

Integrated long-term energy planning with vehicle-to-grid for decarbonization of the Chilean energy system

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HIGHLIGHTS

- The study explores EVs' impact on Chile's energy transition pathways.
- Distribution upgrading costs are included in the long-term energy planning model.
- V2G and PV show synergy via storage use in electric vehicle batteries.
- Distribution costs strongly influence EV adoption in future scenarios.

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ABSTRACT

In this paper we implement a long-term multi-sectoral energy planning model to evaluate the role of electric mobility and Vehicle-to-Grid (V2G) and its potential synergy with renewable development for the decarbonization of the Chilean energy system, a country with a high renewable potential. The contributions of this paper are both methodological and policy-oriented. On the one hand we extend the energy ETEM-Chile planning model to incorporate the V2G dimension and distribution upgrading costs, usually not considered in such models. On the other hand, our results deliver interesting policy insights. They show that distribution costs are important to consider as otherwise it can lead to an over-electrified system with under-estimated system costs of about 6%. The incorporation of V2G technology results in significant system cost benefits from the use of V2G both for demand management and as system reserve. Under stringent climate objectives, we observe (i) a synergy between V2G and solar photovoltaics, with storage of intermittent production in vehicle batteries relying mainly on public charging stations, and (ii) a disappearance of green-hydrogen-based power plants in the electricity mix.

1. Introduction

Due to global growing trends in greenhouse gas (GHG) emissions, a transition to more sustainable energy systems is becoming increasingly urgent as the world faces the impacts of climate change (IPCC, 2021). Countries are aiming to reach Net Zero carbon emissions by 2050 (or earlier), with decarbonization of their whole-energy systems representing one of the main challenges worldwide. Common energy systems decarbonization pathways that have gained momentum over the last decades include electrification and hydrogen uses for heating

and transport (Ruhnau et al., 2019), along with increasing shares of variable renewable energies (VRE) in power systems (Hannah Ritchie and Rosado, 2020).

Electrification of energy services together with increased uptakes of VRE require incorporating technologies that are able to provide flexibility, along with decoupling electricity supply and demand, to ensure a robust power supply in future decarbonized systems. Energy storage systems can play a key role to provide these services to the grid (Olabi et al., 2021), as they are able to (i) increase grid stability

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and reliability, as the grid can better balance electricity supply and demand; (ii) reduce energy costs, as decoupling supply and demand allows to consume energy that was produced in cheaper hours; and (iii) enhance resiliency and emergency response, as energy storage systems provide backup power during emergencies such as natural disasters or power outages (Ould Amrouche et al., 2016).

Growing trends in electric vehicles (EV) adoption bring a large amount of storage capacity into the system. In that context, one expects the deployment of networks of distributed energy resources (e.g. Virtual Power Plants) which consist in clusters of VRE, energy storage, generation systems, and consumers, who connect to electricity grids in a virtual power plant, supplying and managing electricity services to the grid (Inci et al., 2022). These virtual power plants can include clusters of electric vehicles, which not only consume electricity from the network, but also are able to store electricity and supply it back to the grid in what is called vehicle-to-grid (V2G) structures. Alongside lowering GHG emissions from the replacement of fossil fuel vehicles (assuming a decarbonized electricity grid), V2G can offer the aforementioned advantages of energy storage systems, thereby potentially giving owners of electric vehicles financial value (Steward, 2017). It can also provide ancillary services such as ramp-up and -down regulation services, thereby lowering the need for fossil fuel-fired power plants (De Los Rios et al., 2012).

As with many technologies, it can become a complex task to assess V2G's suitability and cost-effectiveness in energy systems. Integrated long-term energy planning models are tools that can support decision-makers to assess cost-effective decarbonization pathways of energy systems worldwide, looking at the impacts and interrelations of different technologies. Different authors have implemented energy planning models to assess V2G benefits and potential impacts in decarbonizing energy systems. In Babonneau et al. (2023), authors implement an integrated deterministic approach to evaluate synergies among renewable energies, electric mobility, and V2G in the Isle of Pines, New Caledonia. As battery storage systems' costs are decreasing, and electric vehicles' batteries can be used as energy storage for the system, the authors conclude that VRE can increase their penetration to up to 94% without an increase in the total system's cost when V2G is available. Prebeg et al. (2016) implement a long-term energy planning model of the Croatian power system, focusing on the integration of electric vehicles with V2G, considering a fixed forecast of electric vehicles penetration. They conclude that V2G could help to provide balance between supply and demand, but conventional energy sources would still be needed for providing reserve at higher shares of VRE. Lund and Kempton (2008) apply the EnergyPlan model (Aalborg University, 2023) to assess the possible benefits of V2G in a system with significant wind potential. EnergyPlan is a general energy system analysis tool to evaluate regional or national energy systems. Their results show that higher shares of wind energy can be achieved when V2G is enabled, as it can maximize the available plant factors of wind farms by decoupling supply and demand, favoring VRE scenarios. Wei et al. (2022) also evaluate possible benefits of including V2G as flexible energy storage in integrated energy systems. They use an optimization-based system planning framework, which allows to incorporate stochastic features of electric vehicle fleets. They conclude that when V2G is enabled in integrated energy systems, higher reductions on cost and emissions are achieved in the first stages of electric vehicles penetration.

