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# Electricity grid and societal vulnerability interconnection: stakeholder implications and integrated solutions in Europe

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## Abstract

The electricity grid is a pivotal element in the energy transition, serving as the backbone for integrating and distributing renewable energy. However, amid rapid digitalisation and decentralisation of energy systems, its limitations have become increasingly apparent, posing significant challenges for inclusive and equitable stakeholder engagement in the transition. Stakeholders including consumers, prosumers, energy communities, aggregators and electricity utilities, face unequal distribution of grid-related costs and benefits. There is thus a need to understand and address coupled grid-societal vulnerability (GSV). However, there is still no comprehensive study identifying factors influencing GSV and the corresponding challenges vis-à-vis stakeholders. Previous studies have predominantly focused on the disparities in access to hosting capacities for new renewable energy projects and grid congestion due to increased energy demand from households and businesses. We contribute to the literature by developing a comprehensive view of GSV through a systematic literature review of 185 peer-reviewed academic papers focusing on the European context. Three main factors influencing GSV are identified: grid constraints, cybersecurity risks, and regulatory barriers. A complex interrelationship exists between stakeholders in the electricity grid and, as a result, we find there are (in)direct implications of their grid challenges across stakeholders. Therefore, tackling GSV and inequalities in the energy transition requires an integrated solutions approach combining supportive policies, regulatory frameworks and market-based mechanisms with technological integration, innovations and consumer engagement.

## Abbreviations:

| | |
|---|---|
| DER | Distributed energy resources |
| EC | Energy community |
| EV | Electric vehicle |
| PV | Photo voltaic |
| EP | Energy poverty |
| GV | Grid vulnerability |
| GSV | Grid-societal vulnerability |
| DSO | Distribution system operator |
| TSO | Transmission system operator |
| P2P | Peer-to-peer |
| GW | Gigawatt |
| ML | Machine learning |

## 1. Introduction

Achieving the historic 2015 Paris Agreement to reduce global warming from greenhouse gas emissions by 2050 necessitates a rapid shift from traditional fossil fuels, and the immediate and extensive deployment of clean alternatives to meet future energy demands [1]. There are also plans to halt sales of new fossil fuel-based passenger vehicles by 2035, while gradually eliminating coal and oil power plants by 2040 [2]. This will lead to more dependence on electricity, spanning various sectors including transportation, building, and industry [3, 4]. The ascendancy of electricity in energy systems is powered by the dynamic growth of renewable technologies, notably solar and wind. An unprecedented increase in the deployment of these renewables is required to meet future energy demands—targeting a 370% increase in solar photovoltaics and 242% for wind by 2030, compared to the 134 GW and 114 GW capacities achieved in 2020 [5].

The great challenge for the electricity grid is to handle all generated and consumed electricity by 2050. It is insufficient, causing problems in access to hosting capacities for the installation of new renewable energy projects and grid congestion due to increased energy demand from producers and consumers (households, businesses, etc). To ensure a resilient grid that can facilitate the energy transition, global investment in grid infrastructure would need to triple by 2030, reaching approximately $900 billion annually [5]. Such massive investment is crucial not only for expansion but also for the modernisation of ageing infrastructure to adapt to the increased integration of renewables [6]. However, as Sovacool *et al* emphasise, without a focus on equity, this investment risks leaving vulnerable communities disproportionately burdened by grid limitations during the transition [7].

Thus, there is an urgent need to better understand and address the intersection between social and equity challenges, and GV. The term GV is well-established and defined in the energy and power systems literature as the technical and operational susceptibility of electricity grid systems to systemic and operational disruptions (e.g. [8–10]. This could be due to physical, cyber, and natural incidents [11, 12]. In this study, we bring attention to a societal perspective by considering stakeholders' challenges and equity issues with respect to the electricity grid. To encompass this intersection and distinguish it from the established GV definition, we refer to it as coupled GSV.

This study aims to understand GSV, which we define as, '*the likelihood of an unequal distribution of costs and benefits vis-à-vis grid services among stakeholders due to the technical, economic, spatial, and legal challenges that arise with the increasing digitalisation and decentralisation of energy systems.*' Stakeholders include households, businesses, energy suppliers, and grid operators. Grid services[4] refer to the opportunities presented by the electricity grid for stakeholders' engagement. These include electricity transmission and distribution services, trading and sharing of electricity, demand response, charging services for electric cars and services to integrate renewable energy.

[4] Similar terminologies are found in the social-science literature for 'energy services' [14, 44].

Low grid capacity can prevent stakeholders from leveraging the electricity grid to participate and equally benefit from the clean energy transition. For example, early adopters of renewables can benefit more from existing grid capacities for clean energy, limiting the participation of disadvantaged households [13]. This could significantly exacerbate the risk of EP. The consequences of this include impacts on good health and well-being [14, 15]. Additionally, over and above grid congestion and capacity limits for new renewable energy installations [16–18], GSV is also related to the information security of stakeholders [19, 20].

Despite the urgency surrounding GSV, there is still no comprehensive study identifying factors influencing GSV and the corresponding challenges vis-à-vis stakeholders. Research on the (in)direct implications for stakeholders also remains underexplored, especially given their complex interrelations in the electricity grid. This study contributes to the literature by developing a comprehensive view of GSV through a systematic literature review of 185 peer-reviewed academic papers. We also propose an integrated solutions approach for tackling GSV consisting of, for example, market-based mechanisms combined with consumer engagement. This leads to the following research questions:

- What factors influence GSV and how do their key features relate to stakeholders?
- What are the (in)direct implications of stakeholders' electricity grid challenges for other stakeholders?
- How can technological innovations, policy reforms, market design, and stakeholder engagement effectively address GSV and promote a more equitable participation in the energy transition?

Considering the diverse nature of the global energy landscape, this study focuses on the European context, where a convergence of policy frameworks presents a unique opportunity for analysis. The European energy landscape is characterised by a suite of harmonised policies, including the clean energy for all Europeans package (CEP) [21], the EU Green Deal [22], and the European SuperGrid [23]. These initiatives highlight the collective European resolve towards sustainability, energy security and market integration.

The study proceeds as follows. Section 2 provides background on relevant developments in energy systems and stakeholders in the electricity grid, serving as a basis to unravel GSV and the corresponding challenges vis-à-vis stakeholders. Section 3 introduces the research design and methods. Section 4 presents our results, while section 5 highlights the complex stakeholder interrelations and resulting (in)direct implications of their grid challenges for other stakeholders.

Section 6 discusses an integrated solutions approach for tackling GSV based on key strategies from the literature. Section 7 provides concluding thoughts.

## 2. Background

The electricity grid (or power grid) is an intricate infrastructural network designed to facilitate the transmission of electricity from its points of generation to end-users [24]. Electricity utility companies (grid operators and suppliers) are responsible for generating, transmitting and distributing electricity to consumers [25]. Large-scale energy suppliers, who operate high-capacity generation facilities, play a vital role in the wholesale electricity market by trading electricity in bulk. Meanwhile, the TSOs and DSOs, collectively called 'network (or grid) operators', maintain and coordinate electricity flows. They are pivotal for guaranteeing the reliability of electricity supply, achieved through balancing the load on the network and fostering the efficiency of electricity markets [26]. On the consumption end of the spectrum lies households, businesses, and/or industries such as data centres that depend on the grid for their electricity needs, thus completing the cycle of energy distribution from generation to consumption.

Historically characterised by a centralised model, controlled by utility companies, European energy systems have become more decentralised and digitised [27]. This transformation—marked by the integration of DERs, such as wind turbines, solar PVs, and EVs—is bolstered by policy initiatives like the CEP, EU Green Deal and European SuperGrid. As a result, new stakeholders have emerged that can actively participate through the generation and trading of renewable energy, namely prosumers and energy communities (ECs) [28, 29]. Prosumers are households, businesses, and industrial actors, that locally generate, consume, and trade excess clean energy [30]. ECs are initiatives formed to foster energy autonomy and reduce carbon emissions by enabling joint investments in clean energy projects. For this purpose, they pool resources [28, 31], share clean energy generation [32, 33] and storage capacities [34, 35], and engage in joint decision-making [36].

Ultimately, the existing infrastructure is strained by the increasing stakeholder engagement [31, 37]. This necessitates substantial financial investments in infrastructure upgrades and expansions to alleviate grid congestion and increase capacity for more renewable energy integration [6]. There is also growing demand for aggregator services to enhance grid stability by optimising demand flexibility from consumers, prosumers and ECs [38–40]. Aggregators play a crucial role in integrating disparate small-scale renewable energy-producing stakeholders and consumers to participate effectively in the broader energy market [38]. They optimise the aggregated energy and demand flexibility—from energy stored in stationary batteries and EVs, and modified user demand profiles—to provide stability and enhance grid hosting capacity [41].

Low grid capacity not only restricts stakeholders' involvement but also exacerbates inequalities in their ability to both benefit from and contribute to the energy transition. For instance, early adopters of DERs—particularly seen among wealthier households [42]—saturate the grid with their excess renewable energy exports, and can hence impact access to cheap and clean energy for new or probable adopters of DERs [17]. As a result, vulnerable stakeholders remain disproportionately constrained, reinforcing existing inequalities within the transition process. It also can significantly exacerbate the risk of EP—aka 'energy insecurity','energy injustice' and 'energy vulnerability'—and lead to broader socio-economic inequalities for stakeholders [43]. In the literature [14, 44, 45], EP is described as a situation in which individuals, households, and communities, '*cannot attain and/or use the energy services required for good health, wellbeing, and the ability to fully participate in society.*' Energy services refer to those services that require energy to function like mobility, cooking, cooling, lighting, and space and water heating [44]. Therefore, EP can be the result of GSV and vice versa.

