

Simulation-Based Quantification of CO₂ Savings in Cellular Energy Systems

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Abstract

Cellular energy systems represent a decentralized approach to energy management, integrating renewable sources across electricity, heat, and mobility sectors to enhance sustainability. This study employed the open-source oemof simulation framework to evaluate eight technology configurations for a typical German household comprising renewable generation, storage, and sector coupling technologies, and electric vehicles. The most extensive configuration setup achieved an 83 % reduction in carbon dioxide emissions and 55 % self-sufficiency compared to a baseline without local renewable integration. However, seasonal limitations, particularly reduced solar output in winter, highlight the need for complementary technologies like wind turbines and seasonal storage. These findings highlight the potential of cellular energy systems to support Germany's 2045 net-zero ambitions, though challenges such as regulatory barriers remain critical to address. This research advances the understanding of decentralized energy systems' role in decarbonization, emphasizing innovation in storage and sector coupling.

Keywords

Cellular Energy Systems, CO2 Reduction, Renewable Integration, Sector Coupling

1 Introduction

Despite significant progress in Germany's energy transition, substantial potential remains for reducing CO₂ emissions within the energy sector. In 2024, the energy industry accounted for 28.5 % of total emissions, making it the largest emitter, even though renewable energy sources contributed 54 % to electricity generation [1, 2]. This duality highlights the scope for further renewable energy expansion while emphasizing that decarbonization must extend beyond electricity production to encompass sectors such as buildings, mobility, and industry. Electrification emerges as a pivotal strategy to lower residual emissions across these domains and meet climate protection targets [3]. However, the shift from centralized fossil-fuel power plants to numerous decentralized renewable sources, coupled with the supply of newly electrified loads, poses complex challenges to the energy system, including the integration of renewables, grid stress, and system stability maintenance [4]. These issues necessitate innovative approaches to advance the energy transition comprehensively. Cellular energy systems offer a promising solution by restructuring the energy system into decentralized units

grounded in energetic subsidiarity. This framework leverages technical and informational advantages to address the demands of a future energy system comprising thousands of small-scale units, ensuring compliance with technical and ecological constraints such as reliable energy provision and greenhouse gas emission reductions in a cost-effective manner while promoting operational continuity and investment incentives [5]. This study explores cellular energy systems, detailing their structure and operation in Section 2. Section 3 describes the simulation environment for modeling multimodal energy cells, analyzing electricity, heat, and mobility demands. Section 4 presents CO2 emission reductions and self-sufficiency from renewable and sector coupling technologies. Section 5 discusses these findings, and Section 6 concludes with implications for decarbonization.

2 Cellular Energy Systems

As the energy landscape evolves towards sustainability, cellular energy systems emerge as a pivotal framework for integrating renewable energy sources and enhancing grid resilience, laying the groundwork for the innovative concepts and principles explored in this section.

2.1 Concept and Principles

The cellular approach redefines energy system organization through energetic subsidiarity, prioritizing local management and decision-making [5]. This empowers smaller units, such as households or communities, to handle their own energy production, consumption, and storage. For example, a neighborhood might generate solar power, store surplus in batteries, and share it locally, reducing dependence on centralized grids while boosting resilience and efficiency with tailored solutions. To enable effective coordination among numerous decentralized components, aggregation of energy and information flows is essential. Drawing from automation engineering, where decentralized intelligent units are networked and managed hierarchically to control processes and process data locally, the cellular approach aggregates data from local energy units to reduce complexity [6]. Advances in technologies like smart grids and real-time data systems make this coordination feasible, enhancing the decentralized framework to cost-effectively meet technical goals such as reliable supply and ecological goals like lower emissions.