On the other hand, green hydrogen has also been recognized as a key energy carrier that can be used as storage for VRE; or directly to decarbonize hard-to-abate sectors, such as heavy-duty transport, shipping and aviation, and specific industrial sectors (Staffell et al., 2019). Hydrogen is also gaining track, with many long-term energy planning models being implemented in different case studies to assess hydrogen's cost-effectiveness for energy systems' decarbonization (Brey, 2021; Choi et al., 2022; Ferrada et al., 2023). To date, however, green hydrogen and V2G have not been studied together to investigate possible complementary features in long-term energy systems' planning.

Moreover, most long-term energy planning models consider the costs of electricity and hydrogen generation, transmission infrastructure, and end-use technologies, but neglect the costs of electricity and hydrogen distribution infrastructure. This is critical for studying the role of hydrogen end-use technologies such as fuel cell vehicles, boilers, or combined heat and power units which would require hydrogen delivered; as well as when assessing electric vehicles and the role of V2G technologies which make extensive use of distribution grids. In both cases, important investments are required for building new or upgrading existing power distribution infrastructure ensuring the system's stability, reliability, and efficiency.

The objective of this article is to evaluate the role of V2G and its possible benefits when assessing decarbonization of integrated energy systems in the long term, in a system which expects high shares of VRE and green hydrogen, such as the Chilean energy system. Indeed, the country's energy matrix already shows a large penetration of renewables: as of October 2024, 64.7% of the installed capacity come from renewable energy sources, with wind and solar power contributing with 43.7% (the remaining 21% correspond mostly to hydroelectric power). Wind and solar also accounted for 33.6% of the total generation in 2024 (Coordinador Eléctrico Nacional, 2024). Moreover, multiple projects for new wind and solar plants are currently under evaluation.

We consider as a starting point the work done by Ferrada et al. (2022, 2023) and Babonneau et al. (2021), where the Chilean energy system was modeled using the ETEM model (Babonneau et al., 2012), including the energy supply and demands of commercial, residential, transport, and power sectors. The Chilean energy system is an interesting case study because of its high VRE plant factors. Due to its low electricity prices, green hydrogen has been shown to be able to reach favorable conditions for deployment (Ferrada et al., 2023); in fact, the country designed in 2020 a progressive National Green Hydrogen Strategy which includes the incorporation of hydrogen heavy-duty trucks and long-haul buses in the medium-term (Ministry of Energy, Government of Chile, 2020). This leads to possible transport sector scenarios in which end-use technologies such as fuel cell electric vehicles (FCEV) and electric vehicles could compete with each other. Additionally, Chile has an ambitious National Electromobility Strategy, which aims — among other goals — for 100% of new private and urban public vehicles sales to be zero-emissions by 2035, including electric and hydrogen vehicles (Ministerio de Energía, 2021).

The main contribution of this work is that it assesses the incorporation of V2G in highly renewable energy systems, using an integrated energy planning model which incorporates the whole energy system, from generation to end-uses, including distribution infrastructure costs of V2G and green hydrogen technologies (see Ferrada et al., 2023 for more details on the latter), which are normally neglected in these types of models. V2G is modeled in two different application scenarios: 1. An *Optimal Charging* scenario, which seeks to optimize the system's installed generation capacity by re-scheduling EV charging hours, thus leading to possible peak shaving services and customers' costs reductions; and 2. A *Vehicle-to-Grid* scenario, in which vehicles can also supply electricity and provide ancillary services to the electricity grid, together with load rescheduling. Both scenarios are compared against a *Charging-as-Usual* scenario which simulates the current charging practices, without any optimization or V2G abilities.

This article is structured as follows; Section 2 describes the methodology and the application scenarios, Section 3 presents results and discussions, and in Section 4 we present some conclusions from the study as well as policy implications.

2. Methodology

This section first describes the ETEM-Chile model as developed in Ferrada et al. (2022, 2023) and Babonneau et al. (2021) and then its extension to include V2G mechanisms and power distribution upgrading costs.

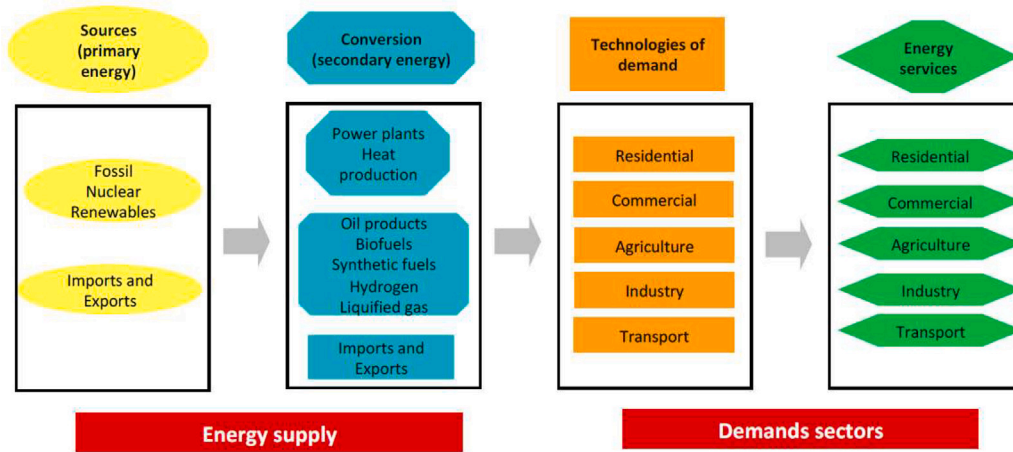


Fig. 1. Illustrative diagram ETEM model.