## 3. Research design and methods

To address our research questions, we applied the PSALSAR framework [46]. It is a six-step process for conducting a systematic literature review, namely the protocol, search, appraisal, synthesis, analysis and reporting.

### Phase 1: protocol and search

There is a growing literature on unequal opportunities for citizens to participate in the energy transition, and terms such as inequalities, unfairness, poverty, privileges, and vulnerabilities have become increasingly popular. We reviewed past literature that address these, and given the research questions, that cover issues related to 'grid congestion', 'hosting capacity', 'grid limits', 'decentralised energy', energy sharing or trading, 'consumers', 'prosumers' and 'ECs'. Following section 2, we also consider articles on 'EP', 'energy vulnerability' and 'energy justice' (search string in appendix).

The Scopus search resulted in 17,579 publications as of April 2025 when the search was conducted[5]. We further refined our search to concentrate on studies pertinent to the European energy context, specifically within the disciplines of 'Environmental science', 'Social sciences', 'Business, management and

[5] A first search was conducted up until 31 August 2023 and has now been updated to 30 April 2025.

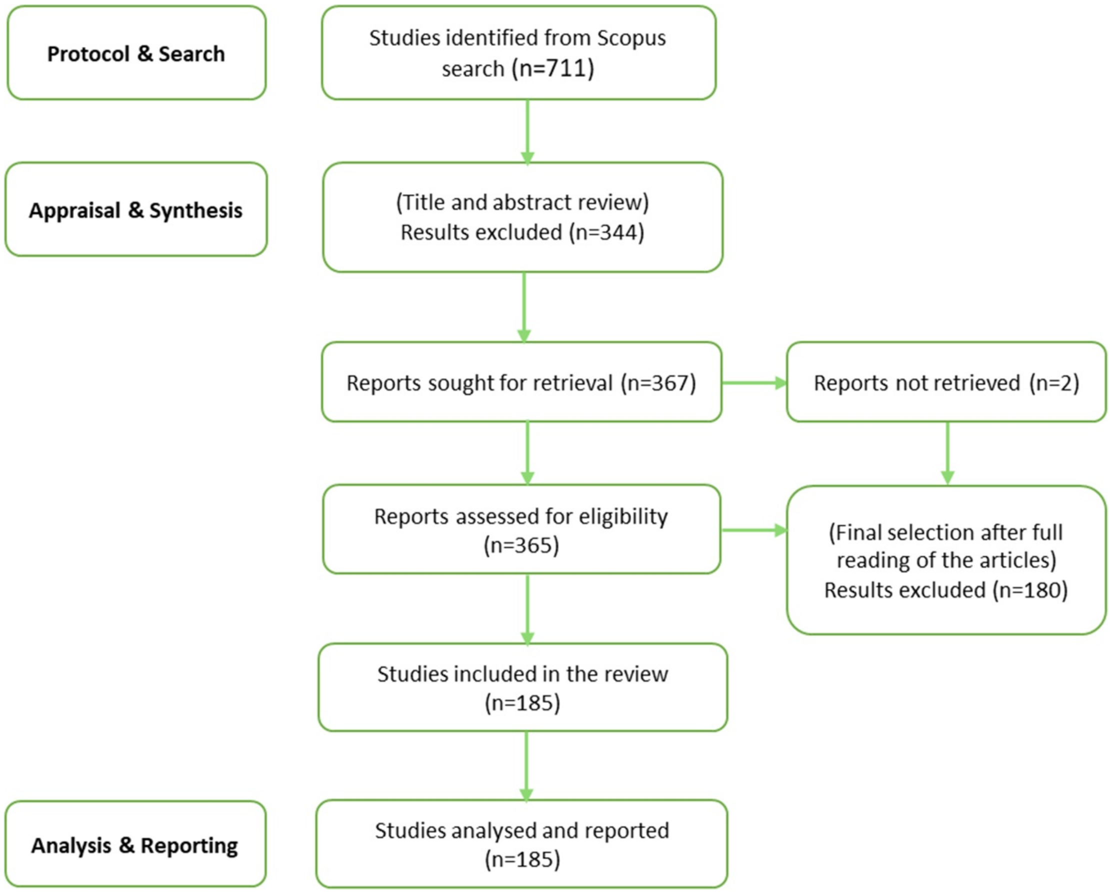


**Figure 1.** PRISMA flow diagram.

accounting', 'Economics, econometrics and finance', and 'Multidisciplinary'. We included peer-reviewed articles published in English since 2000, whereby we identified 711 peer-reviewed articles as seen in the PRISMA Flow Diagram in figure 1.

**Phase 2: appraisal and synthesis**

Next, we read through the titles and abstracts of the selected articles to assess the relevance and quality. A total of 344 articles did not meet the inclusion criteria detailed in appendix table A1, and were excluded; 65 of which were from regions outside of Europe. 367 reports were then sought for retrieval of which two of them were unavailable. The remaining 365 articles underwent a comprehensive full-text screening process, repeating the steps in appendix table A1. This led to an additional 180 articles being excluded. In all, 81 studies involving other regions were excluded from the initially identified 711 reports; Asia ($n = 20$), North America ($n = 14$), Central and South America ($n = 8$), Africa ($n = 33$) and the Caribbeans and Australia ($n = 6$).

Finally, of the 185 peer-reviewed articles identified for our study, four main recurring themes on the electricity grid emerged; namely, grid congestion issues, cybersecurity risks, regulatory challenges and nature-related incidents (also see figure 3). These identified studies have also been complemented with additional grey literature and some relevant studies from other countries which are included in the footnotes. The grey literature was selected from citations in our reviewed articles—primarily from sources such as the European Commission, IEA, WEF, UNFCCC, and OECD. Additionally, from the initial pool of 711 articles, insights from studies in other countries were included where contextually relevant.

**Phase 3: analysis and reporting**

Reports that looked at multiple countries were redistributed across the countries of focus for ease of analysing the distribution of countries considered in the literature. Also, studies involving simulations and reviews have been classified as hypothetical studies and make up about 16% of all reviewed articles. Countries exhibiting strong policies and high levels of citizen engagement in the energy transition such as Germany, the United Kingdom and the Netherlands, have relatively higher representation in the literature, as seen in figure 2.

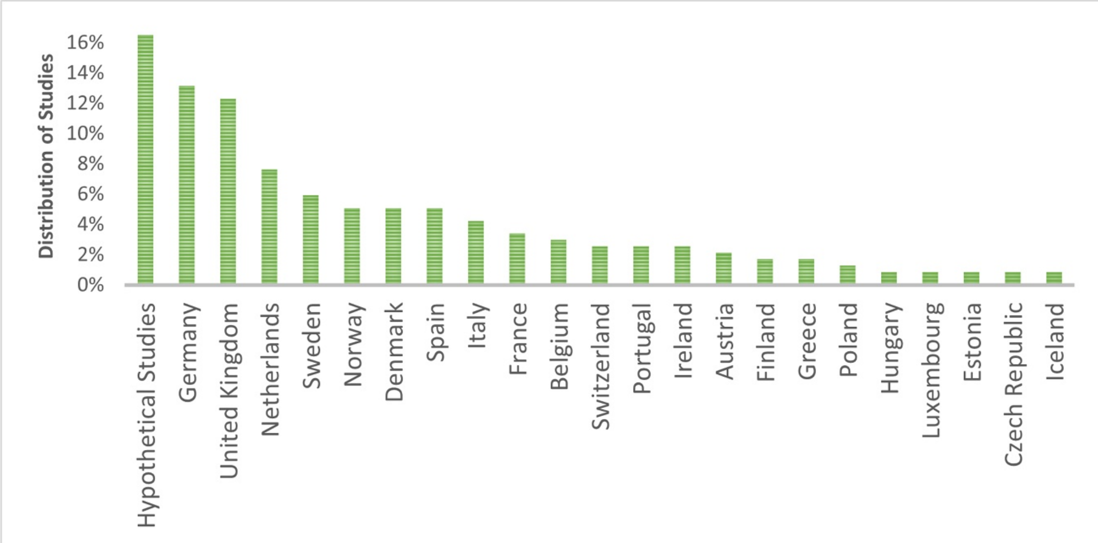


**Figure 2.** Distribution of the countries considered in the reviewed articles.

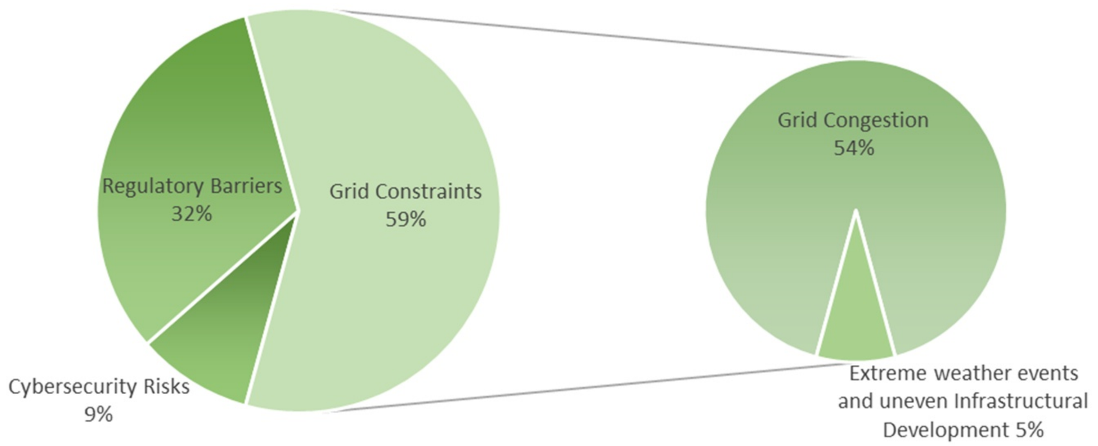


**Figure 3.** Distribution of the factors influencing grid-societal vulnerability.

## 4. Factors influencing GSV

Despite grid congestion being the predominant focus—constituting 54% of all reviewed works as seen in figure 3—we have pinpointed other factors influencing GSV that have been relatively overlooked in existing literature. These include extreme weather events and uneven infrastructural development, cybersecurity risks and regulatory barriers. To structure our results, we have classified the factors directly related to the limitations of the electricity grid under grid constraints. Hence, three main factors influencing GSV were identified—*grid constraints, cybersecurity risks*, and *regulatory barriers*.

