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Energy, Sustainability and Society

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Evolving roles and shared futures: challenges and visions for Switzerland's electricity sector transition

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Abstract

Background As energy systems undergo rapid decarbonization and decentralization, coordination between electricity sector actors becomes increasingly complex. In Switzerland, the federal structure, regional diversity, and emerging forms of distributed energy resources and actors present unique challenges for aligning stakeholder roles and responsibilities. This study investigates how stakeholders across the Swiss electricity sector envision the future of the electricity grid, their roles within it, and the coordination mechanisms needed to support the transition, with particular attention to the evolving role of distribution system operators (DSOs).

Results Drawing on interviews with stakeholders from across the Swiss electricity sector, the application of the socio-technical imaginaries framework reveals a broad consensus on the aspiration for a highly decentralized and flexible electricity grid with a large share of renewable energy, united by the ultimate goal of national decarbonization while maintaining grid stability. However, diverging visions exist regarding the role of local electricity communities, as some stakeholders are optimistic about their potential for decentralization and public engagement, while others express skepticism regarding their viability, limited financial incentives, and the administrative complexity they impose on DSOs.

Conclusions The Swiss electricity sector's transition is not solely a technical undertaking but also a deeply institutional and social challenge. Coordinating system actors requires attention to differing expectations, governance structures, and resource capabilities. This study highlights the importance of fostering shared visions through structured dialogue, intermediary platforms, and capacity-building measures, especially for local actors and smaller DSOs. While grounded in the Swiss context, the insights are relevant to other decentralized energy systems, particularly considering the ongoing European efforts to support energy communities.

Keywords Energy transition, Electricity sector, Socio-technical imaginaries, System operators, TSO-DSO coordination, Energy communities, Energy policy

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Background

The replacement of carbon-intensive resources with renewable energy sources (RES) is a central pillar of the global energy transition aimed at mitigating climate change. However, integrating renewable and distributed energy resources (DER) such as energy storage systems and electric vehicles, poses increasing challenges for electricity grids. These challenges relate both to the physical accommodation of new technologies and to the continuous balancing of generation and demand [1].

Across Europe, policy initiatives (most notably the Clean Energy for All Europeans package) have increasingly promoted grid-connected social innovations such as prosumers and energy communities (ECs) that rely on RES and DER [2, 3]. The rapid integration of these decentralized entities compels established system operators to redefine their roles, transforming electricity grids from unidirectional systems built for centralized power delivery into dynamic, bidirectional networks. As a result, grid operators must now manage fluctuating generation, flexible consumption, and complex power flows, which require new operational strategies, digital control technologies, and adaptive regulatory frameworks [4].

Switzerland provides a particularly insightful case for examining these dynamics. The country's electricity sector is characterized by a highly fragmented structure, with over 600 distribution system operators (DSOs) [5], nearly 200 energy cooperatives [6], and a new energy law (effective 2025) that formally recognizes local energy communities as active grid participants [7]. This evolving landscape requires effective coordination among DSOs, the transmission system operator (TSO), policymakers, and emerging ECs. Without alignment, the objectives of Switzerland's Energy Strategy 2050, including the nuclear phase-out and the massive expansion of renewable energy, may be jeopardized [8].

Successfully navigating these complexities requires not only operational adjustments but also a shared or closely aligned vision for the future electricity system among diverse stakeholders in the electricity sector, including policymakers, energy companies, and grid operators. These visions, i.e. as subjective understandings of a desirable future energy system, play a crucial role in enabling the alignment of key aspects of the energy transition, thereby accelerating the implementation of low-carbon solutions [9].

To explore the different visions held across the Swiss electricity sector, we adopt the concept of socio-technical imaginaries (STIs) [10], which examines collectively imagined futures that guide the evolution of socio-technical systems, including electricity grids. This concept enables us to understand how different stakeholders envision and shape the sector's transformation by considering the technical, social, and institutional dimensions of the electricity sector. By analyzing these visions, we gain insights into how they shape the design, governance, and development of the electricity grid, while also identifying barriers that may hinder the realization of a shared vision for Switzerland's electricity system.

With this research, we address a critical gap in understanding the actors driving the energy transition and the institutional contexts in which they operate – factors often overlooked in quantitative and techno-economic modeling studies [9]. As no prior study has explored sector-wide visions for Switzerland's future grid, we aim to identify possible converging and diverging perspectives for the energy transition. To address this, we pose the following research question:

> *To what extent do stakeholders in Switzerland's electricity sector share a common or have a different vision for the future electricity grid, and what are the key cross-sectoral challenges that must be addressed to realize this vision?*

Operational challenges for system operators

System operators who manage and operate the different voltage levels of the electricity grid are tasked with ensuring a balance between supply and demand by considering different energy technologies that inherently have different operational characteristics, such as intermittency, load profiles, and ramp-up periods. As DER are usually integrated in low and medium-voltage grids [11], DSOs who operate the grid levels are the main stakeholders of the electricity sector that are and will continue to be challenged by the integration of these technologies. Integrating technologies with different operational characteristics places significant pressure on DSOs to manage coordination, planning, and investment decisions to fulfill the technical requirements of the grid and ensure reliability, quality, and uninterrupted supply of electricity [12].

In addition to managing the increased share of DER, cross-sector electrification (such as the electrification of the heating and transport sectors) further challenges the traditional role of the DSO [13]. Due to the technological developments that increase the operational complexity of the grid, this role - guaranteeing distribution capacity to bring power to final consumers - evolves [14]: The DSO is increasingly becoming an engaged, flexible stakeholder in the system [15], as well as an integrator of various intermittent DER.

The increased share of RES in the electricity grid and the evolving role of the DSO also pose challenges for the TSO, an entity in charge of managing the high voltage grid to which the DSOs are connected. To ensure that the entire power system is operated efficiently in terms of balancing, congestion, and voltage controls, the coordination between the TSO and the DSOs is crucial [1, 16].

Such coordination relies on accurate information derived from all grid voltage levels to guarantee efficient system operation and dispatch of DER and controllable network assets [16]. Moreover, the TSO-DSO coordination is necessary to utilize the flexibility of electricity production and consumption to meet the grid operation goals [17]. Burger et al. [18] argue that this coordination covers various topics, including congestion management and investment viewpoints, while Eurelectric [19] stresses the need for anticipatory investment coordination between the DSOs and the TSO to ensure the efficiency and effectiveness of the entire electricity system and reach the decarbonization goals.