Central to this concept are Multimodal Energy Cells (MECs), a type of energy cell that integrates electricity, gas, heat, and mobility into a unified local system. The size and shape of MECs are determined by electricity networks, the most important system for energy transportation. Other networks, such as gas and heat distribution systems, can be fully or partially integrated within MECs, as shown in Figure 1. MECs aim to enable efficient sector coupling, converting and transferring energy across sectors; for example, excess renewable electricity can power electric vehicles, produce hydrogen, or heat buildings, maximizing renewable utilization and supporting decarbonization by reducing fossil fuel reliance. By prioritizing local production and consumption, MECs can lessen the need for grid expansion and enhance system resilience. Partial or full selfsufficiency allows these cells to operate independently during outages, while incorporating renewables (e.g., solar, wind) and flexibility options (e.g., battery storage, heat pumps) optimizes energy flows within the cell. This holistic operation improves overall efficiency and drives lower CO2 emissions, making MECs vital for a cleaner, more resilient energy system.



Figure 1: Schematic of an energy cell compound, showing MECs defined by electricity networks with partial integration of gas and heat networks [7].

Per the VDE [4], an energy cell comprises infrastructure for multiple energy forms, managed by an Energy Cell Management (ECM) system. The ECM balances generation and consumption, often coordinating with adjacent cells, using real-time data to streamline operations of smallscale renewable units and reduce grid stress. A typical MEC at the distribution level, depicted as a hexagonal unit (see Figure 2), operates at lower voltage levels (e.g., medium or low voltage) and integrates diverse components: residential or commercial loads, renewable sources like photovoltaic (PV) systems, and storage solutions like batteries. Connected to overlying grids via electricity, gas, and heat networks, it employs conversion technologies such as heat pumps, combined heat and power units, or Power-to-Gas systems to enable sector coupling, with mobility supported by electric and gas-powered vehicles. The ECM orchestrates efficient energy distribution across these elements. [4, 5, 7]



Figure 2: Schematic of an energy cell, illustrating various loads, generation, storage, and sector coupling technologies [7].

2.2 University Contributions to Cellular Energy Systems Research

The Chair of the Institute of Power Systems Engineering (EVT) at the University of Wuppertal has advanced the field of cellular energy systems through a series of innovative research initiatives. These efforts center on sector coupling, self-sufficiency, and resilience, while supporting decarbonization in alignment with Germany's energy transition goals. By focusing on energy management and renewable integration at the distribution level, EVT's work contributes to reducing CO_2 emissions and enhancing the resilience of the entire energy system.

This focus has driven a comprehensive exploration of sector-coupled energy systems, beginning with their participation in the federally funded Kopernikus Project ENavi. Within this project, EVT investigated the systemic integration of energy system components across electricity, gas, heat, and mobility sectors. The work aimed to enhance understanding of these interconnections, evaluate policy impacts, and develop strategies for a sustainable energy future. A key contribution was the conceptualization of a cellular approach, where energy cells balance local generation and consumption at the lowest feasible level, forming hierarchical structures that enable regional energy exchange [8]. This cellular concept was further refined through EVT's contributions to the VDE Technical Committee on cellular energy systems, with the cellular approach defined more precisely and strategies for combined planning and operation developed, incorporating sector coupling for efficiency, resilience through island operation, and digital control for real-time balancing, and findings documented in "Zellulares Energiesystem" [4]. This provided a technical and operational framework essential for the cohesive functioning of energy cells. Building on these insights, ZellNetz2050, a collaborative project with academic and industry partners including EVT, simulated multimodal cellular energy systems across transmission and distribution levels. This initiative explored hierarchical, sector-coupled energy cells to minimize stress on overlying grids by prioritizing local energy use, integrating a novel market design with independent local and central operators for secure operation, and validated cellular structures as economically viable with reduced Redispatch costs, enhancing resilience through flexibility, and offering insights for future energy system design [9].

A key contribution to the development of energy cells stemmed from Björn Uhlemeyer's dissertation [5], which analyzed self-sufficiency at household, low-, and mediumvoltage levels. Defining self-sufficiency as meeting local demands with renewable energy sources (RES), Uhlemeyer modeled energy cells integrating electricity, heat, and mobility sectors, using PV, battery storage, electric vehicles, heat pumps, and Power-to-Gas. His simulations demonstrated that households can achieve notable selfsufficiency, with an optimal range of 60-75 %, lowering grid reliance and emissions, while aggregating cells at lowvoltage levels showed an optimal range of 35-55 %, and medium-voltage levels an optimal range of 40-95 %, enhancing efficiency through energy sharing and offering a scalable approach to decarbonization.