### 4.1. Grid constraints

Grid constraints originate from the electricity grid's technical and operational limitations. While not directly caused by stakeholder participation, the growing involvement of prosumers, consumers, and ECs in the energy transition reveals and amplifies these existing limitations of the grid. Table 1 summarises the factors influencing GSV and some of the key features as discussed in the literature. Most featured studies on the high penetration of DERs, intermittency of renewable energy sources, spatial and temporal mismatch in energy demand and supply, and capacity limits. To a lesser extent, studies also discuss variations in building occupancy patterns, ageing electricity grid infrastructure and network malfunction. The following subsections highlight findings on the factors classified under grid constraints.

#### *4.1.1. Grid congestion*

Grid congestion is intricately woven into both the supply and demand sides of energy flows. In the

**Table 1.** Factors influencing GSV from the literature.

| Factors | Description | Key features | References |
|---|---|---|---|
| Grid constraints | This relates to the capacity and flexibility of the electricity grid to handle spatial and temporal variations in electricity demand and supply, and ensure reliable and resilient operation. | Uncontrolled charging of EVs | [47–51] |
| Grid congestion | | Spatial and temporal mismatch in energy supply and demand | [52–57] |
| | | High penetration of DERs | [6, 18, 58–62] |
| | | Variations in building occupancy patterns | [63–65] |
| | | Integration of ECs | [33, 66–68] |
| | | Intermittency of renewable energy and inaccurate forecasting | [6, 69–72] |
| Extreme weather events and uneven infrastructural development | | Increased self-consumption | [73–76] |
| | | Growing energy demand from residential, non-residential and industrial sectors | [62, 77–79] |
| | | Capacity limits for DERs and new grid connections | [16, 18, 58, 80–83] |
| | | Ageing electricity grid infrastructure | [15] |
| | | Uneven development and weather-induced disruptions | [84–90] |
| | | Network malfunction | [91] |
| Cybersecurity risks | This relates to the digital infrastructure of the electricity grid, which exposes it to cyber-attacks from malicious entities. | User information security and hacking and impersonation concerns | [92–99] |
| | | Potential disruption of services due to cyber threats | [100–102] |
| | | Electricity thefts | [103] |
| Regulatory barriers | Arising from legal and regulatory frameworks, and the broader policy decisions that may hinder stakeholder participation and the effective development, deployment, and integration of energy technologies and practices in the clean transition. | Regulatory and incentive frameworks that reflect diverse consumer preferences and support storage, efficiency, and demand flexibility | [104–118] |
| | | Customer-centric energy policies enabling P2P energy trading and protecting vulnerable populations | [119–124] |
| | | Grid tariff designs, energy taxes, and legal barriers affecting equitable participation | [30, 125–138] |
| | | Legal frameworks and market design for innovative and flexible grid solutions, and EC initiatives | [26, 33, 139–145] |
| | | Gaps in standardised communication protocols across energy devices and systems | [146] |
| | | Insufficient incentives and regulatory support for smart grid investments and infrastructure upgrades | [147–149] |

*Note:* To enhance readability, a selection of references is included in this table; additional references related to these factors appear in other tables.

literature, this issue is mostly collectively referred to as, 'network congestion' [47] or 'grid congestion' [26] with hardly a clear distinction between electricity feed-in capacity limits and demand-side congestion. Both cases are connected. For example, load curtailment or shifting demand through flexibility measures, to minimise demand peaks, may also enhance the limited grid's capacity for further renewable energy supply when demand is moved to peak generation periods [80, 150]. Hence, for clarity, we separate our findings into two sub-groups: feed-in capacity limits and demand congestion.

*4.1.1.1. Feed-in capacity limits*

Several factors contribute to feed-in capacity limits in the European context, given the rapid expansion of decentralised renewables, especially wind and solar power [6]. This growth can sometimes surpass the capacity of existing infrastructure [18], which was not originally designed to accommodate such a rapid diffusion [15]. As the deployment of DERs continues to expand, the existing distribution network can be strained, leading to costly project delays [18, 77], aiming to increase 'hosting capacity' or 'feed-in capacity', i.e. the maximum level of DERs that the grid can support [80].

Residential solar PV hosting capacities are not evenly distributed [16, 18]. In Sweden, socio-economic deprivation is associated with lower hosting capacity [16]. Communities with higher education, income, home ownership and employment enjoy larger solar PV hosting capacities. Also, single-family houses receive more-than-average incentives to install solar PV in most European countries [18].

Costly grid upgrades are often required to increase feed-in capacity, and these costs can be unevenly distributed among consumers [151]. In Germany[6], the higher network reinforcement costs passed on through electricity bills, disproportionately affects those without solar PV [125] or those living in areas with lower hosting capacity[7] [81]. In Switzerland, projections show that increasing solar PV deployment on low-voltage distribution networks could lead to 18.5% and 13.7% more voltage violations in 2035 and 2050 [18], compared to 0.5% and 2.5% overloading for heat pumps and EVs. Reinforcing the grid to handle this could cost €11.6 billion by 2050, €3,062 per household[8], highlighting the cost implications of expanding hosting capacity and the risk of exacerbating inequality [73, 126].

Feed-in capacity is also affected by the spatial distribution of DERs and by forecasting inaccuracies, both of which can create mismatches between generation and demand [58, 69]. In Germany, high residential PV penetration combined with low energy grid consumption rates has led to overloading of low-voltage networks in the summer months [59], requiring grid operators to re-dispatch the supply[9] [152] and potentially costing up to €5 billion annually by 2025 [66]. Solutions aimed at maximising existing feed-in capacity—such as sharing the grid [81]—could avoid or defer expensive upgrades. For instance, in Ireland, grid-sharing approaches could increase participation from 77.9% to 100% and unlock access for 364,064 customers. Similarly, siting wind turbines closer to demand centres in Spain can reduce the need for grid expansions, effectively preserving available hosting capacity [58].

Prosumers' self-consumption practices also influence feed-in capacity [60]. By using more energy locally, prosumers reduce exports to the grid, easing stress on hosting capacity [73]. This could reduce investment needs in distribution networks by 48% and enable an additional 6.7 GW of solar PV in Belgium by 2050 [153]. That being said, at high levels of self-consumption, there may be trade-offs, including impacts on energy security and potential increases in EP [74]. Local coordination by DSOs through 'smart prosumer' models such as energy hubs and EV parking lots, can optimise exports, reducing grid operational costs by 46.85% while protecting feed-in capacity [154].

The collective activities of ECs can significantly shape local hosting capacity. As community PV capacity and membership grow, higher electricity exports risk increasing congestion in distribution networks [33]. Coordinated control of privately owned batteries for shared objectives can ease these constraints [155]. Also, optimal placement of these battery storage in residential communities could reduce overloading at the low-voltage distribution by more than half, freeing up additional capacity for DER integration [67].

Expanding feed-in capacity can also be achieved through targeted technical innovations. Scheduling flexibility helps accommodate periods of high PV generation [70, 71, 156], while storing excess PV

[6] The same for the findings in the United States [13], although outside the scope of our study. The authors report that unequal access to hosting capacities limits the penetration of solar PVs and EVs particularly among African Americans.

[7] Although, in the long run, these upgrades in hosting capacity could mean that more individuals can adopt PV, and despite incurring expenses (i.e. investment), it would yield savings for owners.

[8] CHF 10.78 billion by 2050, CHF 2,845 per household (Conversion rate as of 04/2025). This is already around 8.3% of the annual Swiss median disposable household income [233].

[9] At some point in the Netherlands, to address the overcapacity of renewable energy in the north, they allowed Google data centres to be built to balance the demand on the grid [234].

electricity as thermal energy can prevent curtailment [157]. Advances such as deep learning-based PV forecasting and battery management can further enhance PV hosting capacity in distribution networks [158]. Grid-support functionalities in inverters can reduce voltage deviations and grid instability [159], while P2P energy trading—when designed to balance local supply and demand—can ease grid saturation [47, 156]. However, scaling P2P trading presents persistent challenges, including managing uncertainty, and resolving transmission and distribution coordination issues, which must be addressed to ensure it contributes positively to feed-in capacity [160].