Considering that grid modernization (upgrading the physical infrastructure to increase capacities and integrate smart technologies and controls to deliver electricity reliably and efficiently) is imperative for managing the grid successfully and ensuring predictability and controllability at the distribution level [20], coordination of the investments in grid modernization stands to be crucial for expanding DER and maintaining grid stability. Coordinated investments in grid modernization can help optimize financial resource allocation, ensuring that technical upgrades align with cross-sectoral long-term goals and maximize the benefits of DER integration. To achieve this, Bolton et al. [21] outline the need for transparent, predictable, and coherent changes in policies and regulatory frameworks to reduce inefficient investments that may hinder the electricity sector's transition.

The rapid establishment of ECs, regarded as a supportive means for decarbonization, can also negatively impact the system they are integrated into. According to Dimovski et al. [22], the expansion of ECs is associated with higher energy losses, worsened voltage profiles, and increased loadings of the grid, as well as energy generation fluctuations, resulting in a mismatch between local generation and consumption patterns. In addition, ECs may import more electricity from the grid, posing a negative grid impact, while at the same time, due to the low correlation between demand and solar photovoltaics (PV) generation, they may require a storage technology to increase their self-consumption [23], further increasing the overall grid operation costs.

On the other hand, ECs may provide grid balancing services, especially in terms of frequency regulation, under certain energy dispatching management strategies [24]. Moreover, ECs with flexible assets may balance power production peaks or loads, thus preventing the overloading of the grid [25]. Regardless of whether they help to alleviate or complicate the congestion issues in the grid, the crucial underlying activities are the balancing and coordination with the respective DSO, challenges that are ultimately imposed on and should be solved by the DSO. This is especially significant in Switzerland, given the high number of DSOs and the potential for energy communities to expand under the new energy law.

Socio-technical imaginaries

The concept of socio-technical imaginaries (STIs) enables the analysis of diverse envisioned futures within socio-technical systems [6]. Unlike traditional methods such as scenario planning or techno-economic modeling, which focus on technical and financial feasibility and policy-bound targets, it explores beliefs, values, practices, and cultures shaping collective visions [26]. This makes the concept particularly well suited to understanding how stakeholder perspectives, rooted in societal and institutional contexts, influence socio-technical transformations. It offers an open and interpretive way of accommodating intangible dimensions like governance preferences, individual norms and beliefs, senses of efficacy, and societal values that are often overlooked in quantitative methods. As Schmid et al. [9] highlight, while the techno-economic feasibility for low-carbon transitions is well-modeled, implementation remains challenging due to conflicting visions of desirable futures. The STI concept complements modeled futures by expanding the design space of what is considered possible. It encourages a broader exploration of alternative futures, fostering innovation and inclusivity in the envisioning process.

The concept of STI was coined by Jasanoff and Kim [10] to explore how actors construct visions of desirable and feasible futures. These imaginaries are defined as "collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology" [10]. Such visions are important as they "deploy stories, narratives, or scenarios that reveal fundamental patterns of human reasoning, and how humans communicate their thinking to others, in a future-oriented context" [27]. Visions are essential elements that help in shaping the future of energy systems as they are the key drivers of energy policy debates [28]. Conflicting visions of a desirable future can lead to delays in implementing low-carbon solutions [9], thereby hindering progress and slowing the pace of the energy transition. However, these visions are subjective perceptions and prioritizations of problems, meaning that different people value problems differently, thus their visions can be different, despite addressing the same physical reality [28]. As the aim of this article is to understand the different visions held across the Swiss electricity sector regarding the achievement of the national energy and climate goals, the STI concept stands to be particularly relevant.

The STI literature offers numerous examples of the concept's application for understanding the shared vision

within socio-technical systems. For example, Kuchler and Bridge [29] used it to investigate the imaginaries surrounding coal mining infrastructure and coal use in Poland since the beginning of the 20th century. Analyzing different grey and peer-reviewed literature, as well as policy documents and newspapers, the authors investigated the meaning of coal for Poland's modernization throughout the decades, from the communist period that forged coal as "black gold", to the current policy debates. Despite the declining output from coal power plants, the current political efforts to rehabilitate coal and secure Poland's energy future are based on coal-fueled national modernization STIs [29].

In another study with a focus on Poland and the STIs related to the country's energy transition, Rabiej-Sienicka et al. [30] analyzed strategic documents of the country's policies as well as government funding programs for science and conducted interviews with actors from the energy sector. The results show that the dominant STI is related to the preservation of the current centralized system, where coal plays a key role, while prosumers act as supporters of the system.

The STI concept was also applied to determine the imaginaries related to a future smart grid in Norway. A study by Ballo [31] focused on analyzing empirical data from interviews with experts from network companies as well as the analysis of regulatory documents in order to understand the future imaginaries related to smart meters and the future smart grid [31]. The author determined that the future narratives are related to solutions that reflect current institutional and technological structures, thus retaining the current structures intact.

Furthermore, Schmid et al. [6] have used the STI concept to understand the shared visions of desirable futures across socio-technical systems, specifically in community energy initiatives in Switzerland. Going beyond the techno-economic approach, the authors operationalized the STI concept by developing two dimensions, aspirations and performances, to understand the visions of desirable futures in energy communities in Switzerland and how those visions translate across the communities' present-day practices. The findings reveal the pluralities across aspirations (linked to a desirable future) and performances (enactment of the future as of today) of these energy initiatives, especially outlining their democratic characteristics that may serve as experimental spaces where "future energy systems can be deliberatively contemplated and shaped, going beyond mere technical expansion of renewables or economic efficiency" [6].