EVT's ongoing efforts in the OMZES project (Optimal Energy Flow in Multimodal Cellular Energy Systems under Resilience Requirements) shift the focus to resilience, aiming to demonstrate how MECs enhance system resilience. This project optimizes energy flows in multimodal cellular energy systems under resilience constraints, establishes a measurable definition of sector-wide resilience, and assesses generation, load, and failure scenarios using a specialized flow algorithm to identify key resilience factors. Findings from this project, presented in [10], reveal that sector coupling can significantly boost resilience against climate-induced disruptions, with Gas-to-Power systems sustaining electricity during outages and Vehicle-to-Grid strategies effectively leveraging electric vehicle batteries to mitigate impacts, thereby laying the groundwork for strengthened overall system resilience.

Parallel to this, the ongoing SysZell project, led by the University of Wuppertal, builds on ZellNetz2050 to explore how energy cells can deliver critical system services, such as frequency regulation (e.g., virtual inertia), in a renewable-dominated future. Emphasizing robust, resilient solutions, SysZell addresses grid stability challenges, including communication failures, through detailed cross-sectoral modeling across electricity, gas, and heat sectors. Collectively, EVT's coordination of SysZell demonstrates how energy cells can provide ancillary services and effectively

manage renewable energy integration and enhance system stability, providing essential knowledge for designing resilient, decarbonized energy systems aligned with Germany's 2045 sustainability goals.

2.3 Key Challenges and open research points

Cellular energy systems offer transformative potential for achieving zero-carbon goals by enhancing renewable energy integration and reducing CO₂ emissions. However, their development and implementation face challenges and open research questions that must be addressed to realize their full contribution to a sustainable energy future.

First, operating energy cells requires establishing key technical prerequisites, including advanced measurement and control technologies to effectively monitor and manage distributed systems. Central to this is an ECM system capable of handling the complexity of sector-coupled systems by integrating diverse energy sources like electricity, heat, gas, and mobility, along with various loads and storage solutions. The ECM must enable reliable real-time decision-making despite fluctuating generation and consumption patterns, such as those introduced by intermittent renewable sources like solar and wind. Additionally, it needs to be scalable, computationally efficient, and able to communicate seamlessly with other ECMs [5]. Field tests are crucial to validate these capabilities and ensure ECMs can manage the intricacies of sector-coupled systems in real-world scenarios.

Second, integrating smart grid technologies introduces significant informational challenges. These include ensuring robust cybersecurity, establishing standardized interoperability protocols for seamless system integration, and implementing efficient data management to handle the vast, complex datasets generated by sector-coupled systems [4]. The absence of these safeguards can lead to system inefficiencies or security vulnerabilities. These technical obstacles are further compounded by regulatory barriers, such as outdated grid codes that fail to accommodate modern technologies, insufficient incentives for sector coupling, and the high costs of smart infrastructure investment. To overcome these challenges, policy frameworks must be updated to encourage sector coupling and smart infrastructure development, aligning regulations with the evolving technical demands of cellular energy systems and fostering the adoption of zero-carbon technologies like PV and energy storage.

Moreover, regulatory and market barriers present additional complexities. While the Bundesnetzagentur endorses local energy balancing, it cautions that cellular systems could hinder necessary grid expansion and disrupt cost-efficient energy markets by restricting inter-cell coupling and circumventing the merit order principle [11]. In contrast, the VDE views cellular systems as integral to future energy markets but highlights risks to supplier choice and market liquidity [12]. To reconcile these perspectives, a new market model is essential that harmonizes the decentralized advantages of cellular systems with the requirements of a stable, efficient, and liberalized energy market. Such a model would ensure that cellular systems contribute to grid resilience and zero-carbon technology adoption without compromising market integrity. Additionally, open research points extend beyond the technical and regulatory domains. Social acceptance, economic feasibility, and environmental impacts beyond CO₂ reduction such as land use or resource consumption remain underexplored yet critical to the success of cellular energy systems. Addressing these interconnected challenges is vital to unlocking the full potential of cellular energy systems and advancing a sustainable, zero-carbon energy future.