*4.1.1.2. Demand congestion*

Growth in energy demand in Europe is driven by transport electrification, heating demands, and other household and industrial loads [48, 78, 161, 162]. Excessive demand can cause demand-side congestion, particularly in urban areas, during peak hours and cold seasons [15]. In the UK, peak demand from heating alone is expected to increase by around 14% for 20% more adoption of heat pumps [78]. Demand-side congestion, e.g. from uncontrolled charging of EVs [51, 163] or variations in building occupancy patterns [63, 64, 164] (see table 1), can cause voltage fluctuations and frequent interruptions in power supply.

The rapid diffusion of EVs strains existing grid infrastructure and impacts the power quality in European cities [48, 51], which can compromise the functioning of the grid in densely populated areas such as Amsterdam [15], prompting further grid investments. Energy efficient buildings on the other hand, can contribute a 75% decrease in transmission grid congestion by reducing peak heating demand in Europe by up to 49% [165]. The €44.2 billion savings in distribution grid investments could in turn lead to lower electricity prices, improving energy equity in pricing and significantly reducing energy bills [165].

With the digitisation of appliances, energy consumers have become active players in energy systems [52]. Aggregators can manage these appliances—either through decentralised or centralised control—to flatten demand peaks [72, 166] in exchange for preferable rates [55, 167]. Demand flexibility can also be achieved through battery energy storage or the smart charging of EVs [50]. However, EV owners tend to prefer manual control over a centralised control [168, 169], while some owners have inelastic demands[10] [137].

A growing number of new or expanded grid connection requests face long waiting lists due to limited transport capacity and required upgrades, resulting in substantial socioeconomic losses [83]. Through 'coordinated non-firm connections', new industrial customers can form ECs with existing grid customers to coordinate flexibility and capacity utilisation [82]. Such coordination can unlock latent flexibility in existing businesses that previously lacked motivation to engage in demand response.

Other than shaving peak demand, demand-side flexibility can be optimised by the supply of renewable energy in the grid [150]. By aligning consumer energy consumption with periods of abundant, low-cost renewable energy, consumption patterns can be optimised to support grid stability [53, 54, 80, 161]. However, it is not yet well understood why people struggle to shift demand patterns [170]. Methods to understand user energy behaviour are often oversimplified, hence the complexity, diversity, and temporal dynamics are overlooked [171]. Sustaining energy-efficient behaviour though visible energy feedback via smartphone apps shows promise—especially among already energy-efficient households [172].

The potential of EV charging via vehicle-to-grid (V2G) and smart charging is estimated to provide a large storage buffer with little to no impact on EV utilisation and cover a substantial portion of household consumption [163, 173, 174]. Emergency cases when the electricity demand exceeds the supply may require grid operators to resort to load shedding, temporarily cutting off power in certain areas [48].

*4.1.2. Extreme weather events and uneven infrastructural development*

In addition to congestion, the grids are constrained by extreme weather events and uneven infrastructural development, affecting grid service accessibility for stakeholders (see table 1), particularly in remote areas such as mountainous locations with high renewable energy potential but low or no grid capacity [88].

Power grids are vulnerable to extreme weather conditions[11] including storms, hurricanes and wildfires [175]. Most grids are designed based on available historical climate data and may not be adequately prepared for climate change [87, 176]. In Greece where overhead lines constitute most of the medium voltage network length due to the rugged terrain and dispersed population centres, nearly 18.54% of the country's exposed grid infrastructure was impacted by extreme weather incidents in 2021,

[10] Price elasticity of demand measures how responsive consumers are to changes in price. The more inelastic, the more unlikely to change their behaviour in response to price signals [54].

[11] Some extreme cases are more frequent in other regions, impacting the health and well-being of the affected populations. They include the tropical cyclones and coastal flooding in Southeast and East Asia [235], and the wildfires and extreme temperature changes in North America [236, 237].

leading to major infrastructure damages and equipment failures [90].

Although decentralised energy systems can increase reliability and resilience to extreme events, they are not immune from the impacts due to their reliance on existing grid services [86]. Previously, weather events such as heavy snowfall, thunderstorms [84] or hurricanes [87] often resulted in blackouts in vulnerable regions in Finland [84] and Poland [87], limiting renewable energy generation and P2P trading opportunities.

Failure of interconnected electricity grids due to weather events can lead to cascading effects[12], severely disrupting power supply for households, businesses, and industries [90]. This urges grid reinforcement to predict and manage future weather conditions [85], reducing the cost of grid failure which consumers would ultimately bear. For instance, in the Netherlands, the €50 million in losses from a 2 h outage every 4 years, cost €2.80 per household and €33.10 for SME firms in 2009[13] [91].

### 4.2. Cybersecurity risks

The least identified factor influencing GSV is cybersecurity risks, appearing in only 9% of previous studies (see figure 3). As reliance on digital communication and control technologies in managing DERs intensifies, the grid becomes increasingly susceptible to a spectrum of cyber threats [98], e.g. data breaches, hacking of smart meters, and denial-of-service, which negatively impact consumers' and producers' confidence in energy transition [92, 102] (see table 2).

The international Energy Agency reported 140 attacks in 2022, with numerous significant social and economic disruptions [5, p 35]. Notable examples are the 2015–16[14] cyberattacks on Ukraine's electricity grid [187]. These incidents highlight the potential for attackers to destabilise critical energy infrastructure on a large scale [96, 101].

Deploying smart meters and EV charging systems in grids introduces new cyberattack vectors [93, 97]. Power overloading cyberattacks on smart meters can exploit the vulnerabilities of load control systems, such as dynamic pricing and direct load control, or the Open Charge Point Protocol for EV charging [100]. Attackers can communicate false electricity prices—creating peaks or demand fluctuations—to overload grid sections, causing blackouts or grid damages [95, 177].

Beyond direct operational disruption, electricity theft facilitated through meter tampering or data interception presents further risks for load forecasting, voltage regulation, and revenue losses for grid operators[15] [103]. In response, ML algorithms have been deployed for anomaly detection in demand patterns and household energy profiles [100, 101]. However, these AI-based solutions are themselves vulnerable to adversarial attacks and data poisoning, underscoring the need for careful integration and risk management [99].

Demand aggregation can contribute to the grids' cyber resilience, providing flexibility and support in recovering critical infrastructure in the event of cyber incidents [94]. Aggregators can provide backup power, frequency and voltage regulation, and isolate and restore affected areas. However, their reliance on real-time data and automated control makes them attractive targets for cyber attacks [96].

The expansion of IoT-enabled devices across grid infrastructures compounds these risks by multiplying potential entry points for attackers, including man-in-the-middle and device impersonation threats [99]. Recent studies have sought to integrate blockchain and physically unclonable functions, to enhance access control and decentralised authentication frameworks [99]. Nevertheless, the deployment of such solutions requires substantial computational resources and also institutional readiness, as organisational and regulatory gaps often hinder cybersecurity preparedness, particularly for DSOs [188].

Advanced computational approaches such as deep reinforcement learning, while offering optimisation advantages, introduce new vulnerabilities. Studies reveal that these models can be exploited through message spoofing and false data injection, potentially destabilising grid operation [187]. In P2P energy trading, while blockchain and ML-based optimisations enhance efficiency and security, they also exacerbate risks like latency and transaction errors, especially with expanding distributed systems [180].

Systemic risks from both physical and digital disruptions, are also intensified by centralised grid infrastructure and the lack of standardised data governance frameworks [177]. This undermines a unified cybersecurity approach across grid operators [188, 189]. As geopolitical tensions heighten the threat landscape, adopting resilient control frameworks—like model predictive control for networked microgrids—becomes critical. These frameworks enable autonomous energy exchanges

[12] This means that the surviving grid infrastructure will have to bear the additional burden from the damaged parts, which may be larger than their maximum loading capacity.

[13] The IEA (2023) report estimates that global economic losses due to power interruptions amounted to at least $100 billion in 2021, with major economies like the U.S., China and Germany being the most affected [5, p 40].

[14] In both of these cases, attackers gained unauthorised access to control equipment and were able to disrupt grid operations, depriving thousands of households of electricity [5, p 36].

[15] Nearly 20% of the electricity generated in India is lost due to theft [238]. In the U.S., the financial losses are estimated to be around $6 billion annually [239].

**Table 2.** The factors influencing GSV and how their key features relate to stakeholders.

| | Grid constraints | Cybersecurity risks | Regulatory barriers |
|---|---|---|---|
| Grid operators & suppliers | Spatial and temporal mismatch in energy supply and demand [55, 56]<br>Extreme weather conditions [84, 85, 87, 89, 90]<br>Ageing electricity grid infrastructure [15]<br>Network malfunction [91]<br>Uneven development of grid infrastructure [88] | Unauthorised access to network control systems, demand manipulation and remote shutdown of grid infrastructure [95, 101]<br>Users' data and electricity theft attacks [103]<br>False electricity price signals [100, 177] | Harmonisation of the power grid to support DER penetration [148]<br>Investment incentives for smart grids [148]<br>Legal frameworks and market design for testing innovative flexible grid solutions [140, 144, 178]<br>Regulatory frameworks for infrastructural upgrades [147]<br>Delays in updating grid codes and market rules [61, 143]<br>Equitable grid tariff and pricing mechanisms for grid cost recovery [30, 125, 138]<br>Legal frameworks to encourage DSO-TSO cooperation for congestion management [26] |
| Aggregators | Intermittency and variability of renewable energy sources [55, 71]<br>Scheduling of stakeholder flexibility [70, 166, 167, 199] | Power overloading cyberattacks [100]<br>Data theft, unauthorised transactions, identity fraud, and physical damage to aggregator platforms [96] | Standardisation of communication protocols for energy devices and systems [146]<br>Regulatory frameworks to support investments in innovative aggregator services and business models [105, 111, 112] |
| Energy communities | Rapid growth in decentralised, small-scale ECs [67]<br>Uncoordinated demand profiles [66, 68]<br>Heterogeneity of ECs; differences in community configurations, size, and prosumer ratios [33, 179] | Privacy breach, reduced reliability/disruptions to clean energy exports, financial losses and impacts members trust [177, 180] | Regulatory frameworks and incentives for the formation of EC initiatives [129, 145]<br>Regulatory frameworks for local energy and flexibility trading within distributed networks [129] |

(Continued.)

