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Grid impact of photovoltaics, electric vehicles and heat pumps on distribution grids — An overview☆

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ABSTRACT

Distributed generation, such as photovoltaics (PVs), and electrification of heating and transportation with heat pumps (HPs) and electric vehicles (EVs) will play a major role in the energy transition. However, these low-carbon technologies (LCTs) do not come without side effects such as voltage violations, power loss increase, component overloading, higher energy consumption, power peaks, and power quality issues, e.g., harmonics and phase unbalance. This work constitutes a review analysis and summary of all the important findings concerning the various grid impact issues that can appear due to the grid integration of these 3 LCTs. The work also encapsulates various research characteristics such as grid topology, seasons, simultaneous operation under various LCT combinations, penetration levels, etc. Moreover, it incorporates a qualitative analysis of the impact level of the most investigated grid issues and quantitative comparisons between the different grid types and LCTs. It has been shown that the combined integration of PVs-EVs and PVs-HPs can result in mitigation effects without extra solutions. Moreover, voltage deviations and unbalance affect more the rural grids while component overloading is more hazardous for suburban grids. Finally, proposed mitigation solutions, such as energy storage, smart charging, etc., are correlated with their respective grid impact issues.

1. Introduction

1.1. Energy transition and Low-carbon Technologies (LCTs)

Energy transition, one of the main focuses of the research community, represents the transition of the energy system's generation and consumption from fossil-fueled to renewable due to the ongoing depletion of fossil fuels and increased carbon emissions [1]. In this regard, 197 nations committed themselves to reducing carbon emissions and keeping global warming under 1.5 °C until 2050 with the "Paris Agreement" in 2015 [2]. Moreover, several European governments pledged to increase the carbon emission goal in 2030 to at least 55% compared to 1999 in the "European Green Deal" of September 2020 [3].

Concerning the global and European carbon emissions, the residential and mobility sectors constitute two of the main contributors. On the one hand, an analysis of 27 European countries (EU-27) found that the residential sector accounts for 24–26.7% of the total annual energy use in 2010, which is mainly fossil-fueled [4]. It also contributed to 70% of the total carbon emissions in 2011 in [5]. Furthermore, residential heating, one of the main parts of the residential sector, is mostly produced by gas-fired boilers in most European countries, e.g. in 84.2% of UK households. On the other hand, 99% of the passenger vehicles in the UK in 2017 were conventional internal combustion engine (ICE)-powered vehicles [1]. Additionally, heating and mobility sectors were reported to be jointly responsible for 60% of all carbon emissions in [6]. Finally, Fig. 1 depicts a more recent published analysis by Eurostat [7], where the mobility sector and buildings account for 23.2% and 15.4% of the total European emissions, respectively.

Therefore, energy transition is responsible for the introduction of multiple technological advances during the recent decades. Important examples are, on the one hand, the emergence of Distributed Energy Resources (DERs), such as Photovoltaics (PVs) [8] for renewable energy generation, and on the other hand, the electrification of demand (transportation and heating) with the transition to Electric Vehicles (EVs) and Heat Pumps (HPs) from ICE-powered vehicles and gas heating, respectively [9,10]. Hence, PVs, EVs, and HPs are considered highly important factors in the energy transition's success and generally fall into the category of low-carbon technologies (LCTs).

However, concerns have risen about the huge forthcoming grid impact that will be provoked by the higher penetrations of the aforementioned technologies and the potential negative consequences to

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Nomenclature

AC	Alternate Current
APF	Active Power Filter
BE	Baloon effect
BES	Battery Energy Storage
C	Cable
CHP	Combined Heat & Power
DC	Direct Current
DER	Distributed Energy Resources
DF	Distribution Feeder
DG	Distribution Grids
DH	District Heating
DL	Distribution Line
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EMS	Energy Management System
EoL	End-of-Life
ES(S)	Energy Storage (System)
EV	Electric Vehicle
FC	Fast Charging
FSPV	Floating Solar Photovoltaics
G2V	Grid-to-Vehicle
GSHP	Ground Source Heat Pump
HD	Heavy-duty
HF	High Frequency
HH	Household
HHO	Harris Hawks Optimization
HP	Heat Pump
HV	Heavy Voltage
ICE	Internal Combustion Engine
LCOE	Levelized Cost of Electricity
LCT	Low-carbon Technology
LS	Load Shedding
LV	Low Voltage
MCS	Monte-Carlo Simulation
MV	Medium Voltage
NZE	Near-zero-energy
OH	Overhead
OL	Overloading
OLTC	On-load Tap Changing
PDF	Probability Distribution Function
PEV	Plug-in Electric Vehicle
PF	Power Factor
PFC	Power Factor Correction
PQ	Power Quality
PV	Photovoltaics
RES	Renewable Energy Sources
RPF	Reverse Power Flow
SC	Smart-charging
SOP	Soft-open Point
T/F	Transformer
TES	Thermal Energy Storage
THD	Total Harmonic Distortion
TIC	Total Imbalance Cost
TOU	Time-of-use
V2G	Vehicle-to-grid
VUF	Voltage Unbalance Factor

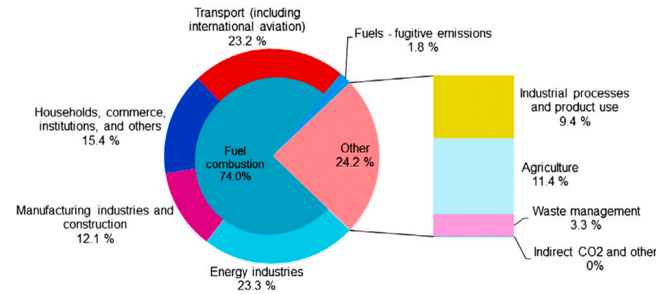

Fig. 1. Greenhouse gas emissions by source sector, EU, 2020 (Eurostat [7]).

future transmission and distribution grids. For example, power quality issues, such as voltage fluctuations and flickering, are caused by intermittent and stochastic PV generation (45%–90% PV output fluctuations due to clouds and changing weather conditions), which can consequently damage electric appliances connected to the network [11]. Moreover, phase imbalance is induced by a high number of connections of single-phase LCTs in different phases (uneven loading), such as residential PVs and HPs or low rated-power EVs [12] with more than 70% UK low-voltage (LV) grids were to reported to have imbalance violations in [13]. Additionally, high penetrations of additional loads, such as EVs and HPs [2,4], provoke already excess energy demand and increased peak power levels, which inevitably cause high grid congestions, especially on the distribution level [14]. For example, the Dutch North Brabant province has already banned the further connection of commercial/industrial loads due to inadequate grid capacity and high expected grid congestion. Overloading of components, such as distribution transformers and lines, constitutes another major product of the higher energy demand and power peaks [6,15], while intolerable voltage violations are seen in both rural and urban grids; over-voltage and under-voltage events by PV and EV/HP integration, respectively [5,16]. Finally, all the above grid issues already decrease the LCTs' grid hosting capacity, preventing their further adoption and integration [17].

Multiple works have been published regarding the individual and combined impact of the future integration of EVs, PVs, and HPs. These works highly differ regarding the investigated grid cases and seasons, LCT combinations and penetration levels, proposed mitigation solutions, consideration of uncertainties, etc. Multiple literature review papers have been published that comprise and summarize the existing knowledge about the grid impact of the individual integration of these technologies, especially of the PVs and EVs. However, according to the author's knowledge, a comprehensive review paper incorporating and comparing insights about the grid impact of combinations of PVs, EVs, and HPs is still missing from the existing literature.

1.2. MV-LV distribution grid topology and LCT connections

A simplified one-line schematic of the power grid and the most common load and LCT connections is depicted in Fig. 2, adapted from the work in [18]. The power grid comprises mainly the transmission and the distribution network. The transmission network is generally heavy-voltage (HV) with voltage levels above 100 kW, is characterized by a meshed topology, and is where all main large, mostly conventional power generation stations are connected. Moreover, large commercial and industrial loads may be connected directly to the HV transmission network. On the contrary, the distribution network is categorized into the medium-voltage (MV) part with a voltage level range of 1–35 kV and the low-voltage (LV) part with voltage levels below 1 kV. LCTs such as solar and wind parks and large-scale energy storage systems (ESSs), e.g. batteries, as well as medium-sized commercial/industrial loads, are usually connected to the MV distribution grid. Buildings with

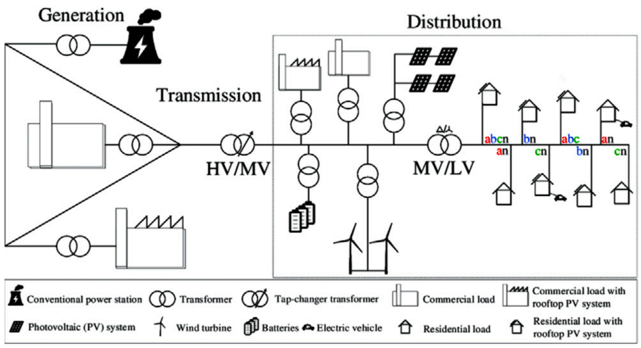

Fig. 2. Power grid schematic with different load and LCT connections [18]. (ccby https://creativecommons.org/licenses/by/4.0/).

or without PV rooftops and HPs (such as households, stores, and offices) and EV chargers are connected to the LV distribution grid. It must be noted that EV fast chargers are mostly connected to the MV distribution grid due to their high-rated power (above 50 kW).

1.3. Literature review search strategy

The search strategy followed in this literature review was based on the following criteria. This study is mostly focused on the grid impact issues of the combined LCT integration in distribution grids. For a better understanding of the combined integration impact, it was considered important to include the most recent works (after 2020) that also assessed the grid impact individually for each LCT. The main search words that have been used during the literature review study were: “grid impact” and all the related issues “over-/under-voltage, overloading, unbalance, power quality, harmonics, hosting capacity, power-consumption profiles, power factor, energy/power losses”, all combinations of “LCTs” (“PVs, EVs, HPs”) and “distribution grids”. Search platforms that have been used are “IEEE Explore, Researchgate, ScienceDirect, Elsevier, Web of Science, and Google Scholar”.

Moreover, the literature review comprises the studies that are mainly focused on the grid impact assessment. Hence, the review considered as an important criterion that the work either is holistically about the grid impact of an LCT or calculates the impact in a case study (usually the base case) and uses other case studies to apply mitigation solutions. As a result, purely mitigation studies, such as power control or smart charging studies, are out of the scope of this review. An included work must always comprise a case where the LCT impact is calculated without any control/mitigation method and is added to the category “Analyzed Research Studies with Mitigation Solutions” if it also applies mitigation measures.

1.4. Contributions

This review paper summarizes the state-of-the-art knowledge about the various grid impact issues caused by grid integration of PVs, EVs, and HPs. It incorporates important research characteristics, such as different penetration levels and combinations, seasons, distribution grids and grid types, uncertainty management techniques, and followed approaches. Moreover, the work provides a qualitative analysis of the impact level inflicted by the different LCT combinations and quantitatively compares the different LCTs and distribution grid types regarding the most investigated grid impact issues. Finally, it summarizes the investigated mitigation solutions and correlates them with the various grid issues. In this regard, the contributions of this review work can be summarized as follows:

- Investigates the various grid impact issues from grid integration of PVs, EVs, and HPs considering the studied penetration levels and combinations, seasons, distribution grids and grid types, uncertainty management techniques, and followed approaches. While such investigations exist individually for each technology (e.g. PVs or EVs), a combined analysis which shows the interactions of these 3 LCTs regarding the grid impact issues when integrated combined, is still missing from the literature.
- Performs qualitative analysis of the level of the inflicted grid impact by different LCT combinations and quantitatively compares it concerning different distribution grid types and LCTs. The interrelated effect of the characteristics of different distribution grid types with different LCT integrations on the level of the various grid issues has not yet been investigated in earlier review works.
- Analyzes the various investigated mitigation effects and solutions for each combined LCT integration in grid impact assessment studies, and correlates them with the appropriate grid impact issues. According to the authors’ knowledge, this analysis is realized for the first time for PVs, EVs, and HPs together and their combined grid integration.

1.5. Organization

The rest of this work is categorized as follows: Sections 2 and 3 comprise the grid impact of individual and combined LCT integration of PVs, EVs, and HPs, respectively. As already explained, due to the abundance of works related to the individual impact of the LCTs, Section 2 comprises only the most recent works (from 2020 and onwards), while most focus has been placed on Section 3 and the combined impact. For more knowledge on the individual impact, the reader is referred to the existing related literature review papers summarized in Section 3. Finally, Sections 4 and 5 comprise the discussion and the conclusions of the work, respectively.