The Swiss electricity sector

Switzerland is undergoing a significant transformation of its energy system. The new Electricity Act (Mantelverordnung) passed by popular vote in 2024 advances the existing Mergers For Self-consumption (Zusammenschluss zum Eigenverbrauch) and recognizes Local Electricity Communities (Lokale Elektrizitätsgemeinschaften) as entities that can market their self-generated electricity through the public grid in the district or municipality [7], a concept fully aligned with the "EU's concept of the Citizen Energy Community (CEC) and Renewable Energy Community (REC)" [3]. The potential uptake and expansion of local electricity communities may pressure the coordination among the system operators and the ECs, considering that Switzerland has a highly decentralized electricity supply, with more than 600 DSOs and one TSO (Swissgrid). The country is unique in terms of the absolute number of DSOs and the varied number of customers served by them, ranging from a few hundred to several thousand, while DSOs can take the form of municipal utilities, co-ops, limited companies, or public sector institutions [5]. Moreover, they are not functionally unbundled from electricity retail when it comes to the supply of electricity to households, meaning that households cannot choose an alternative supplier other than the local DSO [5]. In other words, households are not part of the liberalized market, which means that they cannot choose their electricity supplier.

Given the country's unique federalist structure, where cantons and municipalities have key roles in implementing and shaping energy policies [6], effective coordination becomes even more critical, especially as the energy landscape continues to evolve. The need for increased TSO-DSO coordination in Switzerland is emphasized by Evrenosoglu et al. [32] when it comes to addressing current and mid-term challenges. These challenges are varied and include the dynamic and stochastic profiles from increasing RES and DER capacities across the grid. Furthermore, the decreased generation from conventional power plants, which is also related to the closing of the nuclear power plants, and potentially reduced transfer capacities from neighboring European countries pose significant challenges in terms of TSO-DSO coordination activities. Even though the current coordination among these stakeholders is deemed adequate, Uzum et al. [33] recognize the potential for improved collaboration in the future between the TSO, the DSOs, and the customers that have flexible assets (energy technologies that can adjust power supply or demand), to procure reserve power and maintain the security and reliability of the network operation.

The new Electricity Act is in line with the national Energy Strategy 2050 that outlines the net-zero greenhouse gas (GHG) emissions target by 2050 [34], as it is aimed at reducing energy consumption, increasing the share of RES in the energy mix, and closing down nuclear power plants [35]. The country also aims to reduce the GHG emissions in both the heating and the transport

sectors by promoting the use of electricity-based technologies such as heat pumps and electric vehicles [36]. In 2023, hydropower was the largest source of electricity in Switzerland, accounting for 56.6% of total production, followed by nuclear power at 32.4%, other RES at 8%, and the remaining 3% from thermal power plants and cogeneration [7].

Lonergan and Sansavini [5] argue that solar (PV) production is expected to make a significant contribution to filling the gap resulting from the nuclear phase out, since this technology has a strong annual generation potential. In the last few years, alpine solar PV production has been heavily promoted, due to solar irradiation differences between the lower altitude parts of the country and the Alps [37]. For this reason, the Swiss Federal Council introduced support instruments for solar PV production, placing particular focus on alpine PV systems, due to their importance for winter electricity production. The expansion of solar PV across the country is further strengthened by the public preferences regarding the Swiss electricity system after the nuclear phase-out. A choice experiment study by Plum et al. [35], who conducted a representative survey in Switzerland, found strong public preference for solar energy built in existing industrial and commercial areas.

To navigate these challenges and achieve the goals of Switzerland's national energy strategy, it is essential to assess how the various stakeholders across the electricity sector align their visions for the future grid. These visions are linked to the stakeholders' subjective understandings and expectations regarding the electricity grid of the future related to the uptake of technologies including RES and DER, the continuous integration of grid-connected entities, the technical and governance possibilities as well as the role of policy, and any potential barriers for reaching the net-zero goals. As previously noted, while current TSO-DSO coordination is generally considered adequate, evolving dynamics in the grid, particularly the rise of RES and DER, highlight the need for enhanced collaboration, especially when it comes to the integration of flexible assets and procurement of reserve power to ensure system reliability.

Table 1 The STI concept [6]

Dimensions	Features of emerging new STIs
Aspirations (linked to a desirable future)	Vision of a future energy system
	Operational goals at an organizational level
	Motivations of members
	Envisioned role of technology in the transition
Performances (enactment of the future as of today)	Main activities
	Organizational governance
	Relationship of community energy initiatives with other local actors

Building on the insights of Schmid et al. [6] regarding the diversity of visions across community energy initiatives, the decentralized nature of Switzerland's energy system offers both challenges and opportunities for the application of the STI concept. While studies in more centralized contexts, such as Poland's coal sector or Norway's smart grid, emphasize the influence of national imaginaries on centralized energy governance, Switzerland's federalist structure requires an approach that acknowledges the diversity of local governance and regional priorities. In this context, the STI concept may help in understanding how varied visions, held by different actors, are aligned or misaligned in terms of reaching the national goals. Considering that "sociotechnical imaginaries are inextricably linked with regulations, knowledge-making processes, and practices" [26], adopting the concept may be particularly useful for analyzing the Swiss electricity sector's transformation and illuminating potential barriers and policy gaps.

Methods

Conceptual framework

The purpose of this article is to analyze the shared visions held across the electricity sector in Switzerland to determine potential challenges for the sector's transformation. To investigate these visions and identify sector-wide alignments that can either advance or pose barriers for the sector's transition, we apply the concept of STI as developed by Schmid et al.'s [6], shown in Table 1. This concept, which emerged from an iterative process combining data from Swiss community energy initiatives with STI theory, provides a comprehensive lens for understanding how different stakeholders envision and enact the energy transition. Schmid et al. [6] operationalized the STI concept by defining two main dimensions – "aspirations", or the aim that stakeholders want to achieve and how they conceptualize the future, and "performances", or the efforts that translate future visions into current actions and decisions. The desirable future includes features outlining the vision of the future energy system, the current operational goals and motivation of the stakeholders, as well as the role that technology is expected to play in the transition. The performances, on the other hand, relate to the current main activities aimed at reaching that desirable future, together with the current organizational governance structures and the connections of the ECs with other actors.

Initially developed to explore visions within ECs, the concept's flexibility makes it equally valuable for examining the broader electricity sector. By incorporating the technical, social, and institutional dimensions of Switzerland's energy landscape, it facilitates a nuanced analysis of how diverse and regionally specific visions interact

and align, outlining both shared and conflicting pathways of the energy transition. Its origins in the Swiss context further underscore its relevance for our research, where we adapt only the third feature of the "performances" dimension, focusing specifically on the role and impact of ECs on the grid, rather than their interactions with other local actors. This adjustment allows us to explicitly analyze how the integration of ECs in the grid is expected to influence the overall grid management and coordination of activities.