**Table 2.** (Continued.)

| | Grid constraints | Cybersecurity risks | Regulatory barriers |
|---|---|---|---|
| Prosumers | High penetration of (intermittent) renewable energy and DERs (solar PV, wind turbines, battery storage, etc) [18, 58, 116]<br>Increasing self-consumption [73–76, 181] | Privacy breach and financial losses/disruptions to clean energy exports [92] | Grid tariff designs, tax breaks and incentives for investments in clean energy and storage solutions [134, 136, 182, 183]<br>Regulatory frameworks for the participation of prosumers in LEMs that apply P2P energy trading [184] |
| Consumers | Inefficient energy use and variations in building occupancy patterns [63, 64, 206]<br>Uncontrolled charging of EVs [47–49, 51]<br>Rapid increase in energy demand from households, non-residential buildings and industries [54, 77–79] | Impersonation threats [99]<br>Privacy breach, financial losses from damages to household equipment and potential power outages [98] | Access to financing options for investments in energy-efficient technologies [113, 114, 124]<br>Fair regulatory frameworks for low-income households and vulnerable populations [88, 119–121, 123, 185, 186]<br>Energy policies considering the heterogeneity of consumer preferences for demand flexibility [104–106, 109, 130] |

*Note*: the key features listed are prevalent points from the literature on each of the factors influencing GSV as it relates to the stakeholders. These features, while being positive for some stakeholders, could cause (in)direct burdens/challenges for others. For example, high penetration of (intermittent) renewable energy and DERs also contributes to grid congestions, slower PV uptakes for late adopters and potential increased electricity bills from grid upgrades. Details on these (in)direct effects are discussed in section 5.

during disruptions, mitigating reliance on centralised infrastructure and the cascading impacts of grid failure [189].

### 4.3. Regulatory barriers

Regulatory barriers were the most frequently identified factors influencing GSV, appearing in 32% of reviewed studies (figure 3); defining frameworks and market design for inclusive energy transition [105, 190, 191]. They determine the accessibility and transparency of electricity markets, grid tariffs and fees, the availability and affordability of smart metering devices, and data privacy, security, and ownership. These factors affect the engagement of prosumers, ECs and consumers, and their interaction with other stakeholders, including grid operators and aggregators. Across Europe, regulatory frameworks and, consequently, GSV spatially vary [145, 192, 193].

Some studies have identified the distributive effects[16] of grid costs and incentives for stakeholders [30, 194, 195]. The transition of consumers to prosumers requires more active infrastructure management and reinforcement by the grid operators, increasing grid costs. While prosumers reduce their grid dependence through self-consumption, they benefit from incentives for low-carbon electricity generation and demand [73, 196]. However, consumers may face higher electricity bills and lower quality of service [194] due to the current volumetric pricing mechanism, which is indifferent to customer profiles and grid impacts, and may lead to cross-subsidisation and unfair cost allocation [118, 138]. Volumetric tariffs charge per kWh of used power, incentivising the diffusion of solar prosumers, and creating winners and losers in the energy transition. The regulatory barriers can unfairly distribute the grid costs of offshore wind installations too [197].

Feed-in tariffs (FiTs) influence prosumers' profitability and self-consumption and can incentivise them to export or store excessive self-generated energy [73]. Lowering FiTs[17] incentivises self-consumption over exports, decreases grid operators' revenues, and likely increases consumer energy bills [183]. Some studies suggest implementing self-consumption charges on prosumers [74, 75]. In Germany, for instance, prosumer households pay value-added tax on self-consumed energy and PV investments [182].

Higher FiTs, on the other hand, reduce self-consumption levels and increase PV feed-in, enhancing the grid energy mix and providing affordable electricity for consumers. However, it also risks overloading the grid with peak supplies, causing congestion [55]. Therefore, regulations like Germany's Renewable Energy Sources Act (2017) cap feed-in power at 70% of a PV plant's nominal power to minimise strain on grid infrastructure [59].

The absence of comprehensive policy frameworks that account for household practices and usage behaviours (highlighted in table 1), may result in flexibility instruments[18], which unintentionally widen socioeconomic inequalities [115, 117, 119, 186]. Households with high flexibility potential may be indifferent to price incentives for load-shifting [198]. Flexibility instruments might inadvertently enforce a uniform sustainable energy concept, conflicting with the stakeholders' varied values and living standards [199]. Rather than curbing energy use, these instruments may spawn counterproductive behaviours, leading to the so-called rebound effect [130, 200].

Congestion management approaches reveal critical policy limitations, particularly around fairness and access to grid capacity. Uncertainty about the transaction costs, distrust for grid operators and the complexity of the institutional context may increase transaction costs for households offering demand-side flexibility and reduce effectiveness of grid tariffs [201]. Current regulatory frameworks for the allocation of scarce grid capacity often prioritise existing connected parties over those on the waiting list including new businesses, renewable energy developers, and community energy projects [83].

Smart meter adaptations marginalise some households [123] due to their ICT literacy, participatory attitudes, infrastructure and home ownership, and income. These vulnerable groups, often homogeneously represented, are neglected in allocating public investments and regulatory support [92, 113]. Implementing tradable green certificates presents intricate challenges for market dynamics and overlooks the demand side [141]. Aggregated storage systems and digital eMobility platforms provide grid-scale flexibility and yield sufficient annual revenue to compensate for grid operator losses. However, they are also hindered by regulatory barriers [111, 139].

Regulations hindering flexible electricity pricing mechanisms which ensure a win-win for prosumers and consumers can cost €67 billion in savings on capacity and transmission costs in the EU alone [136].

[16] It is the difference in the grid tariff paid by consumers and solar prosumers due to the diffusion of prosumer self-consumption [30].

[17] As is the case in countries like the United Kingdom [240]. Apart from the FiTs which are largely popular in European countries, the net metering and net purchasing schemes are also mechanisms designed to encourage solar prosumers and are popular in most cities in the U.S. and countries like India [30, 241].

[18] Flexibility instruments for incentivising grid flexibility services include flexible energy tariffs, stakeholder-targeted business models and supporting incentives. The supporting policy frameworks vary across European States [105].

This makes smoothing out demand fluctuations burdensome for all parties involved [133]. However, creating fair grid tariffs that include DERs and EVs is complex and faces significant challenges [126].

Flexible pricing mechanisms must sync with the grid's carbon intensity [128], the 'price elasticity of demand' for EV charging, and price elasticity variations for different income groups [137]. Flexible electricity pricing can promote EV adaptation and V2G trading, reduce operational costs, and enhance user convenience. They, however, can also increase regulatory uncertainty and market distortions [142].

Regulatory barriers and tariff designs also significantly impact the implementation and operation of local electricity markets (LEMs) employing P2P electricity trading among prosumers and consumers (see also table 2). Across EU countries, the regulatory frameworks for LEMs and P2P trading exhibit considerable variation, shaped by national laws, market structures, and grid conditions [129]. Differences emerge in the proximity, participation, and grid tariff requirements for ECs.

Lastly, the deregulation of electricity grids in many jurisdictions poses a hurdle as their integration into market frameworks encounters inevitable delays in updating grid codes and market rules [61]. This delay inhibits the effective utilisation of emerging technologies critical for transitioning towards low-carbon futures [140].

## 5. Complex interrelations and trade-offs between stakeholders' GSV challenges

Figure 4 is a conceptual illustration of the complex stakeholder interrelations in the electricity grid and the associated factors influencing GSV, outlined in table 2. As described in section 2, utility companies (grid operators and suppliers) play a critical role in managing power generation, transmission, and distribution to ensure reliability and efficiency across the grid. Hence, electricity flows from them to other stakeholders. However, the flow of electricity could be in the reverse direction for Prosumers, ECs and even Aggregators who are producers and traders of renewable energy [55]. In the process, financial exchanges could also be in both directions except in the case of the consumers, who rely mostly on energy imports. Demand flexibility is then optimised by the Aggregator and used to balance the distribution networks while the stakeholders involved can receive incentives for their demand response [72]. Therefore, we highlight a direct relationship between utility companies and the rest of the stakeholders, and the same for the aggregators. Between the consumers, prosumers and ECs, an indirect relationship exists (represented by the dashed lines in figure 4) as they are all directly connected to both the operators and aggregators but not necessarily to each other [202, p 5].