2.1. ETEM-Chile model: A brief description

The original version of the Energy Technology Environment Model (ETEM) is a multi-sector linear programming model rich in energy technologies that explores efficient scenarios of capacity expansion and resource flow throughout the energy system. It was designed to analyze the energy transition at the nodal and system level covering a long-term planning horizon. The structure and body of the model are inspired by the MARKAL/TIMES family of models (see Berger et al., 1992, Fragnière and Haurie, 1996 and Loulou and Labriet, 2008) and was developed in the AMPL programming language. In Appendix A, we briefly present the main equations of ETEM to highlight its logic. A more detailed description of the ETEM model can be found in Babonneau et al. (2017).

The ETEM model is driven by exogenously defined useful energy demands and imported energy prices. All technologies are defined as resource transformers and are characterized by technical coefficients describing the input and output, efficiency and economic parameters such as investment costs, maintenance costs and useful life (see Appendices B.1 and B.2). Fig. 1 shows an illustrative schematic of the model.

The ETEM model contemplates a planning horizon that is divided into 8 periods of 5 years (from 2015 to 2050); the length of the horizon is long enough to allow for a full rotation of the technology mix in the energy system. Each model period is disaggregated in 8 typical days, i.e., one for each season $s \in S$ (Summer, Autumn, Winter, and Spring) and by weekday/weekend. In addition, each day is disaggregated into 24-h time slices to represent hourly load curves, demand distribution and resource availability in different seasons. This temporal structure is particularly important to correctly represent the dynamics of demand and how its flexibility can be exploited (e.g. through demand response mechanisms, optimal charging of EV batteries). ETEM calculates an investment plan and a supply/demand balance at each time slice for a set of typical days. In order to adapt to possible variations in demand (in particular, peak demand) and to compensate for the intermittency of variable renewable (e.g. wind and solar), reserve requirements are then modeled in ETEM (Babonneau et al., 2017).

The implementation of ETEM for Chile, i.e., ETEM-Chile, has been detailed in Ferrada et al. (2022, 2023). It simulates and evaluates the transition of the Chilean energy system towards a low carbon economy by 2050. ETEM-Chile includes a representation of the electricity, residential, commercial and transport sectors. In this version, the Chilean transmission grid is represented through 9 nodes and 8 transmission lines, as illustrated in Fig. 2. Demands for electricity, residential heating, commercial heating and cooling and transport (private, public,

inter-regional and freight) are defined exogenously at each node (see Fig. 3 and Appendix C.). All demands are calibrated on the medium scenario trend defined by the Ministry of Energy by 2050 (Ministerio de Energía, 2022).

The model includes equations representing the classical state of charge dynamics of the EV batteries for all typical days as described in Babonneau et al. (2016). It is assumed that each day operates as a closed loop, with the state of charge at the beginning and end of the day being equal. EV batteries connected at each transmission node of the grid are aggregated into one large equivalent battery. These assumptions are classical of such global long-term energy models.

ETEM-Chile looks for an optimal transition minimizing the total system's discounted cost over the whole trajectory, including the costs of investments, maintenance and operations of technologies, energy imports, and reinforcement of the transmission power grid (Babonneau and Haurie, 2019).

The ETEM-Chile model was chosen for this case study as it allows to trade-off multiple technologies, multiple energy vectors, and multiple sectors simultaneously, leveraging the operation of these technologies and their investment and operation costs. Specifically for this case study, the ETEM model allows to include costs and capacities of distribution networks, accounting for multiple end-use technologies connected to them, and modeling their potential impacts at a national scale. Alternative models to study V2G technologies include simulation models (e.g. Mehra et al., 2023, Li et al., 2021) or agent-based models (Yu et al., 2024) examining charging strategies and real-time operational dynamics. However, generally these models do not capture the interactions with the wider energy system (vectors and sectors). The model has been previously validated for Chile in Ferrada et al. (2022, 2023).

2.2. Extension to power distribution costs

Electrification of energy services and, in particular, the increasing use of electric vehicles, will have a significant impact on electricity distribution grids, which will need to be upgraded to properly integrate these new demands. Although the costs of upgrading could significantly affect the optimal transition pathways, they are usually neglected in long-term energy planning models, partly because the distribution grid is not modeled and the associated costs are difficult to quantify (Babonneau et al., 2016). In previous versions of ETEM-Chile, only transmission reinforcement costs are considered (Ferrada et al., 2023). We propose here to use the Added Value of Distribution (AVD) as a proxy to estimate the costs of distribution upgrading. This AVD