2. Individual impact of considered technologies

2.1. Impact of electric vehicles

2.1.1. Analyzed research studies

The future grid impact of the electrification of transportation on the power grid has been studied extensively. EV charging load profiles have been analyzed in [9]. According to their findings, future EV integration will have a significant impact on the future energy mix and increase global electricity consumption up to a 20% level, while excessive peak loads can jeopardize grid stability. Moreover, work-dominant and home-dominant EV charging profiles have been analyzed in distribution feeders (DFs) that comprised residential, commercial, and industrial loads in [19]. While the load rise and, consequently, the line loading and voltage deviations were generally more significant in feeders with residential loads, critical issues were also seen for commercial feeders that were characterized by highly concentrated EV charging. In addition, line loading and voltage deviations were studied for different population areas (rural, suburban, and urban) of developing countries in the probabilistic analysis of [20] using a Monte-Carlo Simulation (MCS) approach. However, it was concluded that no grid upgrades were needed for these case studies since a maximum of 40% and 20% load increase was seen for the transmission lines and transformers in the high EV integration scenario of 2030, respectively. The same conclusions were drawn for the overloading of lines and transformers in the MCS approach of [21] where no violations were observed for 10% and 30% EV penetration of the 2025 and 2030 case scenarios, respectively. In this study, focus has also been placed on the impact of plug-in EV (PEV) diversity on the power grid; however, the analysis was conducted in the IEEE 33-bus distribution network. The stochasticity of the various EV charging influencing factors with different grid impact issues has also been studied in the sensitivity analysis of [22]. It was found that transformer violations correlated more with charger types and penetration levels, while line violations were more dependent on the grid configuration. Finally, the stochastic nature of EV charging patterns has been considered probabilistically with MCS in [12] for the Irish and UK networks where voltage, unbalance, and overloading were analyzed for different penetrations and power levels. While low-power charging modes seemed to inflict no violations, charging above 11 kW can be crucial in future EV integration.

Additionally, peak power and consumption have been compared for uncontrolled and smart charging for 28 European countries in [23]. While a total rise of peak demand up to 35%–51% was observed with uncontrolled charging, smart-charging strategies could decrease it to 30%–41%. However, the observations were highly dependent on the grid characteristics of every instigated country. Moreover, the same comparison was investigated in [24] for the Australian electricity system, considering the levelized cost of electricity (LCOE). By generation profile and capacity analysis for different EV penetrations, a 205 GW installed capacity was needed for 100% EV integration. Furthermore, a technical and economic analysis of the entire European system was conducted in [25] considering both slow and fast charging integration until 2040. Results showed that the EU is ready to accommodate a high EV integration while smart-charging techniques such as vehicle-to-grid (V2G), dynamic charging, and time-of-use (TOU) could reduce the load growth even more. On the contrary, the use of case studies with uncontrolled charging, time, and daily synchronous charging in [26] for voltage and overloading violations in an MV power distribution grid (DG) in Frederiksberg resulted in different observations. It was seen that congestion could be more severe for smart charging techniques than uncontrolled charging if network constraints are not considered due to increased EV charging coincidence. Finally, the impact of uncontrolled and controlled charging on congestion management has been identified in [27]. Both V2G and G2V (grid-to-vehicle) modes have been considered in this load profiles and hosting capacity analysis; however, the investigation was conducted in the IEEE 38 bus radial distribution system.

2.1.2. Literature review studies

Several literature review works can be found that incorporate the forthcoming grid impact by future EV integration. Firstly, an extensive review of the impact of the EV chargers on the utility grid concerning renewable energy sources (RES) integration, grid stability, supply–demand balance, grid assets such as distribution lines (DLs) and transformers, grid voltage, harmonics, and losses has been conducted in [28]. Additionally, the authors in [29] reviewed the impact on the energy demand that different charging levels (namely AC level 1, AC level 2, and DC fast charging) will have in the USA, EU, and China by 2030. The work also incorporated the main limiting factors of EV charger acceptance and deployment in different countries. The impact of different charging levels on the electricity demand has also been reviewed in [30], where the average and peak load of distribution transformers have been summarized for different EV penetrations (0%–100%). Furthermore, EV integration's negative and positive impacts were comprised in the review works [31,32]. While negative impacts such as peak demand, phase unbalance, overloading, harmonics, and power losses could become crucial with high EV integration, positive impacts could also be seen, such as power quality improvement, congestion management, voltage-frequency regulation, and renewable energy support with power management techniques. In [33], the authors expanded their review analysis, focusing on the impact on power quality and power system equipment (e.g. different harmonic levels) that the different power electronics in the EV chargers will have, such as six- and twelve-pulse rectifiers, single-phase EV chargers with or without power factor correction (PFC), etc. Moreover, the analysis incorporated different distribution feeders, such as radial and parallel, with load curves by various population types (rural, suburban, urban).

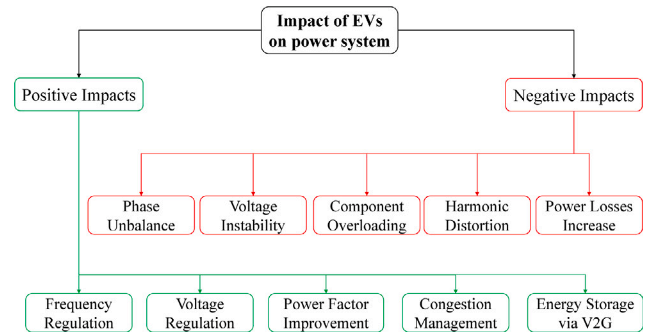

Fig. 3. Positive and Negative impacts of EV integration in future distribution grids. *Source:* Adapted by [32].

2.1.3. Fast-charging impact assessment studies

Finally, due to the vast current adoption of fast charging (FC) stations, some works focused on the future grid impact that FC will provoke. Voltage and load profiles due to heavy-duty (HD) charging have been studied and compared for an IEEE 34-bus system and a California distribution feeder in [34]. The grid case studies were categorized and clustered as worst, mediocre, and good locations for installing HD charging stations according to voltage deviations. Additionally, voltage and current harmonics have been analyzed in [35] due to slow and fast charging (50 and 350 kW) of HD EVs such as electric bus fleets. While the observations were encouraging for the current HD EV integration, supra harmonics of 3–4 kHz are expected with future slow and fast EV charging integration, which will not comply with the voltage quality standards of EN50160. Moreover, power quality issues such as voltage deviations, harmonic emissions, and stability have been reviewed in [36] as well as several trends, standards, architectures, and mitigation measures concerning the future high deployment of FC stations.

2.1.4. Key insights

Despite the differences between the outcomes of the existing works, there are some key insights that can be summarized about the grid impact of EV integration. Low-voltage (LV) distribution transformers in residential grids are more likely to be affected first under high penetrations of EVs, while the lines are also highly dependent on the grid topology. Phase unbalance, voltage deviations, component overloading, and harmonic distortion constitute grid impact issues that can appear due to future EV charging, especially at high power levels, such as FC. However, smart charging and V2G use can reduce substantially the power peaks and energy consumption as well as provide ancillary services, such as congestion management and frequency and voltage regulation [32]. Finally, the positive and negative results of EV integration are summarized in Fig. 3.

2.2. Impact of heat pumps

2.2.1. Analyzed research studies

Concerning the forthcoming impact of heating electrification on the distribution grids, peak power demand, annual consumption, load duration curves, and capacity utilization have been studied for 17 residential regions of the Texas electricity grid with a physics-based approach in [10]. While findings have shown that the grid capacity should be increased to deal with the increased Winter heating load, annual consumption remained similar due to energy saving by a more efficient HP Summer cooling load. Moreover, voltage, current, and reactive power dynamics have been analyzed in [15] regarding future HP integration and combinations with various heating appliances. Significant undervoltage and overloading incidents have been observed for extended periods, especially during extremely cold Winter days,

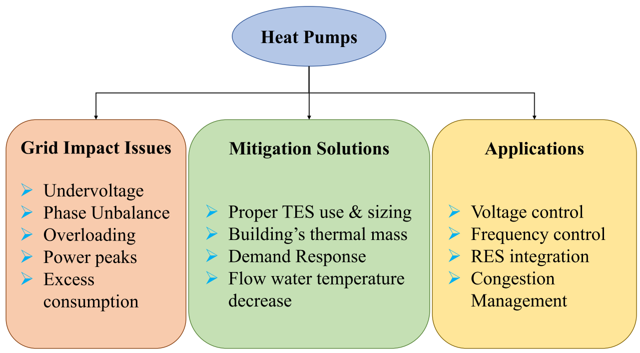

Fig. 4. Negative Impacts, mitigation solutions, and applications of HPs.

while the authors tested various mitigation strategies, such as using decentralized combined heat and power devices (CHPs), grid reinforcements, and PV inverters. Additionally, multiple cable overloading occurrences have been observed in a district heating (DH) connected Swedish area in [37] under full HP integration, showing that the heating infrastructure must remain DH-connected for at least 7% of the heating demand. However, the authors found that overloading could be eliminated if the buildings' thermal mass was used as thermal storage. Furthermore, HP integration with DH and different thermal energy storage (TES) sizes has been investigated in the physics-based approach of [38] under different electricity costs. It was shown that peak loads could be reduced with proper HP and TES sizing, while DH supported increased RES integration. The impact of HP integration with different RES generation mixes has also been studied by electricity consumption and emission factors calculation in [39], showing considerable differences in 10 European countries. Finally, authors in [40] focused on the comparison of future scenarios of national-level heat capacity generation by HPs and other heat sources (such as biomass or natural gas) while [41] investigated the future HP integration impact on frequency regulation and grid balance and reliability.

2.2.2. Literature review studies

In addition, several review papers on HP integration and, among others, its impact on future power grids can be found in the literature. For example, authors in [42] focused on providing a comprehensive review of the most important challenges of HP use for heating decarbonization, summarizing insights about the impact on the power sector as well as about different HP deployment techniques, multi-disciplinary approaches, financial and regulatory barriers, etc. The state-of-the-art findings about the impact of different HP technologies integration on consumption and flexibility potential have been integrated into [43] along with their economic and social acceptance aspects while the authors in [44] focused on future HP integration in different district heating and cooling networks.

2.2.3. Key insights

Overall, HPs will have a significant effect on the increase of energy consumption and power peaks during Winter and will cause overloading and voltage deviations in the future distribution grids. However, power peaks and overloading can be decreased with the building's thermal mass use, proper sizing of the TES, and demand response (DR). Moreover, HPs can also be used in applications of ancillary services, such as frequency regulation, voltage control, RES integration, and congestion management [45]. The grid impact issues, mitigation solutions, and applications of HPs are summarized in Fig. 4.

2.3. Impact of PVs

2.3.1. Analyzed research studies

The impact of individual PV integration has been studied more extensively. Hosting capacity analysis works can be found in [8,46,47]. The authors in [8] realized a multi-national hosting capacity assessment on a national and local level for Germany, Sweden, and the UK, considering the population heterogeneity in the different countries. Results have shown the estimated hosting capacities are correlated with the current generation capacity while the population density is inversely related to the sizing of the new PV integration. Moreover, the dynamic hosting capacity of PV integration has been assessed in real distribution feeders in [46] to also consider the duration and time dependence of voltage and overloading violations. The analysis provided more accurate results about power losses in the distribution lines and needed feeder upgrades. Finally, the effect of temperature and irradiation deviations on PV active and reactive power and voltage profiles has been investigated in [47] while the reaction against three-phase faults has also been studied. In addition, the impact of meteorological effects on PV generation profiles has been studied in [48] where it was found that irradiance was more strongly correlated with performance ratio and efficiency than temperature while capacity factor seemed to have less dependence on both. Moreover, according to the load profile analysis of a city in Pakistan before and after PV integration in [49], PVs could assist in load demand decrease and dependency decrease on fossil fuels, leading to higher diversification of the national energy mix.