As a result of the engagement with the grid and their interrelations, there are (in)direct implications for other stakeholders. For example, the spatial and temporal mismatch in energy supply and demand [55, 56], and extreme weather-induced network disruptions faced by grid operators and suppliers [84, 89] (table 2), can have broader consequences for other stakeholders (table 3). This could be in the form of power outages for consumer households and businesses due to grid operator-induced load-shedding [91], and limited grid capacity to accommodate new renewable energy installations for prosumers, ECs and potential adopters (consumers) [16]. Challenges associated with cybersecurity risks, such as demand manipulation and remote shutdown of grid infrastructure by cyber attackers, can cause damage to household equipment, and difficulties for aggregators to optimise critical demand flexibility [95, 101]. Also, current volumetric grid charges, as discussed in the regulatory barriers (section 4.3.), do not reflect the actual grid utilisation and contribution of each customer and may lead to cross-subsidisation and unfair cost allocation for consumers [30, 118, 125]. Flexible tariffs offer consumers only marginal economic benefits [200]. Inequitable frameworks for energy markets and regulations can hinder the formation and integration of EC initiatives in the electricity grid [145].

Grid aggregators also experience challenges that could have (in)direct implications for others, such as with scheduling stakeholder flexibility to provide grid stability [70]. Potential implications from the literature, as outlined in table 4, are distortions in demand forecasts for grid operators and operational inefficiencies in monitoring and controlling DERs [199]. Furthermore, maintaining reliable electricity exports and imports for prosumers and ECs could prove challenging, impacting the economic viability of renewable energy investments [55, 167]. Also, the fluctuations in energy costs could contribute to EP for consumer households as much more of their income could be spent on energy bills [71, 167]. Cyberattacks such as power overloading, data theft, unauthorised transactions and identity fraud could create challenges in maintaining the integrity and security of customers' data and energy systems, thereby impacting public trust [92, 96]. This may also cause damage to essential grid infrastructure, requiring expensive, time-consuming restoration efforts that could impact further grid operations [100]. Regulatory barriers to investments in innovative aggregator services and business models could impede stakeholders' interest and participation in demand flexibility [105, 112], further hindering attempts at ensuring grid stability [199].

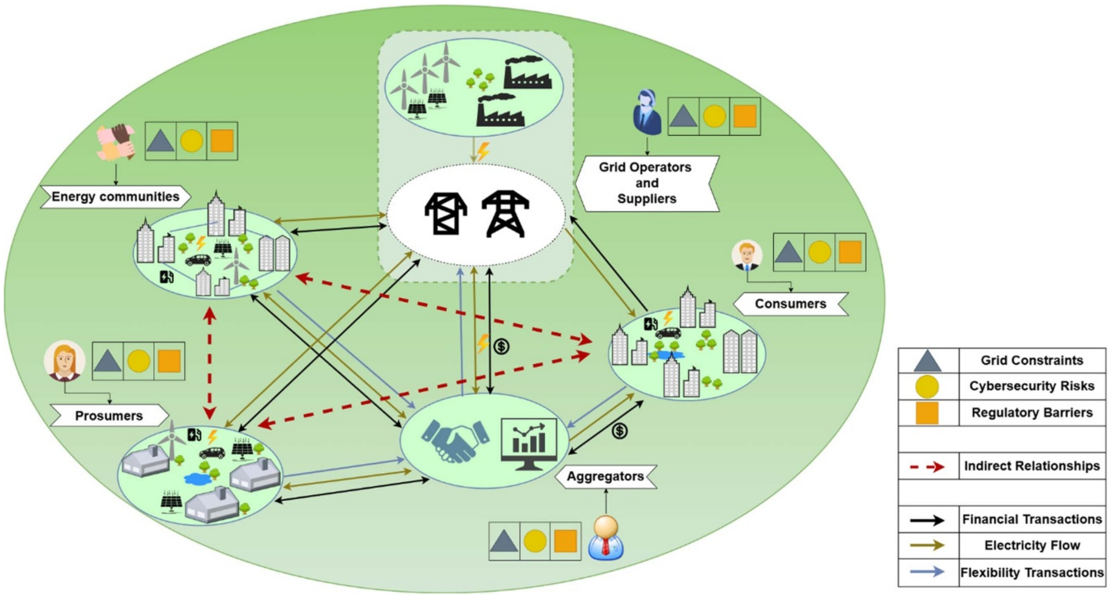


**Figure 4.** Stakeholders' (in)direct interrelations in the electricity grid and GSV factors.

Similar to how electricity grid challenges faced by aggregators can (in)directly impact other stakeholders, the rapid growth in decentralised ECs—varying in configurations, size, and prosumer ratios—can also contribute to grid congestion, exacerbating voltage violations and transformer overloads in distribution networks [33, 67]. The benefits of P2P trading in ECs are almost exclusively shared among prosumers while the late adopters could be vulnerable to inequalities in available hosting capacity for new renewable energy projects [80, 204]. For aggregators, more investments in technologies for managing and aggregating demand flexibility is required [66, 205], as outlined in table 5. Regulatory frameworks for local energy and flexibility trading within distributed networks can incite price disparities in P2P markets and widen socioeconomic inequalities within ECs [129]. It impedes aggregators' efforts to optimise community-based flexibility resources, causing sudden fluctuations in peak demand and supply periods [67].

For prosumers, their distinct energy consumption and production patterns introduce complexities to grid management, affecting forecasting accuracy and contributing to energy imbalances [69]. While, their growing self-consumption supports local energy use and generates economic benefits for community energy projects [33, 184], it may also have indirect implications for consumer households and businesses, as reduced grid operator revenues may be recovered through increased electricity prices [73, 194] (see table 6). It may further impact supply security and intermittency management for grid aggregators [74]. Inequitable regulatory frameworks for the participation of prosumers in LEMs that apply P2P energy trading may limit their formation and participation in EC initiatives [129, 145]. Furthermore, it may encourage unchecked prosumer trading activities that incite fluctuations in electricity prices and exacerbate demand peaks and grid feed-in during off-peak periods [204]. In line with the point of Mlecnik *et al*, it can translate to missed opportunities for the development of new aggregator products, services or business models that cater to the needs of prosumers [105].

Grid-related challenges of consumer households, businesses and industries, as seen in table 2, including inefficient energy use, variations in building occupancy patterns, and the rapid increase in energy demand, contribute to the sudden changes in demand profiles that prevent adequate grid optimisation [63, 64, 78]. Apart from the increased investments required for infrastructure upgrades [136], the grid aggregators' ability to optimise their portfolios and achieve cost-effective energy trading is affected [167] (table 7). On the positive side, there is a growing market for the sale of surplus clean energy to the grid [184, 212]. Flexibility mechanisms, like tariffs and incentives, risk commoditising household behaviours—engaging in demand flexibility mainly for financial benefits—potentially diminishing their participation in renewable energy generation [115], and indirectly exacerbating inequalities within EC initiatives [129]. The resulting unforeseen energy practices could create rebound effects in the electricity grid, such as increased use of energy storage or EVs [115, 130], and prevent reliable aggregators' demand flexibility services in response to rapid load balancing requirements [178].

**Table 3.** Implications of grid operators and suppliers' electricity grid challenges for other stakeholders.

| Grid operators & suppliers | Factors influencing GSV | Direct Impacts | | | |
|---|---|---|---|---|---|
| | | Consumers | Prosumers | Energy communities | Aggregators |
| | Grid constraints | Power outages [84, 85, 87, 89, 91]<br>Reduced power quality [15]<br>Higher electricity bills [88] | Higher feed-in tariffs,<br>Hinders the economic viability of RE investments, and limits the adoption and trading of clean energy [88, 156] | | Potential penalties for not meeting contractual obligations [55] |
| | | Limited grid capacity to accommodate new RE installations [16, 80] | | | |
| | Cybersecurity risks | Potential power outages and damages to household equipment [101, 103]<br>Higher electricity bills and grid taxes to compensate for the revenue losses from energy suppliers [103]<br>Challenges in maintaining the integrity and security of customers' data and energy systems, thereby impacting public trust [95, 101] | | | Challenges in optimising grid aggregation requirements [93]<br>Tighter regulations and standards for grid cybersecurity, potentially increasing costs [98, 102] |
| | Regulatory barriers | Encourages cross-subsidisation and unfair cost allocation to consumers [125, 138, 201] | Impacts prosumer competitiveness in the electricity market [30, 132] | Hinders the formation and integration of energy initiatives in the energy grid [140, 145] | Impedes the assimilation of innovative aggregator business models, technologies, and services in the energy grid [105, 112] |
| | | Delays the integration of renewable energy sources into the grid [147] | | | |

**Table 4.** Implications of aggregators' electricity grid challenges for other stakeholders.

<table>
<tr><th rowspan="2">Aggregators</th><th rowspan="2">Factors influencing GSV</th><th colspan="4">Direct impacts</th></tr>
<tr><th>Consumers</th><th>Prosumers</th><th>Energy communities</th><th>Grid operators & suppliers</th></tr>
<tr><td rowspan="2"></td><td rowspan="2">Grid constraints</td><td colspan="2">Fluctuations in energy costs [71, 167]<br>Reduced economic benefits, customer comfort and satisfaction [167]<br>Damages to household appliances and financial losses [166]</td><td></td><td rowspan="2">Distortion in demand forecasts [70]<br>Power losses [203]<br>Operational inefficiencies in monitoring and controlling DERs [199]</td></tr>
<tr><td></td><td colspan="2">Partly grid-dependent customers may experience challenges in maintaining reliable electricity imports [55, 167]</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Cybersecurity risks</td><td colspan="3">Possible power disruptions [96]<br>Increased vulnerability to electricity price attacks [100]<br>Challenges in maintaining the integrity and security of customers' data and energy systems, thereby impacting public trust [92, 96, 97]</td><td rowspan="2">Attacks distort demand forecasts, cause blackouts and damage to essential grid infrastructure, requiring expensive, time-consuming restoration efforts [100]</td></tr>
<tr><td></td><td colspan="2">Breaches on aggregator platforms may impact the export of excess generated energy [97]</td></tr>
<tr><td></td><td>Regulatory barriers</td><td colspan="3">Limits the availability and adoption rate for innovative aggregator services, and technologies that could enhance energy efficiency and affordability for customers [112]<br>Impedes customers' interest and participation in demand flexibility business models (a potential new revenue stream) [105, 112]</td><td>Hinders load balancing efforts from demand response programs [199]</td></tr>
</table>