We thus use this concept to capture and assess the varied perspectives of policymakers, the TSO, DSOs, energy companies, and other actors in the electricity sector. It enables us to delve into the nuances of how these different actors envision the future, identifying both potential synergies and areas of misalignment that could impact the success of Switzerland's energy transition. By using this concept, we can better understand the challenges, both current and expected, regarding the interactions between the different stakeholders and their alignment for reaching the national energy and climate goals.

Data collection and analysis

To explore the shared visions of the future electricity grid across the Swiss electricity sector, we relied on semi-structured interviews with a diverse range of stakeholders. We interviewed eight stakeholders, including a representative from the Swiss Federal Office of Energy, the national policymaking government entity that shapes the regulatory and strategic direction of the electricity sector, a representative from the single TSO responsible for managing the high voltage grid, and three representatives from three DSOs that manage local grid operations across different regions of the country. To ensure a diverse range of perspectives, we interviewed representatives of DSOs operating in different language regions of Switzerland, varying in the number of employees, customer base, and service areas. Additionally, we interviewed representatives from two of the largest energy companies in Switzerland that are involved in both conventional and renewable energy generation. Finally, we interviewed a representative from an aggregator (an entity that aggregates DER on the demand side) which might play a crucial role in integrating and managing decentralized energy sources for demand side management when the policy environment enables such operations in the country.

We excluded representatives of ECs from our interview cohort because their formal legal establishment in Switzerland is anticipated for 2026 under the revised Electricity Act. This formal recognition is crucial for determining their official roles, rights, and responsibilities regarding grid operations and interactions with other regulated electricity stakeholders. While existing cooperative "energy initiatives" (as documented in Schmid et al. [6]) certainly exist and are active, their current, limited official regulatory status means their direct influence on broader system-level coordination and formal decision-making remains limited for the purposes of this study. Similarly, we excluded households from our interviews due to their limited direct influence on broader stakeholder dynamics and formal decision-making within the Swiss electricity system. However, we indirectly incorporate household perspectives by considering their expressed preferences through popular democratic outcomes, such as the national Energy Strategy 2050 and the new Electricity Act referendums.

Table 2 Profiles of interviewees

Code	Level	Reinterviewed
P1	Policymaking (SFOE)	No
T1	Transmission system operator (TSO)	Yes
D1	Distribution system operator (DSO)	Yes
D2	Distribution system operator (DSO)	Yes
D3	Distribution system operator (DSO)	No
A1	Aggregator/virtual power plant	No
E1	Energy company	No
E2	Energy company	No

On the other hand, we included an aggregator – an entity that currently operates outside of Switzerland. This decision was based on the expectation that the aggregator represents a future, essential market role of managing and coordinating flexible DER at scale. The aggregator's function, which involves bundling thousands of small resources into a utility-scale flexibility product, holds significantly greater potential weight for solving challenges related to grid congestion management and TSO-DSO coordination than the activities of individual end-users. Furthermore, this aggregator allowed us to capture the aspirational technical and market coordination challenges and opportunities that all DSOs and the TSO must actively plan for, even if the formal policy framework for the aggregator's operation is not yet fully in place. Thus, the aggregator serves as an important proxy for a system-critical future function with significant operational leverage, whereas households, while numerous, have a diffuse influence on system-level coordination, and ECs currently lack the formal regulatory leverage to significantly shape national coordination mechanisms.

Through these interviews, we aimed to capture and analyze diverse perspectives, goals, and expectations regarding the future electricity grid that are held by those who are responsible for the daily operation of the current grid. Table 2 outlines the profiles of the interviewees and the corresponding codes referenced in the subsequent sections of the paper.

Some of the participants were invited for a second round of interviews after the public referendum that

supported the new Electricity Act. Specifically, we sought to understand how this new legal framework would influence the planning, operation, coordination, and long-term sustainability of the grid, considering the recognition of local electricity communities and their ability to trade electricity with the grid. Therefore, the focus of these follow-up interviews was to explore the expected implications of the Electricity Act on both the TSO and the DSOs, and assess the anticipated impact of local electricity communities on grid management and the coordination among the system operators. The participants were asked to reflect on how the new law might reshape their strategies and operations, particularly in relation to decentralized energy production, increased integration of renewable energy sources, and the evolving role of local energy communities. The interviews aimed to explore how DSOs and the TSO anticipate managing these changes, including potential shifts in grid demand, fluctuations in energy flows, and a potential need for new forms of coordination and flexibility. By re-interviewing the system operators, we were able to capture their updated visions and concerns considering the changing regulatory environment, offering an updated understanding of the future coordination between local electricity communities and the existing system operators.

To determine the types of stakeholders that we needed to approach to obtain different visions regarding the electricity grid of the future, we did a stakeholder analysis of the Swiss electricity sector. Afterwards, we relied on our networks as well as the snowballing approach to reach the interviewees, with the aim of gathering different perspectives on questions related to (i) the current tasks and activities of the interviewees and the entities they represent, (ii) the future of the electricity grid, including the role of the entity they represent, and the drivers and barriers to reach that future grid, (iii) citizen engagement forms in the electricity grid and related barriers and drivers, and (iv) the understanding of decentralization and associated coordination challenges, both current and expected. After asking the participants questions on these four topics, the final question asked them to rethink the whole electricity system from the ground up, and how they would redo it. The purpose of this final question was to find the similarities and differences between the current, the future, and the ideal electricity grid according to the participants' subjective views, and understand these similarities across aspects including energy technologies, the role of citizens, the structure of the system (centralized vs. decentralized decision making and bundled vs. unbundled institutions) and ownership (public institutions vs. private companies).

The semi-structured interviews from the first and second rounds were conducted in English; they lasted between 45 and 70 min and were carried out online between January and September 2024. The interview transcripts were obtained through the automated transcription service of Microsoft Teams and were manually checked for consistency and possible errors by comparing the transcripts with the recordings. The transcripts were anonymized and coded with MAXQDA. The analysis was conducted by the first author applying a thematic analysis approach [38] to identify the themes that correspond to the STI concept as well as to understand how these themes relate to one another. Lastly, we summarized the results and categorized them according to the features of the emerging STIs from the two dimensions – the aspirations, linked to a desirable future, and the performances, linked to the enactment of the future as of today [6].