Furthermore, the impact of multiple PV penetrations on harmonic distortion, voltage levels, and power losses of LV distribution grids has been investigated in [50], where other non-linear household loads and seasonal effects were also encapsulated. It was concluded in that case study that 50% was the optimum penetration since it improved the voltage profiles and harmonic distortion within the required levels. Voltage and current harmonics were also analyzed in [51] for PV and non-linear loads using both deterministic and probabilistic approaches for accuracy increase. Considering the uncertain character of both PV generation and load profiles, it was concluded that low irradiance leads to higher harmonic levels. In [52], the focus has been placed on the spatial impact on PV integration impact, analyzing the dependence factors of voltage rise and unbalance in simulations of thousands of grids. Linear correlations were found between the PV capacity momentum and mean absolute deviation with the voltage rise and unbalance, respectively. On the contrary, voltage profile levels remained within the limits in the analysis of [53]. PV injections of 3–6 kWps decreased power losses even from 20% PV penetrations while voltage ranges were maintained between 0.97 and 1.05 p.u. complying with the required standards. Moreover, high frequency (HF) PV fluctuations were studied in [54] considering temporal effects, showing that the 15-minute interval that is usually studied in grid analysis works could significantly underestimate power peaks up to 22%. Moreover, the clouding factor has been concluded to be an important contributor to rapid PV power peaks. Finally, the Tunisian power system has been utilized in [55,56] to study the impact of future PV penetrations on voltage stability and regulation, respectively. In the former, it was found that while using STATCOM significantly affected voltage regulation, the voltage dynamics were highly dependent on the short-circuit grid capacity at the point of PV integration. In the latter, it was also shown that PV generation could positively affect voltage regulation due to solar generators' enhancement of reactive power capacity.

Additionally, a multi-impact analysis conducted in an Australian 11 kV distribution feeder in [16] showed that despite undervoltage improvement by high PV penetrations, overvoltage, reverse power flows (RPFs), and consequently shutdowns of inverters will become important issues of future distribution grids. More specifically, 327 half-hourly RPF events increased to 4303 when PV penetration was increased by 40%. Furthermore, by analysis of efficiency and power generation profiles in [57], a comparison between floating solar PV systems (FSPVs) and land PVs showed that FSPVs were typically characterized by higher performance and degradation.

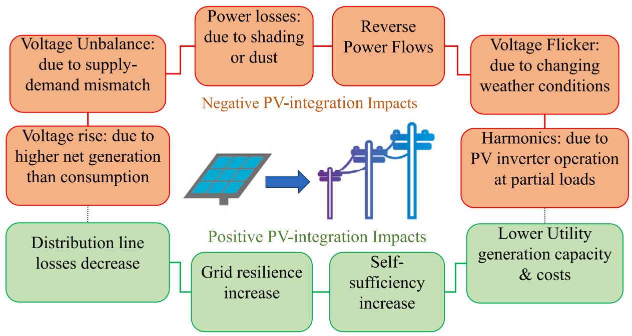

Fig. 5. Positive and Negative impacts of PV integration on future distribution grids.

2.3.2. Literature review studies

Finally, several review works on PV integration can be found in the literature. The impacts of PVs on power grid voltage, frequency, harmonics, protection, stability, and flexibility were summarized in [58]. Moreover, the study incorporated the limits to PV integration and the utilized models in PV impact analysis works. Moreover, mitigation solutions to impacts on power quality, voltage quality, stability, and protection and a related comparison of their advantages and disadvantages have been comprised in the analysis in [59]. Assessment techniques have also been summarized in [60], integrating both deterministic and stochastic approaches where the stochastic models have concluded to be more capable of estimating the system state considering uncertainty in PV generation.

2.3.3. Key insights

PVs are generally the most investigated LCT concerning their future grid impact. PV grid integration can be highly beneficial for future distribution grids since it can decrease distribution line losses and increase self-sufficiency due to local generation. Moreover, PV integration can increase grid resilience assisting in rapid grid response and recovery to major power disruptions. Finally, the increase in local PV generation increase contributes to a decrease in utility grid generation capacity and, therefore, generation costs [61]. However, several negative grid impact issues can be also provoked by an abrupt PV grid integration. Voltage rise and unbalance will be significantly increased due to supply–demand mismatch and high generation rise. Moreover, changing weather conditions such as temperature and irradiance can cause significant voltage flicker, while harmonics are most likely to appear due to the operation of the PV inverters at partial loads. Finally, the expected overvoltage can provoke reverse power flows in the future distribution grids. Fig. 5 summarizes the above positive and negative grid impacts of future PV integration in distribution grids.

3. Combined impact of considered technologies

Section 3 is devoted to the combined impact of the investigated technologies, which is categorized into the following pairs: EVs-HPs, EVs-PVs, PVs-HPs, and EVs-PVs-HPs. All subsections are distinguished as studies without mitigation solutions, studies with mitigation solutions, and key insights. It must be noted that by “without mitigation solutions”, it is meant that the works did not introduce extra solutions (e.g. energy storage) to mitigate the identified grid impact. If any mitigation observations were made, they were only due to the simultaneous operation of different LCTs.

3.1. Impact of electric vehicles and heat pumps

The combined integration of EVs and HPs has been investigated in the literature to estimate the impact of the future electric load in the distribution grids.

3.1.1. Analyzed research studies without mitigation solutions

Load profiles by combined and individual penetrations of EVs and HPs have been analyzed in [62] regarding the Nordic rural area. Focus has been placed on quantifying the impact of consumption and peak power demand on rural areas such as households, consumer places, farms, etc. EVs were identified as the heaviest LCT and increased the annual consumption of the area by up to 3.3% and the annual peak demand by up to 4.4%. On the contrary, HPs had a lower impact; however, they contributed to peak demand increase (up to 5.4% for rural leisure homes) when integrated in combination with the EVs.

Additionally, load profiles and transformer overloading have been studied in the UK national study of [63], where the peak power demand of 60 GW during the evening was raised by approximately 35 GW and 25 GW with the introduction of HPs and EVs, respectively, reaching a total value of nearly 120 GW at 19:00. Moreover, all distribution transformers were overloaded since 75% combined LCT penetration, while more than 90% were overloaded since 50% penetration. However, no overloading was observed for the primary transformers under all scenarios.

Moreover, voltage and component overloading were investigated for residential and commercial grids in [64]. In [64], transformer overloading was found a more hazardous grid impact issue than feeder overloading or voltage deviations reaching up to a 65% violation for the MV/LV transformers under 20% EV and 100% HP penetration levels. At the same penetration level, voltage violation and feeder overloading reached only 20% and 2%, respectively. In contrast with [62], HPs were more closely connected with component overloading than EVs in [64], e.g. reaching 54% transformer overloading at 100% individual HP penetration while the related number for 100% EV penetration was 40%.

The same grid impact issues have also been studied in the bottom-up work of [1] for a real urban grid of Great Britain under 4 increasing combined penetrations of EVs and HPs between 2020–2050. However, in this work, no violations were found except for 40% transformer overloading during the extreme Winter evening of 2050. On the contrary, no violation was seen for the Summer season under any set of LCT penetrations.

In contrast with the previous EVs-HPs works that focused their studies on a specific grid area type (e.g. rural or urban), the authors in [17] evaluated the grid capacities in 4 different types of Austrian grids (city center, outskirts, suburban, and rural). According to their findings, on the one hand, the urban LV grids were characterized by increased capacity for future EVs-HPs’ integration. On the other hand, suburban and rural grids were found to be more problematic, facing inadmissible voltage deviations and overloading even from low penetrations.

Furthermore, authors in [65] focused their investigation on the impact of increasing EVs-HPs penetration on the voltage control for single households and LV distribution networks. It was found that simultaneous EV charging and HP heating would provoke a high voltage regulation problem at any distribution network and the distribution system operators (DSOs) would need a lot of grid reinforcements.

In addition, extensive research has been conducted in the data-driven work of [66]. The work has analyzed overloading, voltage deviations, and unbalance for thousands of Scottish LV grids with newer and older buildings under multiple combined and individual EVs-HPs’ penetrations. In contrast with [64], voltage deviations were found to be more severe than overloading, especially in the HP integration scenarios. Voltage unbalance was also significantly increased during the combined scenarios, greatly exceeding the 2% threshold. Finally, in [67], socio-economic factors such as consumer behavior have been taken into account to interlink social diversity and consumption and model the impact of EVs-HPs integration on the distribution network. It has been found that considering combined penetrations is important for grid impact studies; however, only the transformer headroom has been used as a grid impact metric.

3.1.2. Analyzed research studies with mitigation solutions

EVs were found to be more hazardous for voltage unbalance and deviations than HPs in the balanced and unbalanced scenarios of [68], during the evening charging during 17:10–21:50. In [68], unbalance was also found to increase voltage deviations, especially at the negative and zero sequences at the end of the feeder, which were moderately decreased with the use of TOU tariff. Additionally, slow and fast EV charging has been integrated to analyze a dwelling in [69] and multiple mitigation techniques such as off-peak charging/heating, load shifting, and demand limit. However, only the load profiles have been analyzed. Double consumption and even worse peak power demand, 96% and 155%, respectively, were found in the fast-charging scenarios. While load-sensitive slow and fast EV charging, where charging occurs only when the household demand is below a user-defined maximum, managed to reduce power peaks, off-peak heating did not provide considerable energy savings.

Finally, the authors in [70] have summarized several potential grid impact issues caused by future EVs-HPs integration concerning infrastructure, operation, and planning. Some examples are peak capacity, economic dispatch, resource planning, and voltage regulation. Moreover, several solutions have been introduced for dealing with the future challenges of integration of EVs and HPs, such as device controllers or the use of energy storage.

3.1.3. Key insights

Overall, the key insights from the combined integration of EVs and HPs can be summarized as follows:

- Very hazardous LCT co-adoption: consumption and peak demand (especially during peak hours e.g. 19:00) can be increased by more than 100%.
- Critical grid issues: e.g. voltage deviations, overloading, and unbalance.
- Rural and Suburban grids: most vulnerable for combined integration.
- Winter: most hazardous season due to higher consumption.
- Necessary extra mitigation solutions to assist co-adoption: e.g. smart charging, demand management (DSM) (e.g. load shifting), ESSs, etc.
- Contradictions in the literature regarding grid impact comparisons between EVs and HPs.

3.2. Impact of electric vehicles and PVs

The grid impact of combined EVs-PVs' future integration in distribution grids has been extensively studied in the literature. On the one hand, this is due to the maturity and high social acceptance of these two LCTs. On the other hand, EV charging can enhance PV self-consumption, and PV generation can provide green energy for EV charging.

3.2.1. Analyzed research studies without mitigation solutions

The authors in [71] utilized the Phoenix metropolitan area in Arizona to study the co-adoption of EVs and PVs by analyzing the consumption and peak demand behaviors. It was found that while EV owners consumed, on average, approximately 0.4 kWh additional hourly energy demand compared to the non-EV owners, the hourly demand in the grid was decreased by 1.1 kWh when PVs were also added. Similarly, co-adopting these technologies could reduce the system's peak-hour demand.

Furthermore, the net power profile of the distribution transformers and, hence, their loading conditions have been used as metrics for the grid impact assessment of residential PVs and EVs on a distribution grid in Austin in [72]. Reverse flows due to PV feed-in have been observed through the transformers in the morning and in the afternoon, while demand peaks due to EV charging were seen during breakfast and dinner time. While no significant transformer voltage swells or sags were seen, PV generation was found to have a higher impact than EV charging. The impact of EV chargers and PV modules on the net load of distribution transformers has also been studied in the data-driven forecasting model in [73] to assess asymmetric changes in transformer load patterns. The proposed forecasting method, which used a diffusion pattern generator for the EVs-PVs uptake scenarios, predicted a future transformer net load that could reach up to 100% higher final value than other utilized methods in the literature.

Moreover, a stochastic model for addressing the coincidence between PEV charging and PV generation (hence, PV self-consumption) was also developed in [74], where single and aggregated households with or without PEVs were investigated. Firstly, it was found that PEV charging increases the yearly household consumption by 37%. Secondly, the introduction of PEV charging could be a benefit for PV self-consumption, but mostly in aggregated household-level scenarios.

Additionally, authors in [13] studied the phase imbalance caused by single-phase technologies such as PVs and EVs under increasing LCT penetrations in the form of total imbalance cost (TIC). Distinguishing the TIC in energy losses and capacity wastes, it was found that when LCT penetrations reached 70%, the cost of energy losses surpassed the cost of reinforcement regarding the urban UK networks. A Croatian LV network has also been used in [3] for unbalance investigation with the Voltage Unbalance Factor (VUF). Unbalance during Summer was found to be more severe, reaching up to 19% when all LCTs were connected in one phase. Unbalance was also found to exceed the maximum 2% threshold for 20% of the time, even from 20% LCT penetrations, while it was always present in the network due to single-phase household load connections.