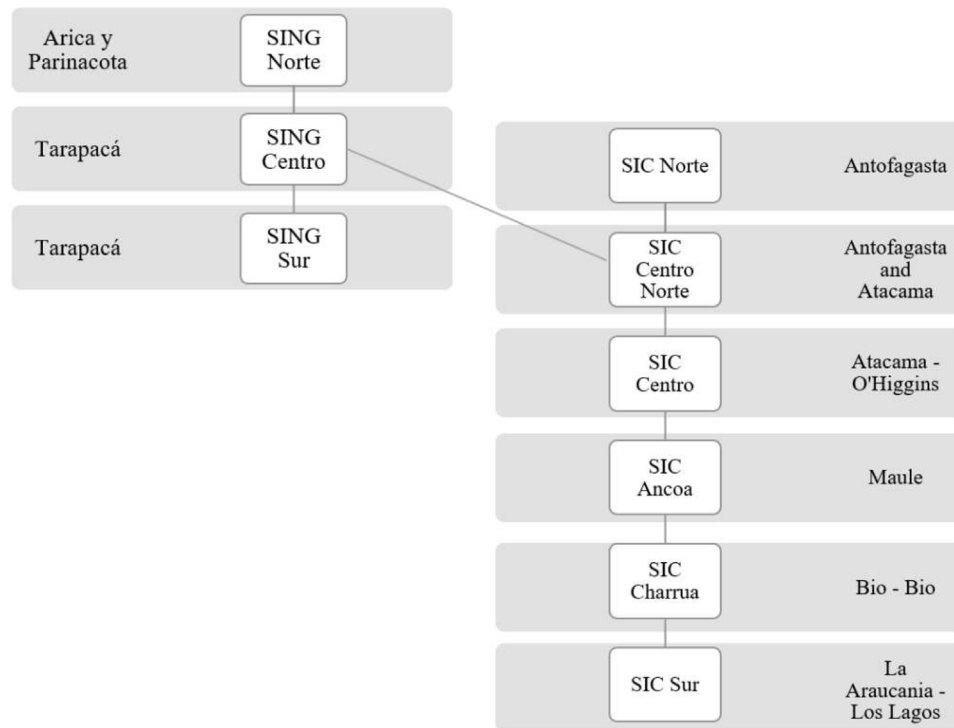


Fig. 2. Diagram of transmission lines and representative nodes from Babonneau et al. (2021). White boxes represent the nodes that simplify the national electricity system, while the names in gray rectangles represent the approximate geographic location in Chile's regions covered in this study.

is defined by the Chilean government as one of the components of the electricity price for consumers.

Chilean legislation states that for all regulated customers (normally with an installed capacity of less than 500 kW), the electricity price is set considering that end users have no bargaining power in a natural monopoly system. For all regulated customers, the electricity price has three main components: (i) the nodal price, which indicates an average cost related to generation and transmission, usually constructed with the energy supplied and the monthly peak power; (ii) a single charge for using the transmission system, which is an additional charge related to the use of the transmission system facilities; and (iii) the AVD, which aims to reflect the cost of distribution. More detailed can be found on the regulator website <https://www.cne.cl/tarificacion/electrica/precio-nudo-corto-plazo/>.

The AVD is set every four years by the Ministry of Energy, based on a technical report by the National Energy Commission (Comisión Nacional de Energía, 2022), which broadly corresponds to an average cost that includes all investment and operating costs of a theoretical distribution company operating in a practical environment. The methodology used to estimate the AVD for the period 2024–2028 takes into account the information of all current distribution companies connected to the National Electricity System. The method — which is defined by the Ministry of Energy — consists in conducting an econometric analysis to estimate the distribution costs of the industry, followed by a K-means clustering technique to identify typical distribution areas based on the population density. Finally, the AVDs are adjusted to the resulting areas for each distribution company. Table 1 summarizes the resulting AVD for each company from Comisión Nacional de Energía (2022), as well as the corresponding installed capacity of low and high voltage networks within the company operations area.

In our study, we use the weighted average AVD, i.e., 180.32 USD/kW, as the unit cost of upgrading the distribution grid. We assume that this unit cost is representative of the estimated distribution

Table 1

AVD and installed capacity of high and low voltage per distribution company connected to the National Electric System from Comisión Nacional de Energía (2022).

Company name	High and low voltage capacity (kW)	AVD (USD/kW)
Chilquinta	443 382	189.9
Emelca	2 535	544.7
Litoral	28 608	341.2
Enel	2 457 805	108.9
EEC	16 387	291.7
Til Til	3 336	398.8
EEPA	57 221	169.5
CGE	2 572 871	173.7
Coopersol	464	723.0
Coopelan	18 203	636.6
Frontel	148 044	578.8
Saesa	402 136	277.9
Endelaysén	19 669	548.2
Edelmag	36 486	290.6
Codiner	14 067	609.4
Edecsa	18 335	242.1
CEC	36 125	186.8
LuzLinares	18 066	565.9
LiuzParral	20 134	533.5
Copelec	30 104	762.5
Coelcha	7 412	937.1
Socoepa	6 312	707.0
Cooprel	7 323	530.7
Luz Osorno	23 023	472.0
Crell	12 285	651.2

cost per installed capacity in the system and that it is constant over the entire horizon. Note that we are aware that this estimate may appear very approximate. However, it is a first attempt to introduce distribution costs into a long-term energy planning model such as ETEM. Given the uncertainty surrounding this estimate, we perform our numerical experiments with and without these distribution costs in order to analyze their possible impact. In the following, these two