Ethical concerns and potential limitations

The interview participants received the interview guide in advance, along with a consent form that explained the ethical considerations involved in the research. Approval from the ETH Zurich ethics commission was obtained prior to conducting the interviews. The transcripts from these interviews were anonymized and are securely stored on the ETH Zurich internal server, providing access only to the first author. The transcripts will be kept for ten years before being permanently deleted.

A key limitation of this study is the small number of interviews conducted. While these interviews provided in-depth insights into the different visions across various levels of the Swiss electricity sector, the limited sample size may not fully capture the diversity of views across the entire sector, especially considering the large number of DSOs. Despite our efforts to interview DSOs that operate in different cantons, serving regions and consumers of various sizes, there is a risk that with fewer participants, certain nuanced or differing opinions might not be adequately represented, potentially leading to an incomplete picture of the shared visions for the future electricity grid of Switzerland. Additionally, the small sample size may limit the generalizability of the findings, as the perspectives gathered could be influenced by the specific roles, experiences, or contexts of the selected participants.

However, the interviews highlight the existence of diverse visions within the sector and among stakeholders, which may turn into potential challenges for the electricity system's transition. Rather than aiming to provide a representative sample of all system operators in Switzerland, this study focuses on demonstrating how variations in visions might impact the sector's evolution. The exploratory nature of this research aimed to check the applicability of the STI concept in analyzing stakeholder perspectives in the Swiss electricity sector. Future research could build on these findings by expanding the

participant pool to capture a broader spectrum of viewpoints in the sector.

Results

In this section, the results from the interviews are presented, structured according to the STI concept developed by Schmid et al. [6] while referring to the specific code of the interviews. As a reminder - the STI concept has two main dimensions: (i) aspirations, related to the visions of the future energy system, and (ii) performances, related to the enactment of the future visions in the current setting. Each of these dimensions has different features, and we put particular emphasis on tensions between different stakeholders according to the features of the STI concept.

Aspirations

This dimension of Schmid et al.'s [6] STI framework captures energy cooperatives' visions of a desirable future energy system, along with their operational goals, motivations, and the envisioned role of technology. It integrates the role of technology with the motivations of cooperative members and the organizational goals of the cooperatives, all of which contribute to achieving their vision for a future energy system. Since we use this framework to analyze the perspectives of various stakeholders across the electricity system, we adapted the features according to our goals. We consider the visions of the future electricity grid to also include the potential challenges and drivers for reaching that goal. Furthermore, we understand operational goals as tasks defined by institutional mandates and regulations that outline an entity's role in the system. Motivations, on the other hand, extend beyond these prescribed roles to encompass the drive to adopt new ideas and innovations that facilitate or accelerate the achievement of operational objectives.

Visions of a future energy system

Decentralized energy production and flexibility emerge as key themes for the future of the Swiss electricity system (D1, D2, D3, T1, P1, E1). Across all interviews, there is a shared vision that demand will follow energy generation and will shift closer to end users, with localized control and increased reliance on decentralized energy generation, particularly through solar PVs, and other DER. Despite this localized shift, critical elements such as grid stability remain imperative, to be coordinated at higher, centralized levels (TSO and DSO levels) to ensure system reliability.

Some interviewees (T1, D2) emphasize the need for hybrid systems that combine both decentralized and centralized elements to maximize efficiency. They suggest that achieving this balance will be critical for the energy transition, particularly in managing fluctuations in renewable energy generation and consumption.

A significant focus across several interviews (D2, E1, T1) is on the potential role of citizens in the energy transition. Despite their currently limited role (A1), the future energy system is envisioned as increasingly citizen-centric, with prosumer models becoming more common. In these models, citizens not only consume but also produce energy, actively participating in energy generation and management. Tools like smart meters and the development of energy communities are seen as essential enablers of this transition.

Public education and engagement activities are recognized by several stakeholders as crucial support factors of the energy transition in terms of raising awareness and ensuring public acceptance (E1, D3, T1, A1). These stakeholders emphasize the importance of raising public awareness about energy issues and creating opportunities for citizens to actively participate in the energy system through models like energy communities and prosumer arrangements. Moreover, there is a perceived need for more inclusive policymaking that goes beyond policymakers and academia to include active participation of citizens who are better informed and educated on energy topics (P1). Active public participation is also seen as vital for the success of decentralized energy systems, particularly in the shift towards prosumer models and energy communities (E1, D3, T1).

The main challenges that interviewees mentioned when it comes to reaching their vision of a future electricity system are varied. The lag between regulatory developments and the pace of technological innovations is a serious obstacle for the transition (E1, E2), as well as overall regulatory uncertainties and changes in regulation (D1). Not in My Back Yard (NIMBY) attitudes or the societal acceptance of energy infrastructures may also present serious barriers (E1, E2), while making complex energy decisions through a popular vote may introduce challenges such as fragmented regional efforts, policy delays, and slower decision-making, which are important factors that can hinder timely and coordinated progress (E1).

Operational goals at an organizational level

The mandated operational goals provide a structured pathway to achieving stakeholders' visions by defining concrete, regulated actions that ensure system stability. A common thread across all interviews is that efficient grid management is a top priority for all stakeholders in the Swiss energy sector. The interviewees emphasize the need for enhancing the efficiency of grid management by incorporating advanced control systems and strategies that optimize the management of DER and prevent losses (D1, T1) to ensure the goal of energy security (P1). Furthermore, balancing intermittent renewable sources with

a stable energy supply requires innovations in storage, demand response, and flexibility, as well as grid control systems (D1, T1, E2). These control systems enable real-time energy flow management across the grid, which is increasingly important for grid stability and reliability as more RES are integrated into the grid. By incorporating sophisticated control technologies such as smart meters, Supervisory Control and Data Acquisition (SCADA), and Distributed Energy Resource Management Systems (DERMS), grid operators aim to maintain grid stability (voltage and frequency within certain limits) while enabling the connection of more DER.

Market liberalization for households in Switzerland is seen as an opportunity by A1. Liberalization will introduce competition and will encourage DSOs to concentrate on innovation. For smaller DSOs, liberalization will open new possibilities for offering tailored services, exploring innovative business models, and introducing dynamic pricing (D3). However, currently, only large consumers can access competitive markets, while small consumers are still under monopoly supply (D2).