In addition, current and voltage harmonic distortions (THD_i and THD_v, respectively) have been assessed by the authors in [75] on the standard IEEE LV 123-node distribution feeder, where current harmonics were found to be more severe than voltage harmonics. Moreover, while both distortions were increased by higher PV injections (THD_i increased up to 18%), they were both decreased with EV charging (THD_i decreased to 7%). However, the mitigation results have been more seen at the proximity of the substation, while combined penetrations still provoked high harmonics at the end of the feeder. The impact of EV charging uncertainty on power quality (PQ), such as harmonic levels and unbalance, was also studied in [76] where the different EV charging locations, power modes, and presence of PVs and other non-linear loads were incorporated. Charging locations were found to have a more significant impact on unbalance and voltage harmonics than power modes, while injections by the 3rd harmonic were higher than of the 5th and 7th.

The power quality issues of unbalance and harmonics have also been analyzed in the rural and suburban grids of [77]. The most important insight was the significance of the distribution line type on the unbalance and harmonics results. For example, the rural grid's overhead (OH) lines were severely violated regarding both issues, even from low combined penetrations (10% EVs, 50% PVs). On the contrary, unbalance and harmonics in the cable lines of both rural and suburban grids did not exceed the predefined thresholds even at the extreme 100% LCT penetrations.

Furthermore, 21 distribution grids from 3 different countries (Austria, Germany, and the Netherlands) have been investigated in [78] regarding overloading and voltage deviations. While most of the simulated grid showed minor violations, suburban grids could become highly vulnerable in the future. The various countries were also encapsulated, showing that Germany had the highest adequacy for high EV charging accommodation compared to Austria and the Netherlands, with moderate PV penetration. The same issues have been investigated in the Maltese LV network of [79] using as a metric the percentage of consumers with grid violations under increasing penetration levels. Voltage violations were first observed from 40% combined or individual penetrations of PVs and EVs, while feeder overloading was not seen even in extreme integration scenarios. Nevertheless, the percentage of consumers with voltage violations was reduced by 15% under 70% combined penetrations, also showing in this work the potential of violation mitigation during combined PV generation and EV charging.

On the contrary, the analysis of voltage and consumption profiles in [80] in an LV Swedish distribution grid showed that EV integration hardly provoked grid voltage decrease (a maximum of 0.01 p.u. voltage decrease was observed under 10% EV penetration level). Moreover, in this work, EV integration did not notably contribute to the minimization of PV curtailment, and hence, mitigation by combined EVs-PVs' integration was not seen. Moreover, analyzing the consumption results for different seasons, a 9.3% and 17.1% consumption increase was observed for Winter and Summer, respectively.

Moreover, the authors in [81] also incorporated system losses apart from voltage profiles, overloading, and unbalance as impact metrics in their investigation. They have found that, on the one hand, increasing PV generation decreased energy losses; however, on the other hand, it also simultaneously increased reverse power flow. Additionally, while increased EV penetration could moderate this reverse power flow, it also provoked asymmetrical loading even from a low number of EVs, increased the neutral voltage as well as overloaded the distribution lines, especially those close to the MV/LV transformer. The investigated issues in [81] and the neutral losses were incorporated in the study of [82]. In this work, EVs were more closely connected with component overloading, whereas PVs were more connected with feeder overvoltage. An interesting insight was that while system losses increased linearly with increasing LCT penetrations, neutral losses showed an exponential increase.

Finally, the impact of PVs-EVs integration on smart grid operation was assessed in [83] considering the Mueller community in Austin-Texas, constituting a residential smart grid of 735 households. Transformers' voltage profiles and capacities, as well as cable losses and unbalance, were analyzed before and after adding 178 PVs and 100 EVs. While the local PV generation created reverse power flows of 12 kW at the transformers, it generally decreased the cable losses while the active power demand of the smart grid was also decreased by 66%. However, the smart grid's reactive power was still provided by the main grid.

3.2.2. Analyzed research studies with mitigation solutions

Two light- and heavy-loaded real-world case studies have been used for load profile analysis in [84]. While the general load deviated around 60 kW in the heavy-loaded case, PV injections in the afternoon increased feed-in power up to 150 kW. On the contrary, EV charging could create a peak power demand of 135 kW in the evening when PV injections were absent. However, by applying smart charging as a mitigation solution to time shift the EV charging load, the residual load could be decreased up to 40 kW. Load profiles were also analyzed in [85] to find the resulting impact of the integration of these technologies on peak power demand and, consequently, on distribution revenues under different rate structures. While combining PVs with EVs could greatly reduce the peak demand inflicted by EV charging, it was found that proposed solutions, such as optimized EV charging and TOU tariff, could create power peaks at different times of the day.

Additionally, the authors in [11] found that rapid PV fluctuations could cause a notable impact on power quality, such as voltage fluctuations in the extreme scenario of 2050. The fluctuations, however, were firstly dependent on the grid characteristics and the distance from the MV/LV transformer and, secondly, could be highly suppressed with coordinated integration of EVs with V2G capability. Furthermore, EVs were highly correlated with unbalance degradation, whereas PVs had a higher impact on voltage deviations in the analysis of [86]. While mitigation of voltage and unbalance issues were found by integration of PVs and EVs alone, the authors proposed a demand side management (DSM) strategy that successfully suppressed the violations further by re-scheduling EV consumption during PV generation.

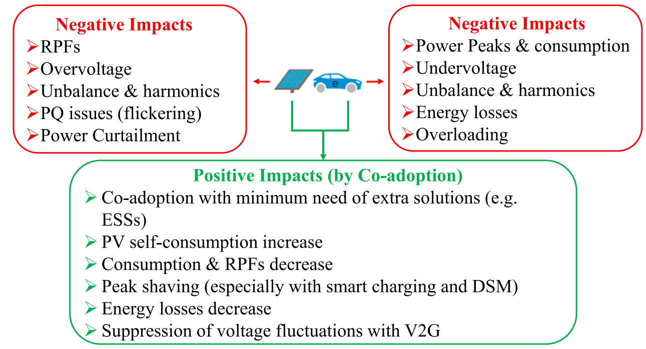

Fig. 6. Summary of negative impacts of PVs & EVs and benefits from co-adoption.

On the contrary, in the power quality investigation of [87], which incorporated case studies with individual and combined penetrations of EVs and PVs, EVs showed higher current distortion than PVs, reaching magnitudes of 10%–12%. Moreover, the authors in [87] proposed the simultaneous connection of PV and EV units on the same phase to reduce as much as possible the voltage distortion. The same observation was also made regarding unbalance since the neutral current increased approximately 100% when PVs and EVs were connected on different phases.

Furthermore, voltage deviations and component overloading have been studied in [88] under varying LCT penetrations for case studies in Denmark, Germany, and the Netherlands. According to their findings, transformer overloading was seen before voltage violations, while cable overloading was less seen in most grids. However, when fast charging was introduced in a remote case study, inadmissible voltage violations were the first grid impact issue to be observed. Moreover, energy storage was proposed as a mitigation solution with size dependent on the case study and LCT penetration. The authors also used voltage deviations in [89] as a metric of assessment of the combined PV-EV hosting capacity in LV distribution grids. Results showed that 100% PV penetration provoked inadmissible overvoltages over 1.1 p.u., while 100% EV penetration resulted in inadmissible undervoltages below 0.9 p.u. Several mitigation solutions were introduced, showing that EV hosting capacity could be increased by smart charging, while PV curtailment would be the most viable option for PV hosting capacity increase. Additionally, the performance of different charging methods (such as voltage droop and price-signal-based methods) in reducing the grid impact inflicted by PV-EV integration in 6 Dutch LV distribution grids was investigated in [90].

Finally, the authors in [91] investigated the low inertia effect of distribution grids with high penetration of RES, such as PVs, and variable load, such as EV charging. According to this study, considerable frequency oscillations could be inflicted by PV generation and EV consumption uncertainties, especially in islanded areas, which could be suppressed with a proper control strategy. The proposed strategy in this work constituted a combination of Harris Hawks optimization (HHO) based Balloon effect (BE) with the use of a virtual inertia controller.

3.2.3. Key insights

As already stated, due to the relatively high simultaneity factor of these two LCTs, their high technology maturity and social acceptance, and the emergence of DSM techniques, such as smart-charging, the co-adoption of PVs and EVs has been studied extensively. As can be seen in Fig. 6, while their individual grid integration can provoke several issues in future distribution grids, their co-adoption and co-integration in energy management systems (EMSs) can provide several benefits and suppression of their individual negative impacts.

For further information about the individual and combined impact and mitigation techniques by EVs and PVs integration, the reader is referred to [92]. In this review work, important conclusions were summarized about the effect of these two technologies on grid stability, power quality, and energy economics.

3.3. Impact of heat pumps and PVs

This section is devoted to the grid impact of PVs-HPs integration in the distribution grids. Compared to the PVs-EVs pair, this combination has been investigated less in the literature, mostly due to the lower simultaneity factor of PV and HP operations.

3.3.1. Analyzed research studies without mitigation solutions

Load profiles were analyzed in [93] for a Dutch all-electric neighborhood in Meerstad comprising 200 households. With the introduction of electric heating and distributed generation, the net consumption was found to be 1.75 times higher than in the reference case, while the required capacity should be increased by 300% (peak demand reached 5.1 kW from 1.7 kW per household). Additionally, voltage fluctuations and transformer overloading were analyzed in [94] for a real LV urbanized area. This study investigated different types of buildings, such as apartments, townhouses, semi-detached houses, etc. While low PVs-HPs penetrations did not have a notable grid impact, the transformer reached a loading of 240% and 190% under 100% LCTs penetration during Summer and Winter, respectively.

Furthermore, the impact of PVs, HPs, and CHPs on a German grid's power and voltage profiles has been quantified in [95]. Moreover, this work highlighted the importance of using pseudo-measurements for quantifying this impact to increase accuracy. Results showed that the usual state estimation methods could be proven highly optimistic about the final impact on the power grid.

Moreover, the authors in [96] used voltage deviations, transformer capacity, and load profiles analysis to address the effect of weather conditions on the grid impact in rural and urban grids in Belgium. The importance of considering weather uncertainty in grid impact studies with PVs-HPs was highlighted since an extremely cold Winter day could result in 10% higher transformer overloading and 2.5% higher voltage violations. The diversity and the effect of the ambient temperature on the peak load inflicted by residential heat pumps have also been considered in the analysis of [97]. According to their findings, an ambient temperature deviation of 4° could nearly double the peak load while a 72% peak load increase was noted from 20% HP penetration when the ambient temperature reached −4°. Additionally, high reverse power flows were seen even from 25% PV penetration, while overvoltage violation reached 14 V at 30% PV penetration.

Additionally, grid losses were also incorporated along with the previous metrics for quantifying the impact of home energy systems with electric heating and PV generation on the power grid in [98]. However, in the German suburban area investigated in this work, which comprises 36 households, no violations were observed of any kind. Unbalance was incorporated with the other grid impact metrics in [99] to calculate needed grid reinforcements in real urban and rural grids. No unbalance was observed for the urban grid, while unbalance was noted only with HP integration for the rural grid, starting from 40% HP penetration. An interesting insight was also that grid reinforcements could lead to significantly higher costs than the costs inflicted by energy losses.

In addition, a comparison between urban and rural grids under increasing combined PVs-HPs penetrations was performed in [5], where the rural feeders were also found to be more vulnerable to overloading and voltage violations than the urban ones. Regarding this work, overloading was deemed a more crucial matter than undervoltage, appearing from lower LCT penetrations. Metamodeling techniques have been used in the probabilistic work in [100] to assist reliable high-level gid impact assessment in rural and urban distribution feeders. Rural feeders were also found more prone to intolerable undervoltage violations in this work. More specifically, voltage levels below 200 V were noted even from 15% HP penetration or fewer than 15 buildings, while the related values of urban feeders were approximately 30% HP penetration and 25 buildings. Similar results were also observed for the PV generation.

Finally, the significance of Belgian building specifications on the PV-HP grid impact has been quantified in [101], finding strong correlations of voltage profiles, transformer peak loads, and distribution losses with characteristics such as total volume, heat load, electricity demand, conductivity factors, etc.

3.3.2. Analyzed research studies with mitigation solutions

Consumption and peak power profiles have been analyzed for an office building comprising PV and ground-source HP (GSHP) systems in [102], where the effect of various PV sizes and the mitigation with various battery storage sizes have been tested. Moreover, peak flows for 3 different types of buildings have also been analyzed in [103] along with the related impact on the LCOE. Different scenarios have been used for the peak demand comparison of combined and individual penetration of PVs and HPs, while two different types of energy storage (battery and heat storage) have been utilized for peak demand shaving and PV self-consumption. According to the work's results, both types of storage achieved a self-consumption rate between 30%–39%. Nevertheless, combining PVs and HPs for grid impact minimization is usually performed using heat storage within demand response techniques.

