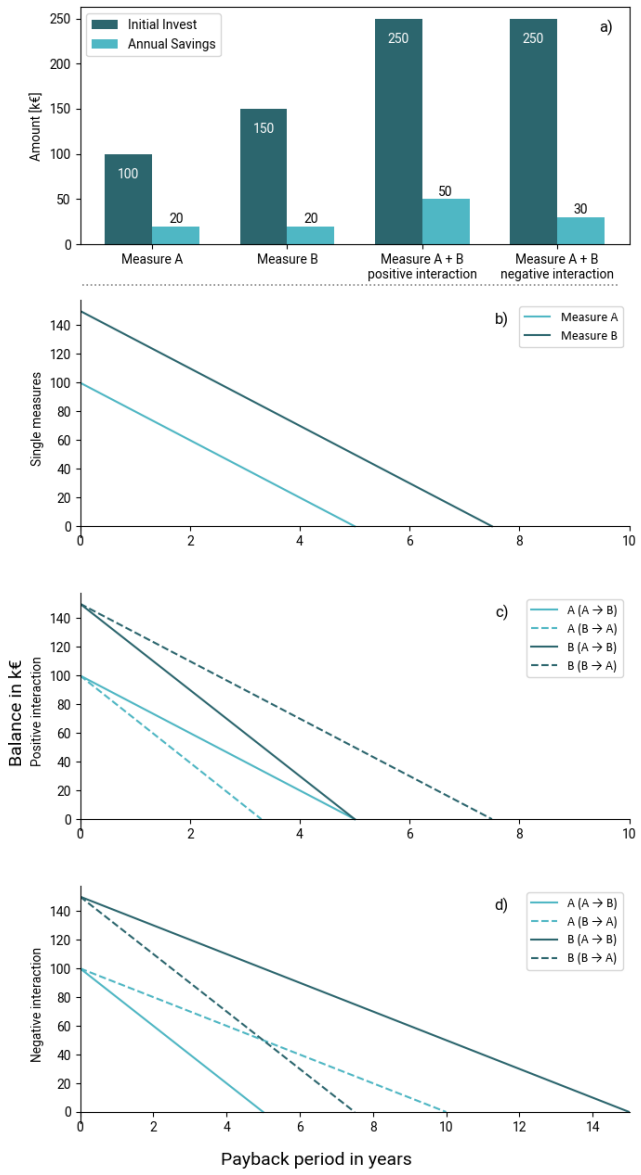


Fig. 2 Positive and negative interactions of multiple measures and their influence on the payback period

produce excess electricity, which a heat pump can utilize to increase overall savings beyond the individual measures' savings. Graph b) shows payback periods for each measure: 5 years for measure A and 7.5 years for measure B. If only one measure is implemented, measure A is preferred due to the shorter payback period. However, to reach the initially defined goal both measures are needed. The following graphs show how positive (c) and negative (d) interactions affect the payback periods when implementing both measures. The continuous line states in both graphs the case, that measure A is implemented first, followed by measure B. The dashed line shows the results when measure B is implemented first, followed by measure A. Graph c) shows a positive interaction between both measures. The total annual savings are 50 k€, with 20 k€ from the first measure and the second measure being responsible for the remaining 30 k€. When implementing measure A first, the payback period of measure B is reduced by 2.5 years, resulting in a payback period of 5 years for both measures. If measure B is implemented first, it's payback period stays at 7.5 years, while dropping to 3.33 years for measure A. In the negative interaction case, presented in graph d), total annual savings reduced to 30 k€, with 20 k€ from th first measure and only 10 k€ from the second. In this case, the payback period for the second measure doubles. When implementing measure B first, the payback period of measure A increases by 5 years. When implementing measure A first and measure B second, the payback period of measure B increases by 7.5 years.

The behavior shown in Fig. 2 is also valid for an increasing number of measures, resulting in increasingly complex relations. These interdependencies are evaluated in a simulation model and the results are used in the development of transformation paths.

4. Case Study

The case study examines an electronics manufacturing plant in Germany, representative of mid-sized facilities in the sector, with the aim of achieving carbon neutrality by 2030. A system analysis identified electricity and natural gas from the grid and district heating as primary energy sources, with useful energy demands categorized as electricity, heat, and cooling. Previously, Imdahl et al. analyzed this use case for hydrogen integration potential [19]. The electricity supply by grid is 10 GWh/a and the carbon emissions are 4,800 t/a [20]. This is below industry standard, due to the supply of district heating. The current study's results were validated through expert reviews involving company representatives, who assessed the feasibility of the proposed measures. The manufacturer's energy consumption patterns align with typical German facilities, supporting the generalizability of findings.