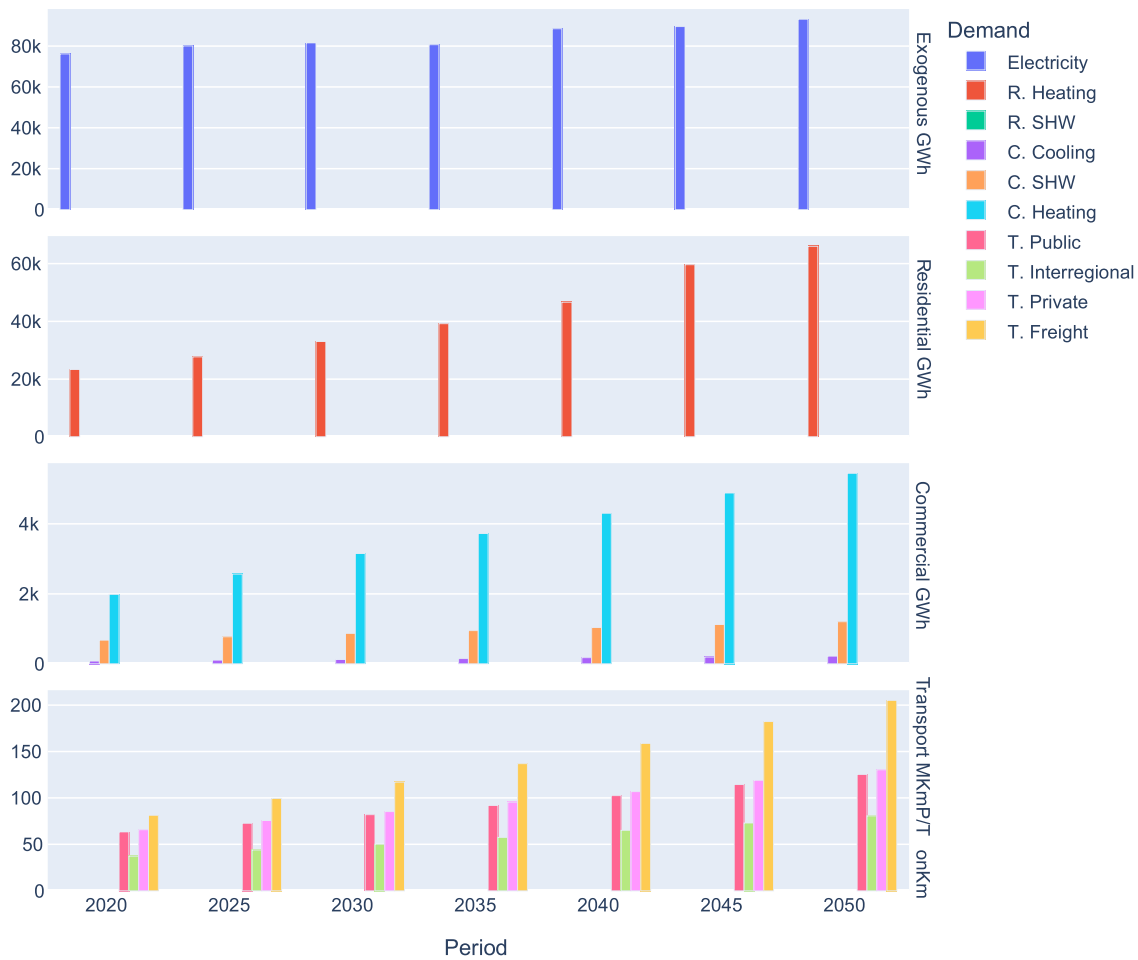


Fig. 3. Energy demands considered in Ferrada et al. (2023). R: Residential sector. C: Commercial sector. T: Transport sector. SHW: Sanitary hot water.

scenarios are called *DistCosts* and *NoDistCosts*, respectively. As discussed in Section 3, we also conduct some sensitivity analysis on the estimate of the distribution cost in order to take its uncertainty into account.

2.3. Modeling EV charging and V2G

In this section, we describe the modeling of electric vehicles within the power sector and the different settings and charging/V2G features used in the numerical simulations. We assume that the system handles different types of vehicles (e.g., private cars, public buses and trucks) characterized by their mobility demand and their charging station infrastructure. In this paper, we consider the following charging stations:

- Level 1, 7 kW AC, usually located in houses and residential buildings, where they require a power connection increase and hardware.
- Level 2, 22 kW AC for public stations
- Level 3, 80 kW DC for commercial purposes such as buses and trucks (Nicholas, 2019).

We assume here that only batteries connected to houses and residential buildings can have controllable charging and can contribute to V2G mechanisms. We define below the possible scenarios considered in the numerical experiments.

Note that the EV charging and V2G strategies implemented in this study relies on a simplified representation of charging and discharging behavior. This modeling choice is intentional mainly to keep the model tractable. The primary objective of the paper is not to develop an

operational or highly detailed short-term V2G model, but rather to assess the potential long-term impact of V2G on energy policy and system planning. To that end, we adopt a stylized yet representative modeling approach that enables us to explore contrasting scenarios (e.g., with or without V2G) and evaluate how V2G integration may influence key system outcomes, such as investment needs, storage deployment under different emissions trajectories.