3 Method

This section outlines the methodological approach for simulating energy flows and quantifying CO_2 savings in MECs using the oemof framework. It begins with an overview of the simulation model, detailing the structure and components of MECs at the household level. The subsequent subsections address data sources and assumptions for energy demands, CO_2 equivalents, and technology parameters, followed by the configuration of simulation scenarios. These elements collectively support the analysis of how different technology combinations impact energy flows and CO_2 emissions in decentralized energy systems.

3.1 Simulation Model Overview

To investigate optimal energy flows in MECs at household and grid levels, this study utilizes the open-source oemof framework [13, 14], a Python-based tool designed for modeling complex energy systems. Using linear and mixed-integer linear programming (MILP), oemof.solph represents energy systems as graphs, with nodes (e.g., buses, sources, sinks, converters, storage) and edges (energy flows). This structure supports the integration of electricity, heat, gas, and mobility sectors within MECs, enabling the analysis of CO_2 emission reductions in decentralized sector-coupled systems. The framework's modular design and commitment to open science ensure transparent and reproducible results.

An overview of the general structure to model MECs is presented in Figure 3, which depicts an MEC at the household level equipped with all possible technology types. At the foundation, the diagram highlights loads representing specific energy demands for electricity, heat, and mobility, alongside generation and storage technologies. These components connect to corresponding household buses, forming the core of the MEC unit. Note that while this model displays all available technologies, actual MECs may include none or only a subset of these, such as generation, storage, or sector coupling options. Sector coupling technologies, including Power-to-Heat (P2H), Power-to-Gas (P2G), Gas-to-Power (G2P), Gas-to-Heat (G2H), and Vehicle-to-Grid (V2G), link different energy types, ensuring demands are met with available sources. Moving upward, household buses integrate with buses representing the overlying infrastructure for energy transport, such as electricity, gas, and heat networks. These grid buses aggregate the total load across household MECs and serve as connection points for higher-level technologies, including wind turbines and large-scale PV systems. Overlying grids, encompassing various energy carriers, can also incorporate sector coupling and storage technologies, forming MECs at the grid level.



Figure 3: Overview of the simulation model including the possible technology combination on the household MEC-Level

For the simulation, a representative set of household MECs is initialized with customizable energy demands, technologies for generation, sector coupling, storage, and connections to additional energy transportation structures, such as heat or gas networks. Each energy source is assigned individual procurement costs and CO₂ emission factors, while MEC components have specific capacity limits and efficiencies. The simulation uses steady-state time-series data at 15-minute resolution, with the oemof.solph solver acting as the ECM, enabling a central optimization of the whole structure. It optimizes energy flows and storage values for each time step, minimizing operational costs while maximizing renewable utilization, in line with the cellular subsidiarity principle.

Mathematically, the ECM focuses on optimizing the active elements to reduce the total operational cost over a simulated time span, denoted as T, representing the total number of time steps from t = 0 to T. The goal is to minimize the sum of costs tied to energy flows for all components that incur costs, collectively referred to as the set X. For each component i in this set, at any given time t, the energy flow, denoted \dot{E}_i^t and representing the rate of energy transfer, is multiplied by its corresponding variable cost, c_i^t . This leads to the objective function:

$$\min \sum_{i \in X} \sum_{t=0}^{T} c_i^t \dot{E}_i^t \tag{1}$$

These energy flows, \dot{E}_{i}^{t} , aren't unrestricted. For each component i and time step t, they must stay within specific limits: a minimum energy flow capacity, $\dot{E}_{\min,i}$, and a maximum energy flow capacity, $\dot{E}_{\max,i}$. This constraint ensures the system operates within the physical capabilities of each component, written as:

$$\dot{E}_{\min,i} \le \dot{E}_i^t \le \dot{E}_{\max,i} \tag{2}$$

Some components in *X* are storage units, forming a subset called *S*. For these storage components, indexed as *j*, the stored energy at time *t*, denoted E_i^t , must also respect