Considered strategies for this factory include the increased self-consumption of on-site generated energy, the reduction of peak load and the increase of energy efficiency of the system. Suitable measures for the case study are the expansion of on-site renewable energy via wind turbines, energy storages in the form of a battery and a cold storage, more efficient pumps for the cooling network, the adaption of process parameters and the inclusion of a heat pump. Fig. 3 gives a system overview of the energy system of the manufacturing plant. The different technologies for energy conversion implemented at the start of the study are present on a white background. Electricity and natural gas are supplied to the factory. A photovoltaic plant

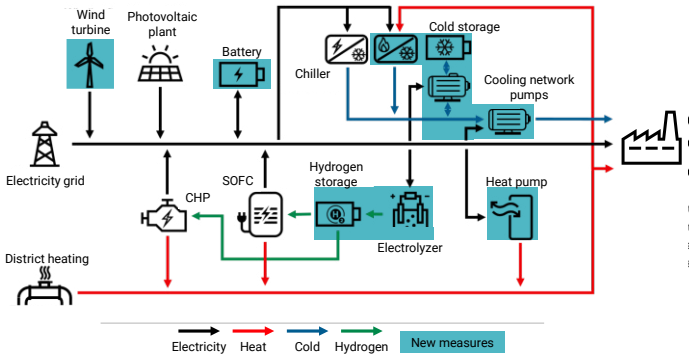


Fig. 3 System overview of the electronic manufacturing plant. Measures to be implemented over the course of the transition roadmap are highlighted in green. The energy flows are depicted via arrows.

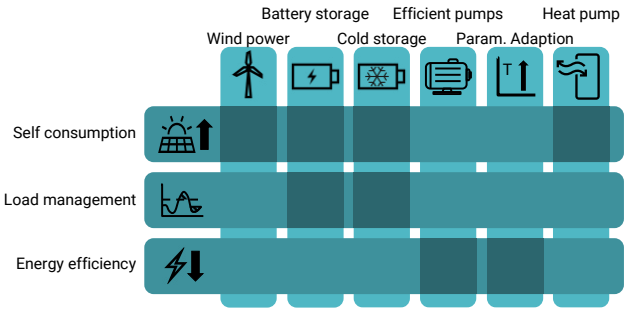


Fig. 4 Valid measures and strategies in matrix structure for the use case. Strategies are rows, measures are columns. Valid measures for certain strategies are indicated through a dark square.

with 4.7 MWp for the generation of electricity is present on site. Heat is supplied by district heat or a combined heat and power plant (CHP) and fuel cells, which also generate electricity to be used in the factory. Cold is supplied by compression chillers. The measures included in the study were identified in a previous assessment and are valid for this use-case. The studied measures are highlighted in blue. As stated in section 3, not all measures apply for all strategies. In Fig. 4 a matrix structure is shown, depicting the applied strategies in rows and the measures as columns. If measures are applicable for a certain strategy, the intersection is highlighted in a dark blue. As an example, the implementation of wind turbines only affects the increase of self-consumption of on-site generated electricity while the implementation of energy storages like batteries and cold storages are valid for the increase of self-consumption as well as for load management. First the measures cold storage, battery storage, efficient cooling pumps, wind turbine and heat pump are studied. The adaption of process parameters is not related to investment costs and therefore not part of the transition roadmap but considered in combination with the heat pump. The KPIs reduction of annual power peak, CO_2 emissions and energy costs are chosen. Different transition roadmaps have been simulated, with the best performing one being discussed.

The results are presented in Table 1. The summed reduction of the annual power peak of individual measures is significantly higher than the calculated reduction of the final transition path. When the cold storage is used for peak load management, the capabilities of the battery are drastically reduced. The capabilities of the cooling pumps are also reduced when comparing it to the potential of the individual scenario. For KPIs reduction of CO_2 emissions and reduction of energy cost, the transition path performs better than the sum of the individual measures. For the CO_2 emissions both efficient cooling pumps and the wind turbine have positive interactions with the cold storage which results in a stronger decrease of emissions. For the energy costs, the effect of the battery storage is slightly decreased, again due to the cold storage. But all other measures record low positive interactions which lead to an overall higher decrease of energy costs. In Fig. 5 the results are presented in form of a transition roadmap. The negative effect of the battery storage on CO_2 emissions can be seen, increasing the overall emissions with implementation. The highest difference between transition roadmap and the sum of individual measures is present for the reduction the annual peak load. Due to the high capabilities of the cold storage, battery, efficient pumps and the wind turbine underperform greatly in comparison to their potential as individual measures. When reviewing the KPI energy cost, the battery underperforms in the transition roadmap, but especially cold storage and the heat pump benefit strongly from positive interactions and result in an overall better performance of the transition path in comparison to individual measures. While the results are specific to the given use-case, it can be assumed, that other manufacturing companies with a similar size can archive savings on a comparable scale with the presented approach.