Furthermore, the work in [104] is an example where voltage control and thermal comfort maintenance were the major objectives. With heat storage, the HP operation was increased during midday when PV generation was highest to reduce the load peaks during the evening and cover, firstly, the thermal load and, secondly, the heat storage temperature. However, the thermal comfort was slightly violated for the effective voltage control performance (maintenance of voltage levels above 0.95 p.u.).

Finally, while most works use extreme cold or warm scenarios to investigate the impact of PVs-HPs integration, authors in [105] took the initiative to investigate the potential of near-zero-energy (NZE) conditions in a dense urban area in Japan under moderate weather conditions, analyzing the net load consumption and generation, voltage fluctuations and system losses. Important findings were that the spread energy efficiency measures could reduce net long-term consumption up to 40%, but NZE condition could never be achieved without the complete use of PV rooftops on the buildings.

3.3.3. Key insights

Overall, the key insights for this LCT combination can be summarized as follows:

- PVs and HPs: similar impact on voltage deviations and unbalance.
- PVs are more correlated with overvoltage and RPFs, while HPs with undervoltage and overloading.
- Rural grids: most vulnerable for combined integration.
- High influence of weather conditions (e.g. ambient temperature) for grid impact
- ESSs, such as battery ESSs (BESSs) and/or TESs: important for their co-adoption due to low simultaneity factor.

The grid impact works that assess the combined integration of PVs and HPs are quite limited compared to the works of the other LCT pairs. This is, firstly, due to the fact the EVs-HPs integration has been studied in extend for the analysis of the total future electric demand. Secondly, PVs and EVs are better coupled with each other for impact and mitigation analysis. While PV feed-in and HP cooling during Summer would seem to be also well coupled, it has been shown in [106] that this is not the case because the highest PV output amount is generated during the day when most of the residential buildings are not occupied.

3.4. Impact of electric vehicles, heat pumps and PVs

In the last part of the review section of the combined LCTs impact, the works investigating the integration of all technologies (PVs, EVs, HPs) are summarized.

3.4.1. Analyzed research studies without mitigation solutions

Load profiles and their strong seasonal dependence have been studied in the yearly assessment of [107] but on a German household level. When HPs were introduced in the place of gas boilers, the household's electric consumption and peak demand were increased by 3.6 and 4.2 times, respectively, while the introduction of EVs had the greatest impact on peak demand (4.7 times higher power peak and 13 times more peak hours). While PV generation succeeded in decreasing total consumption by 85%, it had a minimum impact on decreasing power peaks. On the contrary, the authors in the data-driven approach of [108] focused their research on analyzing load profiles of EVs, PVs and HPs for different urban scales (neighborhoods until municipalities), aiming to understand the spatial effect on different profile characteristics. According to their results, all urban areas could be clustered into "residential", "business", and "mixed" regarding their load profile behavior under LCT integration.

Additionally, the authors have realized a system-wide analysis in [109], which analyzed Winter and Summer load flows and voltage profiles for the MV Irish distribution network comprising 20 different network areas. The main goal of this work has been the discussion of various scenario modeling techniques and the identification of the effect that the changing landscape of the Irish distribution had on constraint identification and load flow analysis. Moreover, energy losses, together with power factors (PF) behavior, voltage fluctuations, and unbalance, were the main grid impact metrics in [110], where PV generation, EV consumption, and HP consumption have been sequentially added to the base load demand. It was generally found that separate integration could be, in principle, tolerated; however, unbalance could notably deteriorate with EV integration, while PV integration caused mainly a decrease in PFs.

In addition, component overloading was added in the probabilistic approach in [111], which was conducted in 128 real-world LV distribution feeders. In this study, PVs were linked highly with voltage violations (64% of the feeders) while HP consumption with overloading incidents (57% of the feeders). However, the number of customers in the feeders also played an important role since feeders with less than 25 customers did not encounter any violations. Lines overloading was also studied in [112] intending to estimate the lifetime of main and distribution cables used in distribution grids under combined and individual LCT penetrations. Individually, HPs did not seem to have such a high impact on cables end-of-life (EoL) such as EVs. However, they could reduce cable EoL up to 30% by 2028 when they were studied in combination. Another important contribution of this work was the utilization of detailed cable models that could incorporate temperature dependencies which was necessary to assess thermal loading impact on cables EoL.

The same metrics were utilized in the study of [113] in three future penetration case studies for a distribution network in Brescia, where home and public chargers were considered. In this study, MV/LV transformer overloading was mostly correlated with EV consumption due to the high-rated charging power of the EV chargers. However, PVs were found to be the most responsible for grid reinforcement, especially at high-level PV penetration.

Furthermore. a spatial analysis of available grid capacity and expected costs was performed in [6], which, however, was focused on the high deployment of PVs, EVs and HPs in a Swiss distribution grid comprising thousands of households. Whereas the results were highly dependent on the penetration scenarios, rural grids generally needed the highest reinforcements due to weaker infrastructure. In addition, the most spread cost values were noted for the HP penetration scenarios, while massive deployment scenarios were found to be more cost-effective than scenarios of current deployment (20%–30%). In [114], the authors investigated two different Dutch distribution grids (1 older and 1 newer), analyzing components' overloading and voltage violations. According to their findings, older distribution grids are insufficient for future LCT penetrations; however, the newer ones are relatively robust. In general, transformer overloading was found a more critical issue than line overloading, which was more critical than voltage deviations.

Moreover, component overloading and voltage deviations were also utilized as grid impact metrics in [14], while unbalance was also incorporated in [115]. However, in both studies, only the individual LCT impact was analyzed. In [115], EV consumption was mostly correlated with component overloading and undervoltage, while PV generation and HP consumption provoked mainly overvoltage incidents and power quality issues such as harmonics and frequency fluctuations. In [14], a probabilistic framework was developed to investigate 25 different UK LV networks with 128 LV feeders in total. It was found that the longest feeders, which served the most customers, were affected the most. While voltage violations began from 30% PV penetration, EVs and HPs were connected highly with transformer and feeder overloading. In general, the smaller feeders were not notably affected under any scenario.

Dutch rural, suburban, and urban distribution grids were also investigated under different combined and individual PVs, EVs, and HPs penetrations in [106]. Whereas HP integration showed more violations and of higher magnitude, EVs were correlated with more prolonged violations due to the duration of EV charging. Furthermore, the analysis of [106] has been conducted with both top-down and bottom-up approaches (the two main approaches used in grid impact studies) to also provide insights about the impact of the utilized approach on the grid impact results. In addition, in [116], the authors took a step further to perform a large-scale simulation investigating thousands of grids and not only analyzed component overloading and voltage deviations but also calculated the costs for the needed grid reinforcement. This study highlighted the importance of the right coincidence factor selection according to different grid case studies. Moreover, the authors tried to reach a conclusion about selecting the right trade-off between computational time (number of investigated grids) and level of accuracy in the grid impact analysis.

Additionally, in the yearly assessment of [117], the authors analyzed, apart from load profiles and carbon emissions, the various inter-effects between the operations of different LCTs in scenarios comprising PVs, HPs, EVS, and CHPs for a Swedish county. They found that PV rooftops could reduce the imported power amount in the investigated area; however, together with HP consumption, they reduced the operation of CHPs. EVs and HPs' consumption also increased highly the consumption of the region, even from low penetrations (30% HP penetration).

Finally, individual LCT scenarios for different penetrations have been applied in analyzing power profiles, overloading, and voltage deviations of [118] for suburban and urban grids in Munich. EVs and HPs were found to produce power peaks of similar magnitude. The share of the grid load remained similar in all scenarios regarding the urban area, which was also significantly lower than the suburban grid load. Considering the different scenarios, the suburban grid load encountered large changes even from low penetrations. While the grids were found to be generally robust for hosting future LCT penetrations, a double energy consumption and a slight line overloading were observed for the suburban area in the extreme scenario of 2030.

3.4.2. Analyzed research studies with mitigation solutions

Load profiles and their seasonal dependence were analyzed in [119] in different grid case studies (rural, suburban, urban). The highest consumption was noted during Winter and, especially, in December while the evening power peaks during the weekdays were shifted closer to 12:00 during weekends. The impact of different tariff utilization was also proven, showing that in contrast with the flat tariffs, peak demands were mostly observed during the morning for the customers with a multi-rate tariff. Moreover, apart from the load profile analysis and the resulting costs, authors in [120] applied different coordinated strategies to reduce power peaks and cost operations such as different tariffs, use of solar and/or battery optimization, and full coordinated control. Moreover, the investigation was conducted in 5 different households for 3 future EVs-PVs-HPs penetrations.

In addition, a clustering method has been applied in [121] to link grid impact issues and potential mitigation solutions with grid case study characteristics. Their results showed that residential transformer loading was heavily dependent on EV charging, for which the use of energy storage has been found to be the most effective strategy. In contrast, using PV generation was more effective in mitigating violations in commercial and industrial transformers. Another data-driven approach in [122] analyzed temporal voltage violations of different LCTs throughout the day. PVs had the highest impact, which occurred during the morning. However, EVs and HPs combined provoked violations of similar magnitude during the evening. Consequently, taking into account various sensitivity factors by historical data analysis, the authors proposed different mitigation solutions such as the use of the flexibility of distributed energy sources (DERs), the use of transformers with tap changers, etc.

Moreover, energy losses were added to the load profile analysis as a metric in the nationalized Swiss study in [2]. In this study, the effects of different parameters of the operations of LCTs on different grid impact issues were analyzed. Some examples were that the flow temperature of the HPs could play a major role in total national energy savings and power peaks, while PV production was highly responsible for incidents of power surplus or deficit.

A probabilistic framework was also developed with MCS in [123] to analyze the impact of these LCTs and micro-CHPs on cable investments, analyzing power peaks and component overloading. Different individual and combined mitigation strategies were introduced, from which the highest investment reduction (54%) was noted with a combination of DSM and smart charging.

Furthermore, the LCT hosting capacity (the maximum allowed LCT penetration) of different distribution grids has also been assessed in [124] under combined PVs-HPs-EVs penetrations by analysis of thermal and voltage violations. With the presence of PVs, the investigated grids could generally accommodate 24.2% HP penetration without any violations. A maximum of 30% EV penetration could also be achieved if no smart charging was implemented. However, with the employment of smart-charging techniques, the EV penetration that could be assessed was greatly increased (more than double in some grids).

Furthermore, different types of grids were utilized in [125] to show the impact of full grid electrification and the importance of battery energy storage systems (BESSs) for its mitigation and maximum PV self-consumption. While no voltage violations were found in rural or suburban grids, much PV curtailment was realized (reaching up to 54% of the total generation) at noon to avoid lines and transformer overloading. With the use of BESs and EVs-HPs' coordinated control, self-sufficiency, and self-consumption were greatly increased, reaching, in some examples, 72% and 40% from 34% and 19%, respectively. The use of PV-BESSs for impact mitigation was also considered in the developed stochastic bottom-up framework in [126], which analyzed load profiles of future grid conditions due to different LCTs integration (PVs, EVs, HPs, CHPs). The peak load for a German neighborhood comprising 1550 houses was increased by 1.3 MW, which was mainly caused by HP integration and was further increased by a factor of 1.8 when the buildings were not well insulated. Moreover, day-night and Summer-Winter load variations increased greatly under high LCT penetrations.

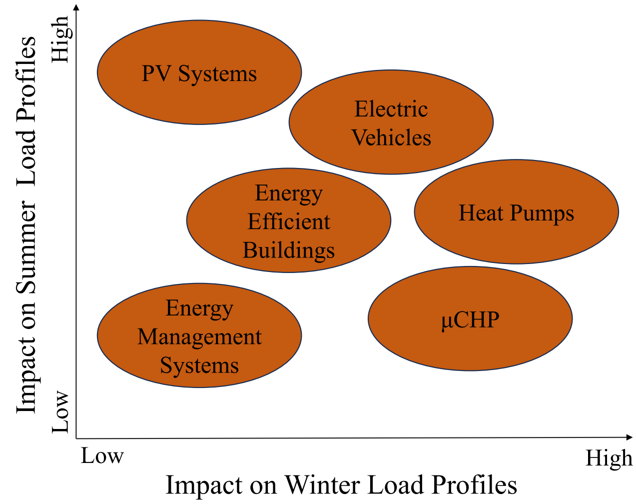

Fig. 7. Comparison of the impact on load profiles of different LCTs and mitigation solutions.
Source: Adapted by [4].