Motivation of stakeholders

Maintaining grid stability and energy security are the core mandated goals for different stakeholders in the Swiss electricity sector. However, innovation and adaptability are additional drivers for stakeholders like E2 and A1, as well as for DSOs, outlined by the ideas they shared regarding the integration of flexible demand-side management and dynamic pricing models. These approaches allow for more responsive energy systems, where consumers can adjust their energy usage based on price signals or available power. A1, in particular, focuses on using technology to create more adaptive energy management systems, which can respond in real-time to shifts in energy supply and demand. However, due to the current legislation, A1 is not able to offer its services to the Swiss market and is therefore operating in the neighboring countries.

Envisioned role of technology

Technology plays a crucial role in several stakeholder's visions of the future electricity sector. Automation, digitalization, demand side management, and flexibility, as well as energy mix diversification, are seen as pillars of the electricity system of the future, with devices and systems being integrated through standardized communication protocols (D1, D3, T1, E2, P1). These stakeholders emphasize the role of smart grids, which allow for a more efficient management of decentralized energy systems by integrating real-time data from various sources. By relying on automation and digitalization, stakeholders can optimize grid operations, reduce inefficiencies, and improve the overall resilience of the energy system, especially as RES increase their share in the energy mix.

Energy storage and customer flexibility are recognized as components essential for managing decentralized energy production (A1, D1, D2). Batteries, both large-scale and residential, offer a critical solution for storing excess energy generated from RES. This stored energy can then be used during periods of high demand or low generation, ensuring a stable and reliable energy supply. Additionally, technologies such as electric vehicle charging systems may play a significant role in optimizing energy consumption patterns. However, while energy storage technologies are valuable for optimizing grid operations, controlling electric vehicle charging presents a more immediate concern for DSOs (D1).

Performances

This dimension of Schmid et al.'s [6] STI framework focuses on how envisioned futures are enacted through present-day activities, organizational governance, and relationships with other actors. The performance dimension captures the ways in which energy cooperatives and other stakeholders operationalize their aspirations within existing structures and through ongoing practices. In this study, we understand stakeholders' main activities as their ongoing efforts to achieve a future grid aligned with their visions. Additionally, we have adapted the organizational governance feature to capture the broader governance of the entire electricity system, including the evolving roles of system operators, the potential centralization of efforts given the numerous DSOs, and debates on public versus private ownership of the DSOs. Lastly, we adapted the feature of the relationships of energy communities with other actors to understand the potential role that the local electricity communities may play in the wider system, considering the introduction of the new law that explicitly recognizes these entities.

Main activities

To realize the envisioned electricity system of the future, the grid infrastructure, including the high voltage lines, needs to be upgraded to better accommodate decentralized energy production and the more volatile flows in the grid (T1). Also, innovation projects and pilot programs need to be supported as they are avenues through which different stakeholders explore new ways to interact, modernize, and redesign the electricity system (D1, D3, A1). These projects often involve testing algorithms for optimizing grid management, experimenting with energy communities, or implementing flexible demand-side management strategies.

Organizational governance

Organizational governance spans the entire electricity system across different aspects, including the centralization of efforts, changing roles of system operators, and debates on ownership. Some interviewees provided different arguments regarding the centralization of efforts to realize the future energy systems (D1, E1, T1). Such centralization is favorable when it comes to grid planning and investments (T1) as well as the centralization of standards, regulations, and interfaces (E1). However, rather than centralizing the efforts, more clarity in regulations and procedures is needed, as real operational challenges are more about the ambiguities of what is allowed, along with the need for more decentralized decision-making freedom within a clear framework (D1). Due to the large number of DSOs and other entities, certain coordination challenges exist, particularly in implementing common standards (E1). Moreover, there is a possibility for the future fusion of actors to simplify grid operations, potentially reducing the number of DSOs (P1).

The roles of some DSOs (D1, D2) as well as that of the TSO (T1) are undergoing a significant transformation. Traditionally focused on operating the grid to ensure grid stability and reliable energy delivery, the TSO's role is evolving into that of a system integrator who needs to coordinate various aspects of the energy system rather than just operate the grid (T1). In this context, system integration refers to the integration of the activities and operations of different market actors (DSOs, energy companies, large consumers), the integration of DER, as well as advanced control technologies and mechanisms to ensure optimized energy flows that balance supply and demand. DSOs, on the other hand, are expanding their responsibilities to include energy innovation, public engagement, and the management of decentralized energy systems. This shift is driven by the increasing complexity of energy networks, with more renewables and DER being connected to the low and medium-voltage grids.

Several interviewees also discussed arguments regarding public versus private ownership of energy infrastructure (D1, E1, E2, T1). Public ownership of critical infrastructure, especially grid assets, is seen as vital for ensuring long-term energy security and stability. The rationale is that public control can align energy policy with national objectives, such as the net-zero GHG goals. At the same time, there is widespread recognition of the need for private sector innovation as a prerequisite for driving the energy transition forward.

Potential role of local electricity communities

The interviews provided a wide range of opinions on the viability and the potential role of local electricity communities in the future electricity grid. Some stakeholders are optimistic about their potential, emphasizing the role that they can play in decentralizing energy production and enhancing public engagement (D2, T1). They see these communities as a promising way to increase local renewable energy generation and encourage citizen participation in the energy transition. However, other stakeholders are more skeptical (A1, D3). They highlight the lack of information and understanding, the limited financial incentives available to participants, and the complexity of managing such initiatives, which could hinder their growth and long-term sustainability. Moreover, the integration of energy communities into the grid may bring additional administrative challenges for DSOs, which is especially relevant for smaller DSOs (D1).

Discussion

Evolving roles and coordination issues

This study investigates the shared visions across Switzerland's electricity sector, outlining the challenges and opportunities that the sector faces in its transformation. The anticipated evolution of the electricity system, marked by increased decentralization, enhanced flexibility, greater integration of RES, and a dynamic balance between centralized and decentralized elements, is consistent with insights from the literature [5, 39]. Achieving this vision, however, requires substantial investments to modernize and strengthen grid infrastructure [40, 41]. Furthermore, the success of this transition hinges on robust coordination between the TSO and DSOs to effectively manage the complexities of the evolving energy landscape.