**Table 5.** Implications of ECs' electricity grid challenges for other stakeholders.

<table>
<tr><th rowspan="2">Energy communities</th><th rowspan="2">Factors influencing GSV</th><th colspan="2">Indirect impacts</th><th colspan="2">Direct impacts</th></tr>
<tr><th>Consumers</th><th>Prosumers</th><th>Aggregators</th><th>Grid operators & suppliers</th></tr>
<tr><td rowspan="4"></td><td rowspan="2">Grid constraints</td><td>Inequalities in available hosting capacity for late adopters of renewables [67, 80]</td><td>Benefits of EC trading are almost exclusively shared among prosumers [204]<br>EC configurations impact the economic viability of prosumers investments [33, 179, 207]</td><td rowspan="2">More investments in technologies for managing and aggregating demand flexibility [66, 205]<br>Enhanced flexibility portfolio from a diverse pool of community DERs [68]</td><td rowspan="2">Voltage violations, transformer overloading and substantial investments in grid upgrades from increased distributed generation, i.e. in (rural) areas with limited capacity [33, 67, 68]</td></tr>
<tr><td colspan="2">Opportunities for participating in local energy initiatives for trading clean and cheap energy [33, 205, 208, 209]</td></tr>
<tr><td>Regulatory barriers</td><td>Inequitable distribution of grid financing costs among consumers [129]</td><td></td><td rowspan="2">Impedes efforts to optimise community-based flexibility resources [129]</td><td rowspan="2">Sudden changes in peak demand and supply periods due to unregulated profit-centric behaviours [67]</td></tr>
<tr><td colspan="3">Price disparities in P2P markets and widening socioeconomic inequalities within ECs [204]<br>Limits the formation and participation in EC initiatives [129, 145]<br>Hinders participation and benefits of local energy and flexibility trading [184]</td></tr>
</table>

*Note*: Cyberattacks on the electricity grid, according to the literature, are mostly targeted at utility companies and aggregators platforms, and the impacts reaching other stakeholders. Hence, only tables 3 and 4—on grid operators and aggregators, respectively—highlight the implications of cyberattacks for other stakeholders. However, there is growing concern that with increased digitalisation and IOT, the other stakeholders could be targeted directly [99].

**Table 6.** Implications of prosumers' electricity grid challenges for other stakeholders.

| Prosumers | Factors influencing GSV | Indirect Impacts | | Direct Impacts | |
|---|---|---|---|---|---|
| | | Consumers | Energy communities | Aggregators | Grid operators & suppliers |
| | Grid constraints | Inequalities in available hosting capacity for late adopters of clean energy systems [16, 58, 81, 116]<br>Consumers bear the cost of infrastructure expansion [18, 194] | Fosters local energy use, and economic benefits for community energy projects [33, 184] | Forecast uncertainties and insufficient demand flexibility to meet load-balancing requirements [70, 119]<br>Self-consumption impacts supply security and intermittency management [74] | Complexity in data collection [210]<br>Rising grid investments in upgrades [6, 18, 151, 162]<br>Grid instability, and transformer overloading [59, 61, 159, 211]<br>Energy losses [59, 60]<br>Revenue losses from increased self-consumption [74, 75] |
| | Regulatory barriers | Fluctuating electricity prices from unchecked prosumer trading activities [204, 212]<br>Higher electricity bills [126] | Limits the formation and participation in EC initiatives [129] | Hinders the creation of innovative aggregator products and business models [105] | Grid feed-in during off-peak periods [204]<br>Inefficiencies in network planning [129, 184] |
| | | | | Impedes the utilisation of distributed renewable energy resources for grid flexibility, balancing, and ancillary services [182] | |

*Note*: See notes in table 5.

**Table 7.** Implications of consumers' electricity grid challenges for other stakeholders.

| Consumers | Factors influencing GSV | Indirect impacts | | Direct impacts | |
|---|---|---|---|---|---|
| | | Prosumers | Energy communities | Aggregators | Grid operators & suppliers |
| | Grid constraints | Existing market for the sale of surplus clean energy in the electricity grid [184, 212] Increased overall energy costs and feed-in tariffs hinder the economic viability of renewable energy investments [72] | | Challenges in optimising their portfolios and achieving cost-effective energy trading [167] | Increased peak demand and investments in upgrades [49, 51, 78] Load shedding and unbalanced distribution networks [48, 80] Sudden changes in demand profiles [63, 64] |
| | Regulatory barriers | Flexibility mechanisms risk commoditising household behaviours, potentially diminishing their participation in renewable energy generation [115] | Exacerbated inequalities among members of energy initiatives [129] | Limits access to real-time information and demand flexibility for responding to rapid load-balancing requirements [178] | Uncertainty in recouping grid investments [127] Hinders savings in capacity and transmission costs [128, 136] Unforeseen energy practices create rebound effects [106, 115, 130] Inequitable incentives and greater investment in upgrades [104, 108] |
| | | Prevents the freeing up of grid capacity necessary for integrating generated renewable energy [107, 133, 185] | | | |

*Note*: See notes in table 5.

Although prosumers and ECs are clean energy producers, they may still be dependent on the electricity grid for some or part of their energy imports; hence, there are some shared implications with consumer stakeholder groups (cf tables 3 and 4). There are also shared implications between the prosumers and ECs, which consumers may not experience. Similarly, implications peculiar to ECs, are seen in tables 5–7. This is because ECs, unlike prosumers, are legal entities with multiple partners.

## 6. Integrated solutions approach to tackling GSV

In the face of rising inequalities among stakeholders in the energy transition, innovative, integrated and adaptive solutions, rather than one-size-fits-all, are needed to harmonise stakeholders' interests, taking into account their GSV challenges. In this section, we synthesis based on the literature, an integrated approach to tackling GSV and the implications for other stakeholders, drawing upon key strategies from the literature outlined in table 8. An integrated solutions approach in the European energy transition requires supportive policies, regulatory frameworks and market-based mechanisms combined with technological integrations, innovations and consumer engagement, to facilitate a resilient and equitable electricity grid.

Supportive policies in this case are aimed at addressing inequalities in the energy transition by redistributing costs and benefits more equitably, ensuring that vulnerable stakeholders receive support while the privileged ones take more responsibility. These policies aim to promote mutually beneficial stakeholder engagement in the transition. For example, consumer-centric energy policies and investment incentives can encourage investments in energy hubs for low-income consumer households living in rented apartments, who ordinarily do not have access to rooftop spaces for PV installation. They can also encourage the participation of vulnerable households in forming community energy projects by prioritising grid connection for renewable energy, ensuring affordable connection prices and the active involvement of local authorities. This is because many of these ECs are in more affluent neighbourhoods with higher grid capacities, and can afford to spend more for the necessary upgrades [16, 18].

Concerning feed-in capacity limits, technological innovations such as household and community energy storage, including stationary batteries and EVs, can soak up excess generated clean energy behind the meter and from the grid, freeing up capacity for more supply. This can be encouraged especially among prosumers by introducing feed-in limits for excess renewable energy exports to the grid [59, 223]. However, it is also important that while we control excess feed-in, there should be a counter policy introducing self-consumption charges, to ensure grid stability and availability of cheap and clean energy supply for consumers including businesses and industries [73]. This would help to control the rate of energy islanding—disconnection from the grid for energy-self-sufficient households [148, p 108, 230]. It will also ensure that costs are not redistributed among fewer consumers [195], potentially triggering a 'death spiral' where the grid becomes unsustainable due to diminishing participation and rising costs [231]. Such solutions, combining supportive policies and technology to check the levels of self-consumption and feed-in, could minimise revenue loss for grid operators while hedging consumers against rising electricity bills and EP.

Next, regulatory frameworks can improve stakeholders' access to grid services by providing a structure to ensure compliance with electricity grid standards and goals for an equitable energy transition. For instance, regulations for infrastructure reinforcement and insulation to enhance resilience under weather uncertainty. Regulations aimed at compensating customers, including households, businesses and industries, for energy supply interruptions, spur grid operators to minimise restoration times, reduce interruptions, and consider backup options like on-site heat and power production to maintain reliability and service quality. The standardisation of communication protocols across different energy devices and systems is fundamental to achieving and ensuring the integration of innovative aggregator services and technologies that could enhance energy efficiency and affordability [146]. Also crucial are frameworks to facilitate the development of new market mechanisms for deploying flexible energy solutions and demand response technologies, making them economically viable and technically feasible for vulnerable households, and updated grid codes to accommodate the increasing penetration of prosumer DERs [61].