2.3.1. Defining charging strategies

In ETEM-Chile and similar bottom-up models, charging activities are defined at an aggregated level and are driven by endogenous marginal electricity prices, which correspond to the dual variables associated with the power balance constraints. The resulting charging strategy is said optimal according to the capacities and the operations of the current energy system. In this context, EV batteries will be charged when implicit electricity prices are at their lowest, for example during periods of excess generation from intermittent sources and/or low demand. This corresponds to an optimal charging (OC) scenario in which a global aggregator decides the most efficient charging strategy for the whole energy system. The strategy is said optimal from a social perspective for the entire energy system.

To evaluate the impact of the OC scenario on the energy transition, and in particular its synergy with intermittent energy sources, we define a charging as usual (CaU) scenario, which simulates the current charging practices. These practices consist of, for example, charging the vehicles when customers are back home from work, causing a peak in electricity demand in the evening. To evaluate the contrast between the OC and CaU scenarios, it is thus necessary to establish occupational profiles of the chargers, which simulate the expected behavior of a large

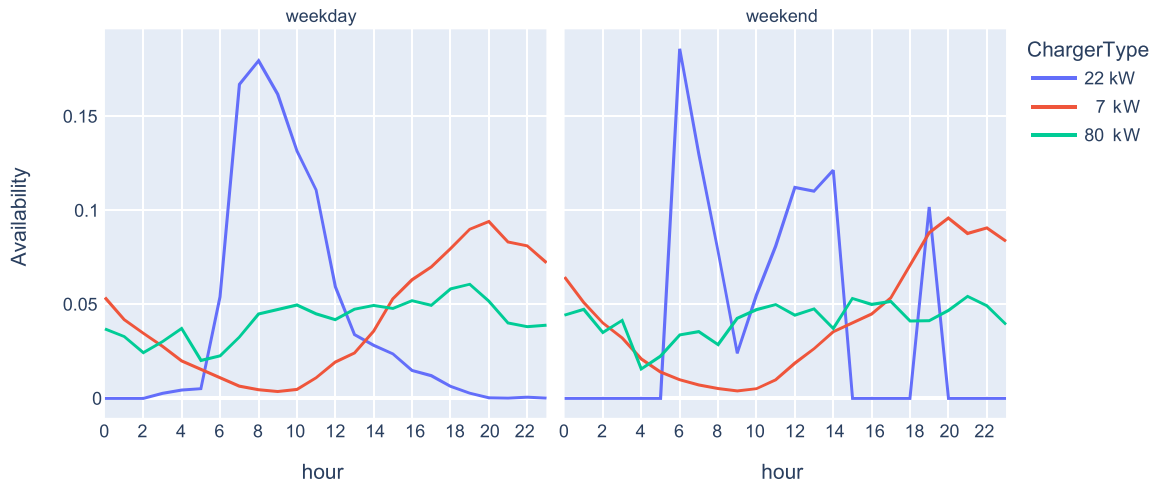


Fig. 4. Utilization profiles for chargers obtained from simulation developed in Gaete-Morales et al. (2021).

number of people, and define the availability factor of the chargers based on their utilization. For this purpose, we consider the study in Gaete-Morales et al. (2021), where 200 load profiles for cars in Germany are considered. The study aims to present an open source Python tool called *emobpy*, which allows users to simulate the charging behavior of vehicles based on mobility statistics, physical properties of electric cars and general assumptions. We thus define occupational profiles of chargers based on this data, for residential, public and commercial services. Fig. 4 shows the resulting charger profiles from aggregating simulated profiles available from Gaete-Morales (2021). These profiles are then used as fixed constraints for charging batteries in the CaU scenario.

2.3.2. V2G calibration

The implementation of V2G will enable the network operator to use the electricity stored in the batteries to both meet demand and contribute to the reserve to cope with the intermittency of renewable energies. This scenario, referred to hereafter as the V2G scenario, is obviously limited by the number of electric vehicles potentially connected to the network at any given time, and by the proportion of users willing to participate in the V2G mechanism. Several factors are considered to calibrate V2G activity. First, it is well-known that cars spend most of their time parked, even during peak hours when only 5% of vehicles are in use (Barter, 2013). Secondly, Uddin et al. (2017) concludes that in a smart grid ecosystem aiming to take advantage of V2G when there is a high share of renewables, battery capacity degradation can be mitigated in up to 9.1%, while power fade can reach 12.1% compared to what is expected when there is no activity in the battery when the car is parked. Finally, the authors in Prebeg et al. (2016) assume 25% of vehicles are available for V2G, considering that the remaining battery capacity after a driving cycle is 50% on average, and that half of vehicle owners have the willingness to engage in V2G. With regards to these studies, it seems to be a common approach to consider 25% of the total capacity of car batteries available for V2G. This capacity takes into account the energy that the battery can inject back to the system, as well as the potential energy that can be used as reserve. In our results, we observed that such percentage is actually an upper bound since the real constraint is given by the chargers.

In addition, it is reasonably assumed that electric cars can contribute to V2G only through 7 kW residential chargers. It seems unlikely that anyone will agree to inject power back to the grid when temporarily connected to a commercial charger. Finally, it is also assumed that this smart V2G scenario can be combined with the optimal charging (OC) scenario as defined previously.

Table 2

Scenarios names according to type of charging allowed and emissions reduction policy.