Moreover, different cable capacities along with individual PVs-HPs-EVs penetrations were considered in [127] for calculating the no-supplied amount of energy and needed grid investments for a typical German urban LV grid. According to the results, a 120 kW capacity cable was needed to facilitate all delivered energy to the prosumers without LCT penetration. While a 200 kW cable capacity was sufficient for power and energy delivery when the prosumers were equipped with PVs and HPs, there was still an amount of 0.16 MWh no-supplied energy when they were equipped with EVs. In addition, a combined technical, environmental, and economic network impact analysis can be found in [128], which studied carbon emissions, consumption, and peak demands as well as costs for different penetration scenarios of EVs, HPs, and energy storage systems (ESSs) combined with PVs. While the impact of EVs and HPs on the load profiles was found to be of a similar magnitude, HPs contributed to a higher emissions reduction than EVs. However, in contrast with EVs, they also greatly increased the multi-energy system's cost, reaching a value of 60% when they replaced the CHPs in the buildings of the DGs.

Finally, the authors in [4] utilized a hypothetical residential LV network to analyze voltage deviations and power profiles of increasing individual or combined LCT penetrations. According to their general findings, without a coordination technique, Summer load profiles were mostly affected by the simultaneity factor between EV consumption and PV generation. On the contrary, Winter load profiles mainly depended on the penetration level of the HPs in the distribution grid. Fig. 7 compares the impact of the different LCTs and mitigation solutions on Winter and Summer load profiles [4].

3.4.3. Key insights

The key insights of this subsection are extensively discussed and analyzed in Sections 4.1 and 4.2.

4. Analysis and discussion

4.1. Introduction

Table 1 summarizes all the works regarding the grid impact of the combined integration of PVs, EVs, and HPs with the related investigated features: areas, sectors, issues, penetrations, approaches followed, seasons, uncertainty management methods, solutions, and mitigation. According to each feature, the explanation of the abbreviations is as follows:

Table 1
Summary of research papers on combined grid impact of PVs, EVs, and HPs technologies.

Ref	Area(s)	Sector	Metrics	Penetrations	Approach	Time	Uncertainties	Solutions	Mitigation
[2]	Swiss Grid	Res-Com-Ind	LP	Multiple C	Data-driven	Yearly	Regression	DSM, LS, ESS	PS-DS
[4]	Hypoth. DG	Res	LP, V	Multiple C&I	B-U&T-D	Wint.-Sum.	SBA, SLPs	TF Cap. Incr	PS
[6]	Swiss DG	Res-Com Rur-Sub-Urb	LP, TF OL C OL	Multiple C&I	B-U	Unspec.	MCS Regression	BES	Load Reduction
[14]	25 UK DGs	Res	LP, V TFC OL	Multiple I	B-U Meters	Sum. PVs Wint. EVs	MCS	No	No
[126]	German DG	Res	LP	Multiple C	S.B-U	Yearly	No	BES, TES, Insul	PS-DS
[107]	German HH	Res	LP	Fixed I	S.B-U	Yearly	PDFs	No	DS with PV
[113]	Brescia MVDG	Unspec.	LP, TF OL	Fixed C&I	T-D Meters	Apr. Workday & Sunday	No	No	No
[123]	Dutch DG	Res	TFC OL	Multiple C	T-D	Yearly	MCS	DSM, SC, ES	PS
[114]	Dutch DGs Old & New	Res.	TFC OL V, H	Fixed C	T-D	Yearly	No	SC, PV Cap. HP power	OL&H Decr by PV-HP
[110]	Adapt DG	Res	V,U,PF,L	Fixed C&I	B-U	Daily Avg.	Stoch. Prof.	No	U Decr by PV
[109]	Irish MVDG	Rur-Urb	V, TFC OL	Multiple C	Meters	Wint.-Sum.	SBA	No	No
[124]	5 UK DGs	Res.	V, Host TFC OL	Multiple C	B-U Meters	Wint.	No	SC	Host Incr by SC
[119]	UK DG	Res-Com-Ind Rur-Urb-Sub	LP	Multiple I	Meters	Yearly	No	Smart Tariffs	PS
[116]	7114 Aust DGs	Rur-Sub	V, TFC OL	Fixed C	T-D	Unspec	MCS	Reinforcement	No
[118]	5 Synthet DGs	Res Sub-Urb	LP	Multiple C	B-U	Yearly	No	No	No
[106]	6 Dutch DGs	Rur-Sub-Urb	V, TFC OL	Multiple C&I	B-U&T-D	Wint.-Sum.	MCS, RS	No	OL,UV Decr: PV-EV
[112]	2 Feeders	Res	Lifetime	Multiple C&I	B-U&T-D	Unspec	S.A	No	No
[111]	25 DGs Comp-based	Res	V, TFC OL L, U	Multiple I	B-U & Meters	PV Sum. HP/EV Wint.	MCS, RS & S.A	No	No
[127]	Typical DG	Urb	Energy Loss	Fixed C	R-B&B-U	Wint.	No	Higher C Rating	Loss Reduction
[122]	6 Euro DGs	Urb, semi-Urb	V, U	Fixed C	Data-driven	Unspec	Regression	DER Ctrl, TCTFs	OV-UV Reduction
[128]	Synthet MG Manchster Univ.	Res	LP, Host V, TFC OL	Multiple C&I	B-U & Meters	Unspec	No	No	ESSs
[120]	5 UK HHs	Res	LP	Fixed C	Real LCTs	Yearly	No	Ctrl Strategies	Demand,Cost Decr
[121]	Swiss ES	Unspec	LP	Multiple I	S.B-U & Meters	Yearly	Stat. Analysis & S.A	Ctrl Strategy	Demand Decr: HPs Mismatch Decr: EVs
[117]	Real-DG TFs	Res	TF LP	Multiple C&I	Data-driven	Yearly	SBA&Cluster.	ESSs	PS by ESS & PV
[125]	5 Synthet DGs	Rur-Sub	V, TFC OL Curtail	Fixed C	B-U	Sum., Wint. Aut., Spr.	No	BES Ctrl Strategy	PV Host Incr: BES Curtail Decr: Ctrl
[108]	15k Dutch DGs	Various Levels	LP	Fixed C	Data-driven	Unspec	Cluster.	No	No

- Areas: Hypoth. for hypothetical, Synthet. for synthetic, LV for low-voltage, MV for medium-voltage, DG for distribution grids, HH for households, and ES for energy systems.
- Sector: Res for residential, Com for commercial, Ind for industrial, Rur for rural, Sub for suburban, Urb for Urban, and Unspec. for unspecified.
- Metrics: LP for load profiles, V for voltage, TF for transformer, C for cable, TFC for transformer and cable, OL for overloading, H for harmonics, Host for LCT hosting capacity, and U for unbalance.
- Penetrations: C for combined, I for individual.
- Approach: B-U for bottom-up, S.B-U for stochastic bottom-up, T-D for top-down, and R-B for rule-based.
- Time: Wint. for Winter, Sum. for Summer, Apr. for April, Aut. for Autumn, and Spr. for Spring.
- Uncertainties: SBA for scenario-based approach, SLP for synthetic load profiles, MCS for Monte Carlo simulation, PDF for probability density function, Stoch. Prof. for stochastic profiles, S.A. for sensitivity analysis, Cluster. for clustering, RS for random sampling.
- Solutions: DSM for demand side management, LS for load shedding, ESS for energy storage systems, Cap. for capacity (of lines or transformers), BES for battery energy storage, Insul for insulation, SC for smart-charging, DER for distributed energy resources, TCTFs for tap-change transformers, Ctrl for control.
- Mitigation: PS for peak shaving, DS for demand shaving, Decr for Decrease, Incr for Increase, Curtail for Curtailment.

Concerning the different approaches that can be followed for the generation of the LCT profiles in grid impact assessment studies, the main two categories are the bottom-up and top-down approaches. B-U approaches usually generate the LCT profiles by modeling the LCTs and their physical operation and then scaling them up to the size level of the study. Their main advantages are the interpretation of the physical laws, expandability, modifiability, and low need for input data, However, their outcome depends highly on the case study characteristics and conditions, while uncertainty management must be added by other means, such as stochastic profile generation using PDFs (S.B-U). On the contrary, T-D approaches usually handle generalized national-level data and scale it down to the size level of the study. Their main advantage is the lower dependence on the case conditions and uncertainties because the data has already been processed using data analysis methods; however, they often need accessibility to large-scale data for the generation of the profiles. Using real measurements by installed meters at HHs is a subcategory of the B-U approaches since they use the profiles of a low number of LCTs and scale them up to the needed study level. However, they do not use LCT models and have been accounted for as a separate category [106,126].

Solutions and mitigation have been distinguished because solutions mean the authors used extra means to reduce the grid impact, such as ESSs, DSM, etc. On the contrary, mitigation can also occur by inverse operations of different LCTs (e.g. PVs and EVs) without the use of any extra solutions.

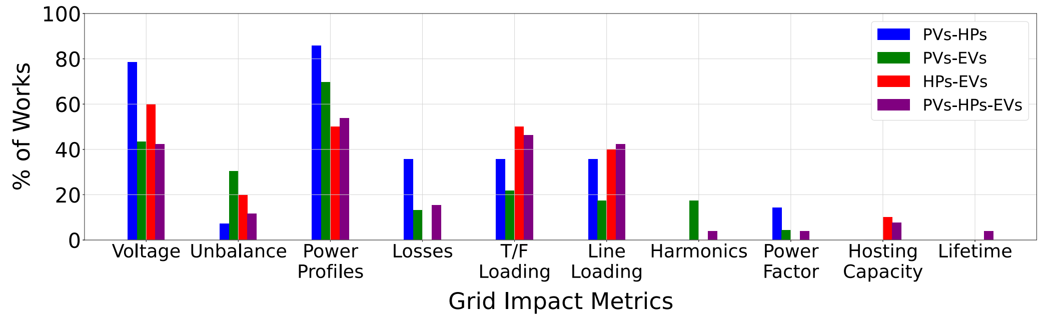

Fig. 8. Percentage of PVs-HPs, PVs-EVs, HPs-EVs works related with grid impact metric investigation.

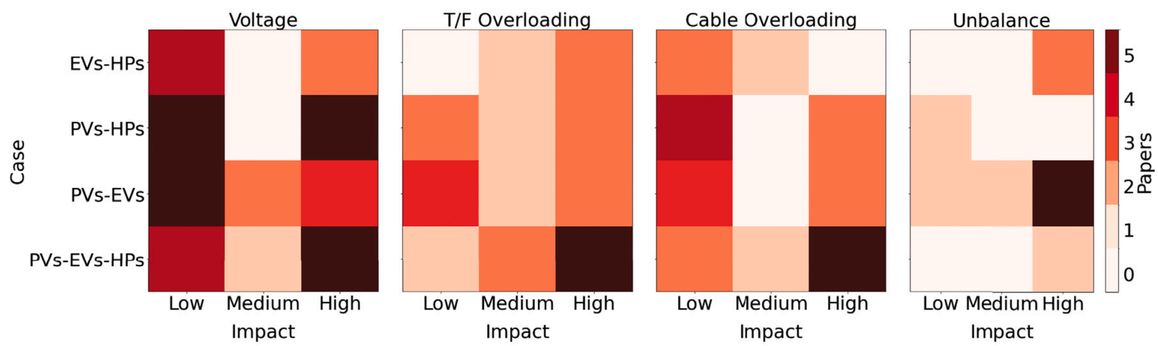

Fig. 9. Summary of impact assessment for all LCT combinations concerning Voltage, T/F & Cable Overloading and Unbalance.

4.2. General key insights

The most important general key insights from Table 1 are summarized below:

- 80% of the works used real-world grid case studies.
- 57% focused only on the residential sector.
- 60% utilized multiple LCT penetrations to identify the grid impact. However, only very few works used both combined and individual penetrations to identify the overall inflicted impact and compare the contribution of each LCT.
- The approaches used can be mainly categorized as bottom-up, top-down, and measurements from real meters, while some works incorporated a combination of them, e.g., for the different LCTs.
- 68% followed a yearly assessment or used the extreme seasons, Summer and Winter. Since Summer is a more hazardous season for PV generation and Winter is more hazardous for EV and HP consumption, they are combined in one case study in some works.
- Mitigation effects such as peak shaving and loading/loss reduction have been observed by combined LCTs integration or using mitigation solutions such as DSM, use of BES, control strategies, etc.
- Some works have incorporated uncertainty management techniques such as MCS, regression, clustering, etc, but without addressing all uncertainties that were present in the investigations.