capacity limits. Specifically, E_j^t , must lie between a minimum storage capacity, $E_{\min,j}$, and a maximum storage capacity, $E_{\max,j}$, for every storage component j in S and every time step from t = 0 to T. This is expressed as:

$$E_{\min,j} \le E_j^\iota \le E_{\max,j} \tag{3}$$

The energy flows, \dot{E}_{i}^{t} , account for different energy carriers within the system. These include P_{el} , representing the electrical energy flow; P_{ch} , indicating the chemical energy transported by the gas infrastructure; P_{th} , thermal energy flow; and P_{f} , the chemical energy tied to the fuel infrastructure within the MEC. Each of these energy flows operates under its own constraints and efficiencies, as defined by the broader system model, ensuring a comprehensive optimization across all energy types. Building on this, the CO₂ emissions of the MECs are calculated by multiplying each CO₂-relevant energy flow with its respective CO₂ emission factor. The self-sufficiency α is computed as the ratio of energy won by RES within the cell $E_{w,m}$, minus exported energy $E_{ex,m}$, to the total energy demand $E_{d,m}$, for each sector m of the MEC, following [5]:

$$\alpha = \sum_{m} \frac{E_{\mathrm{w},m} - E_{\mathrm{ex},m}}{E_{\mathrm{d},m}} \tag{4}$$

3.2 Data Sources and Assumptions

Household energy demands, production capacities, and technology efficiencies vary significantly depending on factors such as household type (e.g., residential, commercial, industrial), number of occupants, building size, construction year, and personal behaviors like driving habits or preferences for technology adoption. To ensure results are clearly interpretable and enable direct comparison of CO_2 impacts across different technology configurations, this study simulates a representative German residential household based on typical demand profiles, time-series data, and typical CO_2 equivalents.

Electricity demand: The annual electricity demand for the household is set at 2,600 kWh, derived from the total private household electricity consumption of 107.9 TWh (excluding electricity used for heating) [15], divided by 41 million private households [16]. To simulate accurate daily load profiles, standard load profiles from the Bundesverband der Energie- und Wasserwirtschaft (BDEW) for residential households [17] are selected and scaled to match this annual consumption. The CO₂-equivalent emission factor for grid electricity is 363 g/kWh, based on the latest available data from the Umweltbundesamt (UBA) [18], reflecting recent shifts in Germany's energy mix toward renewables.

Heat demand: Likewise, the annual heat demand is established at 12,700 kWh, derived from the total private household end energy consumption for heating of 522 TWh [15], adjusted for 41 million private households [16]. To capture typical seasonal and daily variations, standard load profiles for heating demand are adopted based on [19]. The CO₂-equivalent emission factor for district heat varies depending on production methods, such as renewable or

fossil-based sources. The UBA suggests an average CO_2 equivalent of 244 g/kWh for total district heat production [20]. For scenarios involving natural gas-based heat production, a CO_2 -equivalent of 201 g/kWh is applied [21].

Mobility demand: The annual mobility demand is based on an average mileage of 12,320 km per car, derived from national statistics on average annual mileage [22]. This translates to an energy consumption of 8,501 kWh per car for gasoline-powered vehicles, assuming an efficiency of 0.69 kWh/km [23], or 2,464 kWh per car for battery electric vehicles (BEVs) with an efficiency of 0.20 kWh/km [24]. The CO₂-equivalent emission factor for gasoline-powered cars is set at 263.9 g/kWh [21], reflecting the carbon intensity of fuel combustion.

Technology parameter: The technology parameters are selected based on the energy demands of the representative residential household, incorporating typical technologies for generation, storage, and sector coupling that are suitable for a household of this size. These include common and anticipated options such as a heat pump (P2H) for converting electricity to heat, as well as hydrogen production and reuse through an electrolyzer (P2G) and fuel cell (G2P). The oemof simulation environment enables detailed modeling of these technologies, allowing for the specification of power limits, storage capacities, efficiencies, losses, ramp limits, and other constraints and the key parameters chosen for this simulation are summarized in Table 1.