Charging/V2G scenario	Emission reduction policy scenario		
	Free	84%	100%
Charging as usual strategy	CaU_Free	CaU_84	CaU_100
Optimal charging strategy	OC_Free	OC_84	OC_100
V2G with optimal charging strategy	V2G_Free	V2G_84	V2G_100

2.4. Summary of scenarios definition

In order to see the possible contributions of optimal charging strategies and V2G in the system, and the possible impacts when coupled with emission reduction policies, we consider the implementation of the combination of different scenario of Charging/V2G (CaU, OC and V2G) together with three different emission reduction policy scenarios: (i) *Free* scenario: it is assumed that no emission reduction policies will be implemented. This is included for benchmarking purposes; (ii) *84%* scenario: in line with Ferrada et al. (2023), 84% reduction of carbon dioxide emissions represents reaching carbon neutrality when the sectors not considered in this study follow their historical emissions trend, and land use, land use change, and forestry sectors induce net negative emissions; and (iii) *100%* scenario: this scenario represents a 100% reduction of carbon dioxide emissions by 2050. Both 100% and 84% scenarios assume a linear trend of emissions reduction from 2035 to 2050. It is also important to note that 84% and 100% are percentages of what is emitted in the model in the last period without emission boundaries (65 million tons). Table 2 summarizes the specifics of each simulation scenario.

Finally, given the uncertainty on the estimated costs for the distribution grid upgrade, we simulate the above scenarios with (*DistCosts*) and without (*NoDistCosts*) distribution costs.

3. Results and discussions

In this Section, we describe the numerical simulation results for the different scenarios of charging methods, emission reduction objectives and distribution costs. We first discuss their impact on the electricity sector and then on the evolution of the transportation sector. Finally, we present the economic benefit of the advanced charging methods.

3.1. Impact on the electricity sector

Figs. 5 and 6 depict the installed capacity and energy generation in the electricity sector in 2050 for the different scenarios, respectively.

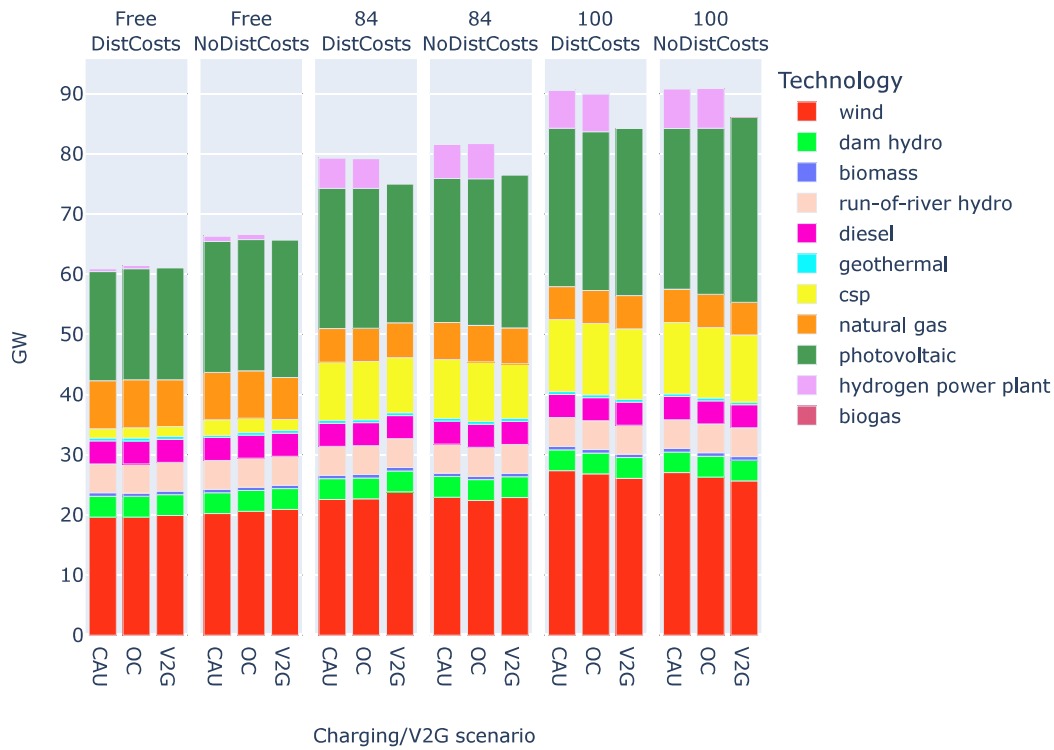


Fig. 5. Installed capacities in the power sector in 2050 for the different scenarios.