The findings underscore the need for improved coordination between system operators, particularly in grid planning and investment, due to the large number of DSOs in Switzerland. This need for enhanced coordination is also outlined in the literature [42–44]. While the possibility of merging or consolidating DSOs could reduce coordination complexities, such measures would entail significant challenges, including the loss of local control, which is a key feature of Switzerland's municipally owned DSOs.

To address these challenges, DSOs must take an active role in shaping support measures to ensure technical feasibility and grid preparedness are prioritized from the outset. Given the diversity in size, capacity, and resources among DSOs, implementing solutions at the municipal or DSO level, rather than through a top-down federal approach, is crucial. This localized strategy would accommodate the specific needs and operational contexts of individual DSOs, enabling tailored and effective solutions that align with the unique characteristics of Switzerland's electricity sector.

The results highlight the evolving roles of system operators, particularly DSOs, as they adapt to the growing

integration of DER. While the integration of these technologies presents challenges, such as variability and grid stability issues, it also offers significant opportunities to enhance flexibility and provide advanced grid services. In Switzerland, the findings emphasize the pressing need for DSOs to prioritize managing electric vehicle charging, as its variability poses immediate operational challenges. This priority aligns with the literature, which underscores the importance of mitigating grid power peaks caused by such charging and addressing its inherent unpredictability [45, 46].

To manage flexible demand and localized energy production effectively, DSOs must adopt advanced technologies and innovative strategies that optimize grid operations, address network constraints, and balance variable energy flows, which is particularly relevant for smaller DSOs with limited financial and human resources. These findings are consistent with the International Renewable Energy Agency (IRENA) report [47], which highlights the critical need for DSOs to implement systems that facilitate the integration of DER and improve grid performance. Similarly, the Council of European Energy Regulators (CEER) [48] emphasizes that the DSO role has undergone a significant transformation over the past decade and will continue to evolve as the energy transition accelerates, requiring even greater adaptability and innovation.

For Switzerland, these changes in the DSOs' roles are especially critical given the large number of DSOs, each with varying capacities and resources. Smaller ones, in particular, face greater challenges due to limited financial and technical capabilities, which may hinder their ability to adapt to the new demands. Addressing these disparities requires tailored approaches that support all DSOs in navigating their evolving roles while ensuring their ability to contribute effectively to the energy transition. This highlights the importance of localized strategies and targeted measures that reflect the diversity and unique operational contexts within Switzerland's electricity sector.

In line with enhancing TSO-DSO coordination, it is equally critical to prioritize effective collaboration between DSOs and other grid-connected entities to mitigate operational challenges, particularly for smaller DSOs with limited resources. The findings indicate that various forms of citizen engagement, including prosumers, Mergers For Self-consumption, and energy cooperatives or Local Electricity Communities, are expected to play a significant role in the future energy system. This aligns with arguments by Meister et al. [49] who emphasize the importance of citizen-driven initiatives in advancing renewable energy adoption.

The introduction of the new Electricity Act is anticipated to accelerate the uptake of RES through the expansion of ECs. To support their effective integration into the DSO grid, targeted measures are required. From a financial standpoint, these measures should be designed to ensure the long-term sustainability of ECs by facilitating access to various forms of financial support [50–52]. Such support may include subsidies, loans, or tax incentives [53], but careful consideration of housing ownership structures is essential. Since the majority of households in Switzerland are tenants [54], financial mechanisms must align with these housing realities, as not all forms of support are equally suitable across different ownership situations.

Research on financial support mechanisms for community energy initiatives in Austria, the Netherlands, Norway, and Spain highlights that property owners can access different types of financial support with relative ease [55]. However, for tenants, implementing financial support often requires coordination and agreements with landlords. According to Kerstens and Greco [55], loans are the most viable support mechanism for tenants, given their flexibility and compatibility with rental arrangements in the analyzed countries. These findings underscore the importance of tailoring financial policies to the specific socio-economic and ownership types in Switzerland to maximize their effectiveness.

Beyond evolving roles and coordination issues

The results highlight the critical role of public education and engagement activities in promoting the energy transition by raising awareness and ensuring public acceptance. This is also supported by the literature, as such initiatives are essential for fostering an informed citizenry capable of participating meaningfully in energy system decisions [56–58]. Energy issues are often complex, and many citizens struggle to understand their role within the broader energy system or recognize the direct benefits of their participation. Enhanced public engagement and education efforts can bridge this gap, improving policymaking by ensuring that citizens are better equipped to comprehend energy-related topics. In the context of Switzerland's direct democracy system, where citizens vote on federal policies such as the new Energy Law and the new Electricity Act, these activities are especially crucial. Studies on direct democracy show that exposure to voting initiatives enhances political knowledge [59, 60]. Expanding public education and engagement efforts would further ensure that citizens can make well-informed decisions aligned with their best interests.

Beyond public engagement, the findings underscore the need for regulatory frameworks to evolve in step with technological innovations. Some of the interviewees emphasized the importance of addressing regulatory uncertainties, which can hinder the implementation of innovative solutions essential for accelerating low-carbon transitions. This aligns with broader observations that

regulatory frameworks often fail to keep pace with disruptive innovations [61], creating significant barriers in rapidly changing fields like the energy sector. Such barriers can stall experimentation and delay the adoption of technologies crucial for decarbonization [62]. As regulatory and institutional structures are key determinants of the success or failure of energy transitions [63], it is vital that they adapt proactively to support emerging technologies and align with the broader goals of the energy transition. To this end, clear, firm, and long-term regulatory and policy frameworks are needed to ensure energy systems transformations [64]. For Switzerland, addressing regulatory uncertainties and accelerating the pace of regulatory development will be pivotal to integrating technological advancements across all grid voltage levels.

Lastly, the results suggest that market liberalization for households and the unbundling of distribution and retail activities for DSOs could foster the development of innovative business models and enhance the efficiency of the household retail market. This perspective is widely supported by the current literature [65–68]. However, in the Swiss context, such reforms face significant obstacles. The country's emphasis on retaining local, municipal ownership of DSOs, combined with repeated delays in the full liberalization of the electricity sector [69], suggests that major changes in this area are unlikely in the near future. These constraints highlight the need to balance market efficiency with the preservation of local governance structures and community ownership, which remain central to Switzerland's electricity sector.