Market-based mechanisms rely on energy market design and economic measures to guide and ensure fair and inclusive engagement of consumers and prosumers. They should be designed to be flexible enough to adapt to changes in the electricity market by efficiently allocating resources to drive innovation and stakeholders' participation in the transition, through market signals. Flexible grid tariff structures and energy taxes could incite smart energy management using smart meters, enabling consumers to be more intentional about their electricity use [133, 185]. This would engage the residential, non-residential and industrial consumers in shaving demand peaks through demand flexibility, minimising network fluctuations that require aggregation services and expensive investments in

**Table 8.** Strategies for addressing GSV.

| Main categories | Examples | References |
|---|---|---|
| Technological integration and innovation | | |
| Smart energy management | Home energy management system | [68, 97, 213] |
| | Smart energy hubs | [94] |
| | Smart meters for smart grids | [95, 98] |
| Grid enhancement | Grid infrastructure reinforcement, insulation and expansion | [6, 18, 77, 87, 89, 147, 151] |
| | Active power management in low voltage networks | [60] |
| | On-site combined production of heat and power | [157, 214] |
| | Enhancing hosting capacity for DERs via optimal load re-phasing | [80] |
| | Enhancing grid infrastructure resilience under weather uncertainty | [85, 86] |
| Energy storage | Energy storage solutions—household and community energy storage | [56, 59, 67, 155, 157, 205, 209, 215, 216] |
| Advanced grid technologies | Blockchain technologies and ML-based frameworks in energy systems | [65, 93, 99–101, 103, 158, 187, 217] |
| Electric vehicles | Flexible EV services: vehicle-to-Grid and Smart charging of EVs | [15, 47–51, 62, 116, 150, 153, 163, 203, 218–222] |
| Policy and regulatory frameworks | | |
| Supportive policies | Policy frameworks that match energy consumer preferences to encourage electricity storage, energy-saving measures and demand flexibility activities | [104–115, 138, 181] |
| | Introducing self-consumption charges | [73–75] |
| | Introducing feed-in limits for excess renewable energy exports to the grid | [59, 223] |
| | Consumer-centric energy policies and investment incentives to enable participation of the most vulnerable population in the energy transition | [16, 58, 81, 88, 119–123, 183] |
| | Customer-centric energy policies for P2P energy trading | [92, 124] |
| | Policies that encourage the formation of community energy projects | [33, 145] |

(Continued.)

**Table 8.** (Continued.)

| Main categories | Examples | References |
|---|---|---|
| Regulatory frameworks | Infrastructure upgrades, and investment incentives for smart grids | [91, 122, 148, 149] |
| | Integrating new grid codes and market mechanisms for facilitating innovative and flexible grid solutions towards the energy transition | [61, 71, 139–144, 224] |
| | Standardisation of communication protocols for energy devices and systems | [146, 148] |
| | DSO-TSO cooperation for grid congestion management | [26, 138] |
| Market design and economic incentives | | |
| Economic measures | Fairer grid tariff designs and energy taxes | [30, 76, 118, 122, 125–137, 182, 183, 185, 194, 197] |
| | Locational incentives for future renewable energy projects | [58] |
| Energy trading and markets | P2P energy trading, local energy and flexibility market design | [47, 82, 152, 156, 160, 178, 184, 204, 208, 212, 225] |
| Consumer engagement | | |
| Sector-specific Demand response | Demand response in the residential, non-residential and industrial sector | [52–55, 57, 64, 66, 70, 72, 78, 79, 161, 164, 166, 199, 206, 211, 226–229] |

infrastructure upgrades. A tariff structure, with maximum and minimum limits for grid charges around the average rate coupled with a capacity-based tariff for prosumers' grid exports, could address the unfair cross-subsidisation of solar prosumers by consumers in current electricity grid tariff designs by redistributing costs more evenly.

Furthermore, the location of future renewable energy projects might be a relevant consideration from the socio-economic welfare point of view when private decisions might affect the power system efficiency [58, 232]. Incentives for new projects are necessary for discouraging such developments in areas where the demand is not, as this could constrain locations for future hosting capacity and raise energy prices. Also important is the design of equitable P2P electricity markets, since the benefits are almost exclusively shared by prosumers (see section 5 and table 5). With the increasing volatility in the public market, prosumers could mostly benefit as they can buy electricity from the grid when prices are low, and sell at high margins in later periods when public electricity prices are high [204]. This would send prices soaring in the P2P markets, incite socio-economic inequality among stakeholders and discourage the formation of ECs.

## 7. Conclusion

The electricity grid, central to the energy transition, faces challenges due to the rapid decentralisation and digitalisation of energy systems. These developments on the already ageing grid hinder its ability to support inclusive and equitable stakeholder engagement [7]. Stakeholders including utility companies, aggregators, ECs, prosumers and consumers, can face an unequal distribution of costs and benefits vis-à-vis grid services due to technical, economic, spatial, and legal challenges arising from the grid limitations. We refer to this as GSV, providing a societal perspective to GV from the power systems literature. Consequently, this leads to disparities, where some benefit significantly while others bear disproportionate burdens.

The literature mostly focuses on the disparities in access to hosting capacities for installing new renewable energy projects and grid congestion due to the increased energy demand from households and businesses [13, 16–18]. However, there is still no comprehensive study identifying factors influencing GSV despite its pressing nature, nor on the corresponding challenges vis-à-vis stakeholders. This study contributes to the literature by developing a comprehensive view of GSV and stakeholder implications through a systematic review of 185 peer-reviewed articles in the European context, as well as synthesis based on the literature, an integrated solutions approach to tackle GSV.

Three major factors influencing GSV are identified, namely, grid constraints, cybersecurity risks and regulatory barriers. The literature highlights various primary causes of grid congestion; however, it often fails to differentiate between congestion originating from feed-in capacity limits (supply-side) and demand-side issues challenging stakeholders' participation. Also, cyberattacks threaten the integrity and efficiency of the electricity grid and are particularly targeted at disrupting grid infrastructure. However, the resulting stakeholders' challenges, encompassing a range of issues, extend beyond technical vulnerabilities for the utilities and aggregators. They also impact consumers' and prosumers' confidence and engagement in the energy transition. Complex interrelationships exist between stakeholders in the electricity grid, and as a result, there are (in)direct implications of their grid challenges for other stakeholders, which in some cases can contribute to EP. Consequently, a uniform policy approach to tackling GSV and inequalities risks neglecting vulnerable groups in the pursuit of net zero goals.

In essence, policy decisions may have unintended implications, especially for vulnerable stakeholders. For instance, demand flexibility instruments, rather than curbing energy use, may spawn counterproductive behaviours like the increased reliance on energy storage or EVs, leading to rebound effects—shifting peak demand times to other times in the day—on the electricity grid. This could disrupt demand forecasts and even electricity prices. These indirect implications may not be totally avoidable, as the perfect policies for tackling GSV and inequalities in the energy transition may not exist. Therefore, an integrated solutions approach based on the comprehensive understanding of GSV and the implications for stakeholders is crucial.

Insights from the study can inform future policies and studies for a more equitable energy transition. By recognising GSV and the (in)direct implications for stakeholders, policymakers can put measures forward that are more effective, adaptable, and equitable, to achieve a fair and sustainable energy future. Also with increased digitalisation, future cyberattacks could be more targeted at households and businesses, i.e. through security gaps in their electrical appliances and EVs while connected to the grid. The cybersecurity literature makes up 9% of the study on these societal perspectives and should warrant more attention. Further studies can explore policy-backed innovations, like blockchain technology to address cybersecurity risks in the energy transition. Other studies can also explore the interconnections of GSV and transport poverty, particularly as the growth of e-mobility relies on users' access to an adequate network of charging stations, which is constrained by the electricity grid's limited capacity.

## Data availability statement

No new data were created or analysed in this study.

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## Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix

Search String: ('Prosumer*' OR 'Consumer*' OR 'Household*' OR 'Energy community*' OR 'Community energy' OR 'Community renewable energy*' OR 'Energy cooperative*' OR 'Energy vulnerability*' OR 'Grid vulnerability*' OR 'Energy Justice' OR 'Energy poverty' OR 'Distributed energy') AND ('Energy grid' OR 'Power grid' OR 'Electricity grid' OR 'Grid capacity*' OR 'Hosting capacity*' OR 'Grid limit*' OR 'Grid congestion*' OR 'Distribution congestion*' OR 'Network constraint*' OR 'Distributed* network' OR 'Transmission network')

**Table A1.** Selection criteria for identifying relevant articles on GSV for the study.

| Steps | Criteria | Decision | Reason |
|---|---|---|---|
| 1 | Articles focusing on countries outside of Europe. | Exclude | The research scope focuses on studies within the European context. |
| 2 | Articles of a technical/non-technical nature on the electricity grid, exploring the intersection of social and equity challenges in the energy transition, including; | | |
| | a. Articles exploring various perceptions on the limitations of the fixed electricity grid and the impact on stakeholders in the energy transition. | Include | The research objective is to understand GSV, identify the key influencing factors and the corresponding challenges vis-à-vis stakeholders. |
| | b. Articles addressing the challenges stakeholders face in actively participating in the energy transition due to the inequalities in accessing reliable connections in the electricity grid. | Include | The research scope focuses on the implications of GSV for stakeholders. |
| | c. Articles analysing solutions to the issues plaguing the electricity grid and causing inequalities among stakeholders in the energy transition. | Include | The study aims to identify key strategies for tackling GSV (i.e. through policy interventions, technological advancements, etc) and ensure equality for stakeholders in the energy transition. |
| 3 | Articles analysing solutions to electricity grid-related challenges, with no intersection with stakeholders' concerns and equity issues with respect to the electricity grid. | Exclude | It goes beyond the research scope. |

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