4.3. Grid impact analysis

4.3.1. Correlation of LCT combinations with grid impact metrics

In Fig. 8, the percentage of PVs-HPs, EVs-HPs, PVs-EVs, and PVs-EVs-HPs works related to different grid impact metric investigations are depicted. Most works have used as metrics the grid supply and demand power profiles for all combinations, observing energy consumption and power peaks (more than 80% of the PVs-EVs works), and they have not proceeded in investigating directly the impact on the power grid. Voltage and overloading of transformer and distribution lines represent the next most investigated impact metric, reaching 60%, 50%, and 40% for HPs-EVs works, respectively. On the contrary, unbalance and losses have much less been studied until now, while analysis of harmonics, power factors, lifetime, and LCT hosting capacities is still missing from the literature for most of the LCT combinations.

4.3.2. Assessment of grid impact issues by LCT combinations

Focusing on the four most important grid impact issues: voltage deviations, T/F and cable overloading, and unbalance, Fig. 9 summarizes a qualitative comparison of the works from the different LCT combinations. The results of the works are categorized as low, medium, and high, mainly using as a metric the magnitude of violation: <10%, <50%, and >50%, respectively. However, it must be noted that each work uses its own metric of violation, and thus, it was necessary to use our own metric to categorize the works as low-, medium-, and high-impact. The two main methods used in the literature are either the magnitude of violation on a specific component (e.g. % overloading of a transformer) or the percentage of violated components in the distribution network (e.g. % overloaded distribution lines or components). Additionally, some works utilize a combination of the above two methods to conclude about the level of grid impact of the investigated LCT or LCT combination. Finally, the remarks and conclusions of each work about the level of the impact on the investigated grid and its conditions have also been taken into account for the qualitative comparison of Fig. 9.

Moreover, Fig. 9 depicts the number of works investigating each grid issue to show the comparison's trustworthiness level. As can be observed, most works that integrated all PVs, EVs, and HPs found a high impact level for voltage and overloading. However, impact mitigation was observed for PVs-HPs and PVs-EVs combinations, especially for the voltage deviations. For example, the coincidence of EV charging or HP heating/cooling with PV generation reduced the grid impact of both LCTs. These observations were more seen for the PVs-EVs combination because of the higher simultaneous operation, e.g. HP heating occurs more in the evening when there is no PV generation.

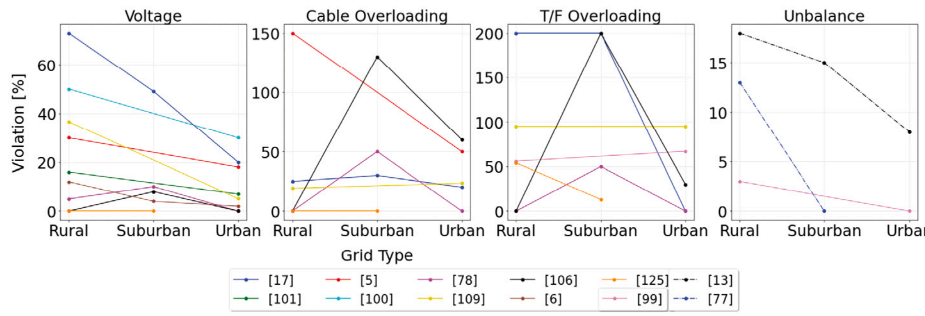

Fig. 10. Summary of impact assessment for rural, suburban, and urban grids concerning Voltage, T/F & Cable Overloading, and Unbalance.

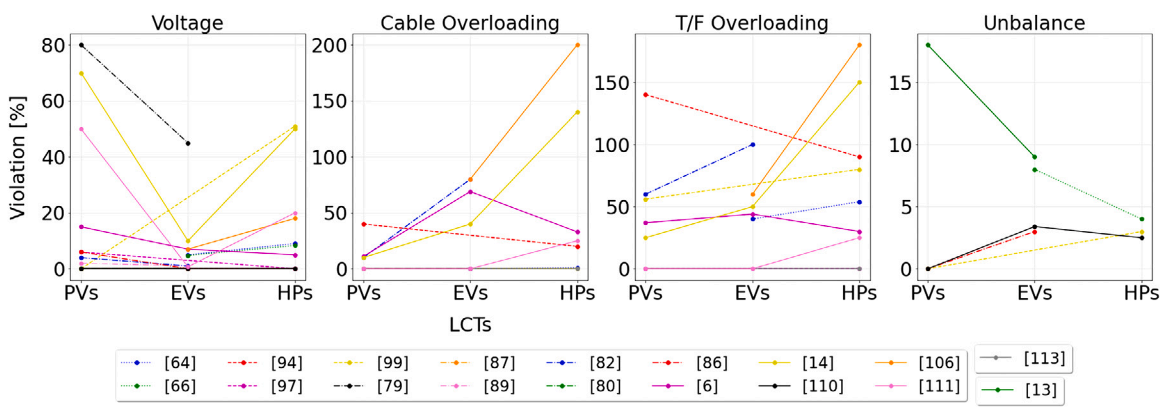

Fig. 11. Summary of impact assessment for PVs, EVs, and HPs concerning Voltage, T/F & Cable Overloading, and Unbalance.

On the contrary, the PVs-EVs combination showed a higher impact regarding phase unbalance than PVs-HPs because of the simultaneous power injections and withdrawals from different phases, which can occur more frequently for PVs and EVs. Additionally, EVs-HPs and PVs-EVs-HPs combinations were both found to inflict a high unbalance impact. However, it must be noted that only a few works have studied phase unbalance and incorporated all 3 LCTs in the analysis.

Finally, in several cases, it has been observed that the majority of the works are concentrated in the low or high-impact levels. On the one hand, this can be justified by the fact that grid impact assessment works usually use either one fixed moderate LCT penetration level to study the current or near future situation or multiple penetrations, focusing on the 100% penetration level to study the totally sustainable future. Consequently, results are more likely to fall into the low or high-impact categories, respectively. On the other hand, this observation is mostly made for the PV-integrated case studies and for the voltage and cable overloading grid issues. Voltage and cable overloading represent local grid issues, for which most of the studies utilize as metric the maximum violation (lowest/highest voltage or highest cable overloading) that occurred in the investigated network. As already explained, simultaneous PV generation with consumption of EVs, HPs, or EVs-HPs has resulted in several studies in mitigation phenomena that have the highest influence on local grid components, such as nodes and distribution lines. However, the success of these mitigation events also depends on the conditions of each study, such as the LCT modeling, the considered simultaneity factors, the setup of scenarios, etc., and are not always present in the studies.

4.3.3. Grid type and LCT comparison for different grid issues

Figs. 10 and 11 depict quantitative comparisons between the different grid types (rural, suburban, and urban) and LCTs concerning voltage, cable and T/F overloading, and unbalance, respectively. Regarding the grid comparison, the rural grids suffered the most from voltage deviations in most works. This is justified by the fact that the rural grids have, in general, longer line lengths (and hence, higher line impedances) than the urban and suburban grids, and the loads cause higher voltage drops. Rural grids were also found to be the most vulnerable to phase unbalance compared to the two other types of grids. This is also due to the higher voltage deviations which jeopardize further voltage and current unbalance. On the contrary, suburban grids were found to be more vulnerable to cable and T/F overloading because of the higher population that usually lives in the city suburbs. Additionally, for the above reason, the work in [106] represents an exception where the suburban grids were found to be the most vulnerable regarding all 3 grid issues since the Dutch suburbs are usually extremely populated areas.

Considering the LCT comparison in Fig. 11, PVs were mostly correlated with voltage deviations and less with cable and T/F overloading. This can be justified because all grids usually have an existing loading, which cancels out a fragment of the PV production. On the contrary, EVs and HPs were mostly associated with cable and T/F overloading. In most studies, HPs caused higher overloading and voltage issues than EVs due to the higher number of HPs than EV chargers under the same penetrations. This is because the correlation of HPs (and PVs) with the penetration is straightforward. A penetration level of 100% means that all buildings are equipped with an HP or a PV. However, the method that the number of EVs or EV chargers per penetration level is calculated in each study varies and depends on the assumptions of the authors and the conditions of the study, e.g. statistics for each investigated country. For example, some works assume that every building is equipped with an EV charger at 100% penetration levels. However, other works define the 100% penetration as the number of passenger cars that are replaced by EVs. If, according to the country's statistical data, there is an average number of passenger cars per number of people, which can be, e.g. different for rural and urban regions, then the total number of EVs is calculated in that way and distributed to the grid home or public chargers. As a consequence, the number of EVs that are added at each penetration level at each study is always lower or equal to the number of HPs and/or PVs.

Table 2
Correlation of mitigation strategies with grid impact issues.

Mitigation strategies	Power peaks	Excessive consumption	Voltage violations	Thermal overloading	Harmonics	Unbalance	Losses - efficiency	Fault limit
ESS	✓	✓	✓	✓				
DSM	✓	✓	✓	✓			✓	
LS	✓	✓	✓	✓		✓		
EV SC	✓		✓	✓		✓		
Smart-tariffs	✓		✓	✓				
LCT var. power	✓		✓	✓	✓	✓		
TF Cap. Increase	✓			✓				
OLTC			✓					
LCT efficiency		✓					✓	
HP flow Temp.		✓						
Building Insulation		✓					✓	
Cable Rating increase				✓			✓	
APF				✓	✓			
SOP			✓	✓		✓		✓
Reinforcement	✓	✓	✓	✓	✓	✓	✓	✓

Moreover, HP operation is more frequent since the buildings need to be heated and cooled regularly during Winter and Summer, respectively, while EVs are usually charged around 3 times per week due to their large range. However, there are some studies that contradict these findings. For example, in [99], HPs caused up to 50% voltage violations compared to 0% violation by PVs. This was justified because the study was conducted on a radial Belgian rural feeder where significant undervoltage events occurred, especially at the end of the feeder, during the cold Winter days when HP consumption was at its highest. Moreover, PVs and EVs were found to be more hazardous than HPs for overloading in [6,94], respectively. For the study in [94], this was possibly due to the use of large-scale PV systems in the PV integration case, which caused high-level PV power flows in the LV network. Regarding the work in [6], the study was focused on a Swiss distribution grid of 170 000 households that comprise both residential and public zones. In the extreme scenarios, HPs were assumed to equip 100% of only the residential buildings while, on the contrary, all passenger cars were replaced with EVs being charged in residential and public chargers.

Concerning phase unbalance, there are contradictions about which LCT is the most hazardous for grid unbalance. Most works agreed that EVs could highly jeopardize grid unbalance if they are charged by one phase since they are charged with higher power ratings. This is true for EVs with charging ratings up to 7.4 kW, which are charged single-phase and withdraw up to 32 A. However, the authors in [13] found an 80% higher violation of phase unbalance by PV phase injections than by EV withdrawals. Nevertheless, such comparisons between LCTs and grid case studies regarding grid unbalance have been performed in only a few works, and more investigation should be conducted to strengthen these insights.

It must be noted that these contradictions have been expected because these comparisons are highly grid case-dependent, and it is difficult to extract a conclusion that can be generalized across all the grid impact assessment works. Moreover, as explained, every work has its own metric of violation (% magnitude of transformer overloading or % overloaded transformers in the distribution grid). This is why there is a significant difference between different works for the same grid impact metric. While this is less significant for the qualitative analysis of Fig. 9, where the authors' conclusions can also be used for the categorization, high precision gains more importance in quantitative comparisons. Hence, it is recommended that the results shown in Figs. 10 and 11 should not provide insights by comparisons between different works but only by comparisons between different grids and LCTs within the same work where the setup and input parameters are the same.

4.3.4. Mitigation strategies to grid impact issues

The correlation of different mitigation strategies with various investigated grid impact issues is summarized in Table 2, where ESS, DSM, LS, EV SC, OLTC, APF, and SOP denote energy storage systems, demand-side management, load shedding, EV smart-charging, on-load tap charging, active power filters, and soft-open points, respectively. ESSs, DSM, and LS are mostly used for peak and excessive consumption reduction and mitigation of overloading and voltage violations. Varying the LCT power levels, such as with EV smart-charging or variable-speed HP operation, can also assist with the aforementioned issues and unbalance, but not with consumption reduction. On the contrary, consumption reduction can be better achieved with higher building insulation, lower HP flow temperature, and increased LCT efficiencies. OLTC transformers have been used to mitigate voltage violations, while active power filters can assist with overloading and harmonics presence. Finally, SOP power electronic devices are often utilized for undervoltage-overvoltage, unbalance, and thermal overloading mitigation.