Contributions

This article contributes to the literature on the transformation of the electricity sector by building on previous works that highlighted the importance of aligned visions for achieving a net-zero electricity system [9, 70, 71]. Adopting Schmid et al.'s [6] STI concept, we analyzed the shared and divergent visions of key stakeholders in Switzerland's electricity sector, including transmission and distribution system operators, energy companies, policymakers, and others.

The novelty of this article lies in its exploration of how differing and converging visions across the sector may impact the effectiveness of Switzerland's energy transition. By integrating multiple cross-sectoral stakeholder perspectives on the future Swiss electricity grid, the study illuminates the opportunities and challenges inherent in aligning diverse visions. A key contribution of this study is its sector-wide perspective on TSO-DSO coordination challenges, regulatory uncertainties, and the evolving roles of stakeholders amidst the rise of RES and DER.

By applying the STI concept, the article expands our understanding of the complexities involved in imagining and realizing a sustainable energy future for Switzerland. As such, this article offers an important contribution that goes beyond a static analysis of energy policy, providing a socio-technical perspective on the transformation of Switzerland's electricity sector and advancing the discourse on achieving decarbonization and energy security goals.

Conclusions

This study aims to investigate the shared visions within Switzerland's electricity sector regarding the future electricity grid, emphasizing the challenges and opportunities presented by the energy transition. The integration of RES and DER, including prosumers and ECs, represents a transformative shift in the country's electricity grid. Our findings highlight that achieving an aligned vision among key stakeholders such as the TSO, DSOs, policymakers, and energy companies is essential to ensuring grid stability, energy security, and long-term sustainability.

To explore these dynamics, we apply the STI framework by Schmid et al. [6], originally developed in the Swiss context to study energy cooperatives and adapted here to the broader electricity sector. This framework provides valuable insights into how diverse stakeholders envision and operationalize the future grid, identifying areas of alignment and potential misalignment. By adopting a socio-technical perspective, this study reveals that the transition to a sustainable electricity system requires more than technological advancements; it demands alignment across social, regulatory, and institutional dimensions.

Key findings from this research underline the importance of coordinated investments in grid modernization and enhanced TSO-DSO collaboration to manage growing shares of RES and DER effectively. Stakeholders' aspirations reveal a common desire for a decentralized, flexible energy system that integrates citizen engagement, smart technologies, and renewable solutions, while emphasizing the need for grid stability and coordinated, hybrid solutions that balance centralized and decentralized elements.

We define four sector-wide policy implications emerging from our findings, and they include the following:

Enhanced coordination between TSO and DSOs: Despite adequate TSO-DSO coordination, policymakers should push for improved coordination across the grid through flexibility options like demand response and distributed storage, ensuring seamless integration of DER across different grid voltage levels while maintaining system stability. This coordination is necessary for optimizing grid operations, managing bidirectional power flows, and facilitating the energy transition.

Investment in grid modernization: Coordinated, anticipatory investment planning is critical to upgrading and expanding grid infrastructure, including advanced

control technologies and energy storage. Policymakers must establish clear, predictable regulatory and policy frameworks to attract and guide these investments.

Regulatory flexibility and clarity: Energy regulation must evolve in tandem with technological advancements to reduce uncertainties and promote innovation. This includes adapting regulations to support new energy actors and pilot projects and providing a clear path for integrating innovative solutions into existing systems.

Support for energy communities and citizen engagement: To maximize the potential of local electricity communities, policies should provide targeted financial incentives, technical assistance, and engagement strategies. Localized measures must address the diverse capacities of DSOs, ensuring smaller operators are equipped to integrate new entities without compromising grid reliability. The integration of ECs can pose challenges such as balancing supply and demand or maintaining grid stability, making tailored support for DSOs, particularly smaller ones, essential.

While our findings align with widely recognized policy directions such as improving coordination, enabling local flexibility, and aligning stakeholder visions, the key challenge lies in operationalizing these goals. Our findings suggest several potential pathways. First, establishing or strengthening intermediary coordination platforms can help bridge communication gaps between system operators, policymakers, and local initiatives. Second, targeted capacity-building for smaller DSOs and municipalities is essential to ensure they can meaningfully participate in strategic planning and system integration. Third, iterative and structured stakeholder dialogues, beyond one-off consultations, are needed to align socio-technical expectations and capabilities across levels. Lastly, establishing one-stop shops for DSOs, energy companies, and citizens interested in energy communities is crucial. These hubs would centralize information on regulations, technical guidelines, and financial support, streamlining the process and encouraging participation.

While this study focuses on Switzerland's decentralized electricity sector, many of the insights are applicable beyond the Swiss context. The challenges of aligning stakeholder visions, adapting regulatory frameworks, and coordinating between system operators and other entities in the system are shared across many countries characterized by different energy transition pathways. In particular, the European Union's promotion of energy communities as part of its Clean Energy for All Europeans package represents a major step toward decentralization. The lessons from Switzerland, including the importance of locally tailored governance, flexible regulatory and investment support, and enhanced coordination across system levels, offer guidance for EU member states implementing these provisions. By highlighting how socio-technical imaginaries may shape institutional alignment, this study provides a transferable framework for supporting decentralized energy transitions across diverse governance settings.

Abbreviations

CEER	Council of European Energy Regulators
DER	Distributed energy resources
DERMS	Distributed Energy Resource Management Systems
DSO	Distribution system operator
EC	Energy community
GHG	Greenhouse gas
IRENA	International Renewable Energy Agency
PV	Photovoltaics
RES	Renewable energy sources
SCADA	Supervisory Control and Data Acquisition
STI	Socio-Technical Imaginary
TSO	Transmission system operator

Author contributions

Conceptualization: VD, BP, MS; Design: VD, BP; Data collection: VD; Analysis: VD; Writing: VD, BP; Review: VD, BP, MS; All authors read and approved the final manuscript.

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Data availability

The data gathered in this study are available upon request. Interested parties should contact the first author, Vanja Djinlev, at vanja.djinlev@usys.ethz.ch to obtain access to the data.

Declarations

Ethics approval and consent to participate

Ethics approval (Reference #22 ETHICS-205) was obtained from the ETH Zurich Ethics Commission before data collection commenced.

Competing interests

The authors declare no competing interests.

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