The implementation of hydrogen shown in Fig. 3 was not considered as a part of the transition roadmap. During the study, it was found that the potential of hydrogen on energy costs and CO_2 emissions is independent of other measures. Therefore, electrolyzer and hydrogen storage does not need to be allocated in the transition roadmap, but should be implemented as soon as economically feasible.

5. Conclusion

This paper presents an approach for designing transition roadmaps for factory energy systems, focusing on TBS. Applicable across all manufacturing sectors, the approach targets cross-sectional technologies and supports achieving a defined goal within a specified timeframe. Strategies are formulated as intermediate management level objectives. Measures to be implemented are cross-referenced with the strategies and based on a simulation positive and negative interactions are determined. By considering these interactions and differences in payback periods, the roadmap optimizes the sequence of implementations to minimize payoff time while adhering to strategies and achieving the goal. The approach is able to consider multiple final energy sources and useful energy demands and depicts the whole energy conversion chain present in a factory. Applied to an electronics manufacturing plant in Germany, the method successfully identified an optimal roadmap to reduce carbon emissions, peak loads, and energy costs, demonstrating its suitability for guiding factory energy transitions. Also, the advantages of considering the whole transition roadmap over the course of an extended period while viewing the energy supply system with all present energy carriers became evident. The useful energy demands are based on historic data. Further development of this approach could involve integrating predictions for energy demand trends over the considered period, as well as anticipated changes in grid energy prices and emission factors. This would enhance the roadmap's accuracy and adaptability to future energy system dynamics.

Table 1. Results for the transition roadmap in comparison to the sum of individual measures for KPIs CO_2 emissions, power peak and energy cost.

	Cold storage	Battery storage	Efficient pumps	Wind turbine	Heat pump	Sum of all individual measures	Transition roadmap
CO_2 emissions	- 0.68 %	0.08 %	- 0.22 %	- 5.05 %	- 0.48 %	- 6.35 %	- 6.66 %
Power peak	- 6.26 %	- 9.64 %	- 2.55 %	- 2.14 %	0 %	- 20.59 %	- 12.3 %
Energy cost	- 0.79 %	- 0.77 %	- 0.30 %	- 4.20 %	- 0.39 %	- 6.45 %	- 6.76 %

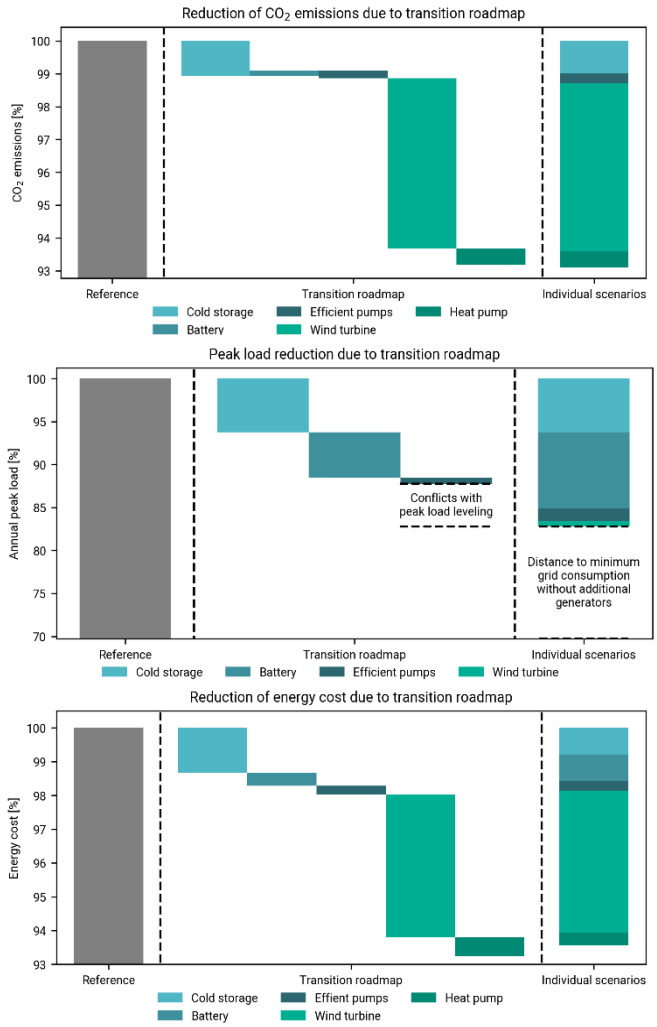


Fig. 5 KPIs CO2-emission, annual peak load and energy cost as normalized values for the reference, the transition roadmap and the sum of the individual measures.

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