4.4. Limitations and recommendations

Overall, the grid integration of PVs, EVs, and HPs has been extensively studied in the literature. The positive and negative impacts of all LCTs and LCT combinations investigated in this work are summarized in Table 3. The right side of Table 3 (green color) belongs to the positive impacts, while the left side (red color) belongs to the negative ones. It must be noted that the positive and negative impacts of PVs-EVs-HPs grid integration are omitted because they are a combination of the positive and negative impacts of the partial combinations (PVs-EVs, PVs-HPs, PVs-EVs-HPs), respectively. However, there are still certain aspects regarding LCT grid integration that need to be further investigated.

As already seen in the previous section, while many of the findings of the existing grid impact assessment studies are in agreement and can be generalized, others are contradictory because they depend heavily on the considered conditions of each study. One such aspect is the comparison of the different types of DGs (e.g. rural, suburban, urban,

Table 3
Positive and negative impacts of grid integration of various LCTs and LCT combinations.

Negative impacts		Positive impacts: PVs	Positive impacts: EVs	Positive impacts: HPs
	PVs	Grid Resilience Self Sufficiency DL Losses decrease Lower Utility Generation Lower Generation Costs Overvoltage Unbalance RPFs Voltage Flicker Harmonic Distortion Power losses (shading)	Co-adoption with minimum need of extra solutions (ESS) PV self-consumption increase RPFs & Energy losses decrease Peak Shaving (esp. with SC or DSM) Mitigation of: unbalance, overloading & voltage deviations Voltage Fluctuations suppression by varying PV output with V2G Frequency regulation & Congestion Management LCT hosting capacity increase Unbalance control (same LCT phase-connection)	PV self-consumption increase RPFs and Energy losses decrease Peak Shaving (DSM/TES needed) Solar-powered TES Mitigation of: unbalance, overloading & voltage deviations with extra solutions Frequency regulation & Congestion Management LCT hosting capacity increase Unbalance control (same LCT phase-connection)
	EVs	High risk of: overloading, voltage deviations, harmonic distortion, unbalance, PV curtailment (without proper control strategies)	Frequency Regulation Voltage Control PF Improvement Congestion Management Energy Storage (V2G) Undervoltage Unbalance Overloading Harmonic Distortion Power Losses	Frequency Regulation Unbalance Control with phase-changing chargers Use of V2G for heating flexibility Congestion Management (use of V2G or TES)
	HPs	Extra solutions needed (e.g. ESS) High risk of: overloading, voltage deviations, harmonic distortion, unbalance, PV curtailment	Most hazardous co-adoption: consumption & peak demand can be increased >100% Critical grid issues: voltage deviations, overloading and unbalance Necessary extra mitigation solutions (e.g. SC, DSM, ESSs, etc)	Voltage Control Frequency Regulation RES integration Congestion Management Undervoltage Unbalance Overloading Power peaks Excess Consumption

etc.) concerning the grid integration of PVs, EVs, and HPs and various grid issues. Observing Table 1, only the works in [6,106,109,116,119,122] have conducted such a comparative analysis utilizing real-world DGs. Moreover, most studies utilize only one DG for their investigation except for [106,116,122]. However, the grid impact analysis in multiple DGs is important for the generalization of the findings. Finally, the analysis of the seasonal effect on the different LCT integration in different grid types has only been accounted for in [106]; however, only voltage deviations and component overloading have been assessed in this study, while issues such as unbalance, harmonic distortion, voltage flickering, etc. were left out from the analysis. The profiles of different LCTs highly differ during different seasons, affecting greatly both their individual grid integration and their interaction during combined integration [109,125]. The knowledge about the vulnerability of each DG type to the integration of each LCT/ LCT combination considering the weather and seasonal dependency is critical for the analysis of the DSOs regarding the available LCT hosting capacity and needed reinforcement for the successful deployment of the various LCTs. Especially, the Winter and Summer seasons that constitute the worst-case scenarios for EV-HP consumption and PV generation, respectively, should always explicitly be investigated in grid impact assessment studies for the proper LCT deployment and DG reinforcement planning by the DSOs.

In this regard, due to the high influence of the grid characteristics in each country, an analysis that comprises DGs and representative grid types from different countries and investigates the LCT integration under the same conditions (e.g. penetration levels and LCT combinations, seasons, etc.) to show the extent of the generalization of the grid impact results in different countries. The authors in [78] utilized 21

LV DGs of three countries (Austria, the Netherlands, and Germany) in their analysis; however, the investigation included only the impacts of voltage deviation and overloading and was mostly focused on the hazards of the EV grid integration. As also found in [106], the existing loading of a DG plays an important role in the final grid impact level, especially under 100% penetration level, and should always be taken into account when selecting the representative DGs in each country for grid impact assessment.

Additionally, nearly all grid impact studies considered only EV slow charging. While fast charging and comparative analysis with slow AC charging can be found in [34,35] for individual EV integration, only [69,88] studied FC integration with other LCTs.

However, PV and HP grid integration were left out of these studies, respectively. The installation and installation of FC chargers are highly emerging, and their grid integration study, combined with other LCTs, will play a vital role, especially for MV DGs.

Furthermore, while the grid impact of PV-EV integration and the benefits from their co-adoption have been extensively studied, a smaller amount of works were found for the other combinations, and most of them remained on load profile analysis, overloading, and voltage deviations. There is no grid impact study that assessed phase unbalance in the PV-HP category, while only 3 unbalance assessment works were found in the PV-EV-HP category, which, however, did not take thoroughly into account the interdependencies between the grid specifications, seasonal effects, and various LCTs. Moreover, harmonic distortion has mostly been assessed in the PV-EV integration. Power quality issues, such as phase unbalance and harmonic distortion, are highly expected in the future DGs with high LCT penetration levels, and are, thus, highly recommended for future research. Additionally, PF and energy losses assessment is still missing from the literature for the EV-HP integration and can be critical for the combined integration of these technologies when local PV generation is not present to reduce the distribution losses. Finally, most studies have assessed grid impact issues; however, only a few of them have taken a step further and found the final grid impact results for the DSOs, calculating the available LCT hosting capacity and needed grid reinvestments, such as [116,124,128]. The final calculation of grid reinforcement and reinvestments for the integration of different LCTs can be of great importance for the DSOs and the future planning of the MV and LV DGs.

In addition, only 4 and 3 grid impact assessment studies comprised mitigation solutions in the PV-HP and EV-HP categories, respectively. The use of BES, TES, BES-TES combination, and energy efficient measures (e.g. buildings of improved energy labels) were the solutions studied for PV-HP integration. However, the influence of different price tariffs, such as TOU or dynamic pricing, can also be critical mitigation measures in DSM studies due to the high price volatility of the future energy market. On the contrary, different pricing mechanisms, application of demand limit, and off-peak charging and heating were investigated as mitigation measures for the EV-HP integration; however, the use of ESS for grid impact mitigation is still missing for this category. It must be noted that there is an abundance of power control works for LCT integration in the literature, which were left out of this review because they did not integrate uncontrolled LCT integration cases. However, the combination of grid impact assessment and mitigation in specific grid case studies is valuable for the LCT integration in different countries and is, thus, recommended for future research.

Additionally, many studies chose to generate the LCT profiles using a specific approach, e.g. T-D, B-U, real measurements, etc. Only a limited number of them used the advantages of multiple approaches, such as [111,112,127], and only the authors in [106] studied the influence of the approach on the grid impact results, comparing the T-D and B-U approaches. It was found that B-U approaches are generally more capable of addressing the worst-case scenario of simultaneous operation of LCTs resulting in more pessimistic findings regarding the magnitude of the grid violations. However, T-D approaches can address the uncertainties more efficiently by averaging the results in time, lowering the violation peaks, and extending their duration due to uncertainties. In [106], it was concluded that both approaches should be considered in grid impact assessment studies to combine their advantages and for cross-validation. However, the work analyzed only voltage and overloading violations; the influence of the followed approach on grid issues such as phase unbalance, and harmonic distortion can strengthen our insights concerning future LCT integration and the needed grid reinforcements. It must also be noted that the simultaneity factor of LCT operation has a significant effect on the resulting power peaks, and hence, voltage violations, component overloading, and consequently, the final LCT hosting capacity. However, the simultaneity factor is highly grid-specific and it also depends on the social factors of each country and grid region. Hence, a multi-disciplinary investigation is needed for the appropriate grid reinforcement and LCT installation.

Moreover, regarding comparisons between LV and MV distribution grids, some similar insights can be drawn for both distribution levels. For example, such as in the LV DGs, urban MV distribution feeders suffered most from overloading, while voltage violations were more prominent in the rural MV feeders [109]. Unfortunately, very few studies assessed the grid impact of LCTs in a wide-scale distribution network focusing on impact comparisons between the MV and LV elements. In [64], the MV distribution lines were more vulnerable than the LV lines of a German DG concerning both voltage and overloading violations. However, the MV/LV transformers that fed the LV feeders were found to be the most vulnerable grid elements for both EV and HP integration, which was also endorsed for PV integration in [113]. On the contrary, HV/MV transformers usually contained the required capacity to adopt the new LCT penetration levels in all studies. In some studies, such as in [26], EV integration was not found as hazardous for the MV feeders as it is for the LV feeders in the near future, but higher simultaneity factors with future EV adoption rates were predicted to increase the overloading risk. Moreover, most grid impact assessment studies comprised only slow EV charging in their investigation and ignored the impact of fast chargers, which are emerging and will be connected to the MV feeders of the future DGs. Overall, while similar insights can be drawn for MV and LV DGs regarding LCT and grid type comparison, MV feeders will likely be more vulnerable to most grid impact issues than LV feeders at higher LCT penetration levels, especially when FC adoption increases further. On the contrary, concerning transformers, MV/LV T/Fs are more vulnerable than HV/MV T/Fs and will have higher and faster reinforcement needs. However, more studies are needed to investigate LCTs' grid impact on MV and LV DGs under the same conditions, to further strengthen our conclusions.

Finally, most of the real-world studies reviewed in this work focus on European countries (e.g. the Netherlands, Sweden, Denmark, Germany, Italy, Spain, etc.) and the UK. There are also a number of studies that investigate LV grids in the USA, such as in California, Arizona, and Texas, while some very limited works investigate areas from other parts of the world, e.g. Pakistan or Australia. The exact cause of this observation is not known to the authors. On the one hand, a reason could be the technological advance and the high rate of LCT adoption in Europe, which has already provoked grid issues and congestions in several distribution parts of the highly interconnected European power grid, especially in the Northern-Western countries, such as the Netherlands, Germany, Belgium, etc. On the other hand, the authors assume that such grid impact assessment studies in other countries with vast adoption of LCTs, e.g. China, are published in their native languages or they are communicated via different forms than scientific articles (e.g. presentations, reports, etc.). Nevertheless, a multi-country and multi-continent grid impact assessment of LCT integration can provide crucial insights into the challenges of LCT adoption around the world and the differences between LV and MV DGs of different countries and is, thus, highly recommended for future research.

5. Conclusions and future work

In this work, a literature review assessment has been realized regarding the grid impact of PVs, EVs, and HPs in LV distribution grids. Various investigated issues have been summarized for different LCT combinations while research characteristics have also been incorporated, such as penetration levels, seasons, grid types, uncertainty management techniques, and followed approaches. The grid impact level of the most investigated grid issues has been analyzed while different grid types and LCTs have also been compared concerning their violation levels. Finally, mitigation solutions have been summarized and correlated with respective grid issues. Results have shown that mitigation effects can be observed for PVs-EVs and PVs-HPs combinations, especially for voltage violations without extra solutions. Moreover, rural grids were found to be more vulnerable to voltage deviations and unbalance while suburban grids were more associated with transformer and line overloading.

While power profiles, voltage deviations, and component overloading have been extensively analyzed, other grid issues such as unbalance, losses, and harmonics are still inefficiently investigated. Additionally, future studies that comprise both grid impact assessment and mitigation solutions for the PV-HP and EV-HP grid integration can strengthen the existing knowledge for the combination of these technologies. Comparisons between different grids, seasons, approaches, and LCTs for various grid issues are especially important and recommended for future research so that the grid operators are prepared for the forthcoming risks of energy transition to the distribution grids. Finally, while there is extensive existing literature about European countries, multi-country grid impact assessment studies that also comprise DGs from other countries in the world are still missing and can give further light on the extent of the generalization of the already known insights.

CRediT authorship contribution statement

Nikolaos Damianakis: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Gautham Ram Chandra Mouli:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Pavol Bauer:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nikolaos Damianakis reports financial support was provided by Dutch Research Council.

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Data availability

Data will be made available on request.

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