Table 1: Key technology parameters for simulation [25, 26]

Туре	Power	Capacity	Efficiency		
	in kW	in kWh	in %		
PV	10	-	-		
Solar thermal	6	-	-		
Battery storage	6	10	95		
Heat storage	10	12	90		
Gas storage	20	300	99		
P2H	6	-	350		
G2H	20	-	90		
P2G	7.2	-	70		
G2P	7.2	-	50		
V2G	11	50	90		

3.3 Technology Configuration Scenarios

To quantify CO₂ savings and analyze energy flows within MECs using the oemof framework, this study simulates a range of technology combinations for a representative residential household. These simulations aim to explore how different configurations of generation, storage, and sector coupling technologies impact CO₂ emissions, grid reliance, and self-sufficiency. The table below presents eight distinct scenarios, each defined by a unique combination of technologies across electricity, heat, gas, and mobility sectors. The abbreviations used are as follows: EG (Electricity Grid), PV (Photovoltaic), BS (Battery Storage), P2H (Power-to-Heat, e.g., heat pump), P2G (Power-to-Gas, e.g., electrolyzer), HG (Heat Grid), ST (Solar Thermal), HS (Heat Storage), GG (Gas Grid), GS (Gas Storage), G2P (Gas-to-Power, e.g., fuel cell), ICEV (Internal Combustion Engine Vehicle), BEV (Battery Electric Vehicle), and V2G (Vehicle-to-Grid). The checkmark (\checkmark) indicates the technology is included in the scenario.

Table 2: Technology combinations for simulation scenarios

	Electricity					Heat		Gas			Mobility			
Case	EG	PV	BS	P2H	P2G	HG	ST	HS	GG	GS	G2P	ICEV	BEV	V2G
1	\checkmark					\checkmark						\checkmark		
2	\checkmark								\checkmark			\checkmark		
3	\checkmark					\checkmark	\checkmark	\checkmark				\checkmark		
4	\checkmark	\checkmark							\checkmark			\checkmark		
5	\checkmark	\checkmark	\checkmark						\checkmark			\checkmark		
6	\checkmark	\checkmark	\checkmark						\checkmark				\checkmark	
7	\checkmark	\checkmark	\checkmark	\checkmark									\checkmark	
8	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark					\checkmark	\checkmark		\checkmark	\checkmark

4 Results

To quantify CO_2 savings and self-sufficiency in MECs, all eight technology configurations outlined in Table 2 were simulated over a year using the oemof framework, capturing annual CO_2 emissions, and energy flow volatility across electricity, heat, and mobility sectors. Based on a representative German household (Section 3.2), the simulations optimize energy flows via the ECM to minimize operational costs while maximizing local RES utilization, following the cellular subsidiarity principle.

Figure 4 illustrates the electrical energy flows for Case 6 during a representative summer week, highlighting the ECM's optimization of local RES and storage. Battery storage (BS) absorbs excess photovoltaic (PV) energy during peak production, supplying it to meet base loads and mitigate battery electric vehicle (BEV) charging peaks, thus reducing grid reliance. However, the BS's capacity, efficiency, and power limits restrict its ability to fully offset the BEV's 11 kW charging peaks. Overall, the ECM optimizes local RES and storage to minimize residual load from the grid, showcasing effective load balancing within its technological constraints.



Figure 4: Electrical energy flows for Case 6 during a representative summer week

To elucidate seasonal impacts, Figure 5 presents the annual residual electricity demand profile for Case 6, extending the weekly insights from Figure 4. From April to October, PV generation significantly reduces grid electricity demand, limiting BEV charging peaks, and enables surplus energy export. Conversely, from November to March, limited PV output increases grid dependence, highlighting the seasonal constraints of relying solely on PV and BS for decarbonization and self-sufficiency.



Figure 5: Annual net electricity flow profile for Case 6

Figure 6 depicts the sector-wide CO_2 emissions for Case 1 (EG, HG, ICEV), with no RES and sector coupling technologies. It can be seen that emissions are lowest in summer due to reduced heating demand, but consistent electricity and mobility demands drive steady CO_2 output, resulting in 0 % self-sufficiency, as no local RES is utilized.



Figure 6: Annual sector-wide CO₂ emissions for Case 1

In contrast, Figure 7 shows the CO_2 emissions for Case 8 (PV, BS, P2H, P2G, G2P, HS, GS, BEV, V2G), the most storage-integrated and sector-coupled configuration. Here, the combination of technologies enables capturing sufficient energy from RES and storage to achieve 100 %

self-sufficiency in the months from May to October, resulting in near-zero operational CO₂ emissions, assuming negligible incremental emissions from RES operation. Emission spikes, caused by the steep BEV charging curves, occur during November to March as RES output does not meet overall demand, requiring grid support.



Figure 7: Annual sector-wide CO2 emissions for Case 8

Figure 8 summarizes the annual sector-wide CO₂ emissions and self-sufficiency across all configurations for the simulated year 2025. Case 1 yields 6.29 tonnes CO2-equivalent with 0 % self-sufficiency, serving as the base case without technology. Case 6, incorporating PV, BS, and BEV, reduces emissions to 3.42 tonnes (54.4 % reduction) with 27.3 % self-sufficiency, illustrating the efficiency improvements and CO2 reduction that comes with electrification. Case 8 achieves 1.07 tonnes CO₂-equivalent (83.0 % reduction from Case 1) and 55.1 % self-sufficiency, driven by extensive RES integration and sector coupling (e.g., P2H, P2G, V2G). Across all scenarios, higher RES, storage and sector coupling technologies correlate with lower emissions and increased self-sufficiency, though winter limitations and BEV charging peaks highlight the need for continuous grid support.



Figure 8: Annual sector-wide CO_2 emissions and self-sufficiency for all configurations in 2025

5 Discussion

The results demonstrate that integrating RES with storage and sector coupling technologies at the household level significantly reduces CO_2 emissions for households with typical energy needs and technology sizes available today. In this study, MECs equipped with the requisite technology achieved up to 55.1 % self-sufficiency; however, they continue to depend on the electrical grid, especially in winter months. As shown in [5], there are still various opportunities to further reduce CO_2 emissions and improve self-sufficiency. On the one hand, advancements in technology and falling costs will enable larger storage capacities and higher power outputs, enhancing the economic viability of bigger technology sizes. Scaling RES size is particularly important, as Equation 4 indicates that annual self-sufficiency requires the energy produced to at least equal the energy demand. On the other hand, overall energy demand can be further decreased with efficiency improvements and electrification. Lastly, as the energy transition progresses, the grid's energy mix will become cleaner, further decarbonizing the system.

On a larger scale, moving to MECs levels above the household, the findings advocate for incorporating additional RES, such as wind power, to ensure energy provision during low-sunlight months. Moreover, large-scale seasonal storage and sector coupling solutions, such as hydrogen storage, could serve as a critical mechanism for supplying energy during periods without sunlight or wind with minimal CO_2 emissions.

6 Conclusion

Cellular energy systems represent a transformative, decentralized approach to energy management, integrating renewable sources across electricity, heat, and mobility sectors. This framework enhances sustainability by prioritizing local RES production and consumption, reducing dependence on centralized grids and advancing Germany's decarbonization objectives. The research employed the open-source oemof framework to simulate various technology configurations for a typical German household, modeling combinations of renewable technologies like PV, battery storage, and sector coupling solutions such as P2H and V2G. These simulations assessed impacts on CO2 emissions and self-sufficiency over a year. Findings demonstrated that configurations combining renewables with storage and sector coupling significantly cut CO2 emissions, up to 83 % in the most effective cases, while boosting self-sufficiency. However, seasonal constraints, particularly in winter with reduced solar output, revealed limitations in storage capacity and grid reliance. Looking ahead, Cellular Energy Systems offer a promising pathway to support Germany's 2045 net-zero target by optimizing local energy flows and reducing emissions from the ground up. To fully realize Germany's climate ambitions, future efforts must tackle cost-effective deployment of technology and seasonal storage challenges through innovative market designs, expanded renewable integration, and longterm storage solutions like hydrogen, to ensure a resilient, zero-carbon energy future.

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