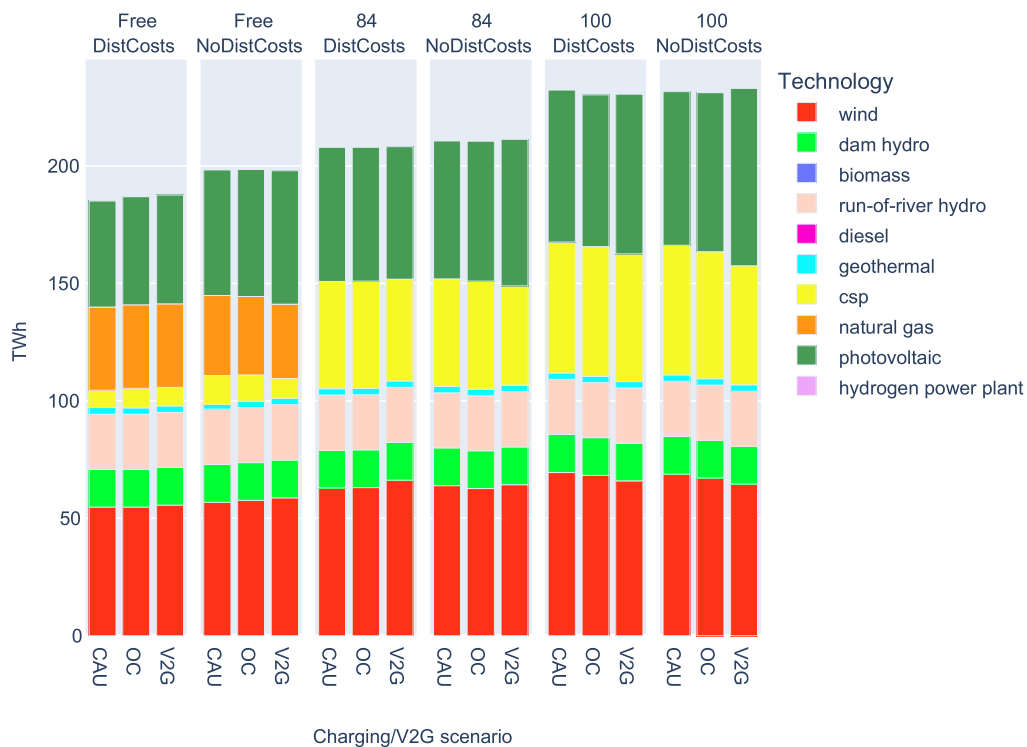


Fig. 6. Total electricity generation in the power sector in 2050 for the different scenarios.

In all scenarios, we observe a high penetration of renewable energy sources, mainly PV, CSP and wind. Note that although Fig. 5 shows diesel and natural gas power plants installed capacity, we see in Fig. 6 that natural gas power plants are only used in the two Free emission scenarios, and diesel is never used. No fossil fuel power plants generate electricity in 2050 in the other emissions scenarios.

As expected, the more stringent the emission reduction target, the more electrification of the system takes place, including electric mobility and heating.

Regarding electric vehicle charging and V2G strategies, we observe that optimal charging (OC) has a relatively small impact on the electricity system compared with the CaU scenario—although we

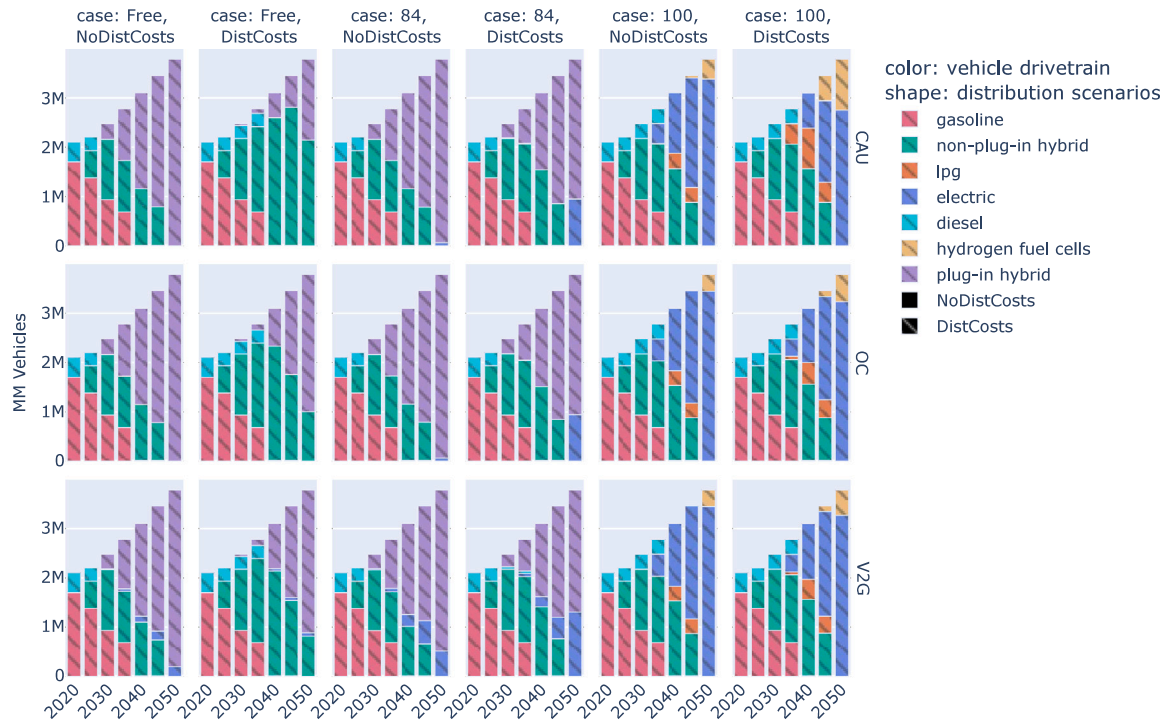


Fig. 7. Evolution of light vehicle technologies over time for the various scenarios considered in the study.

see, for example, that in the 100% emissions reduction scenario with distribution costs, the installed capacity under CaU is slightly larger than under OC, even though there are more electric vehicles in the latter case (as will be discussed in Section 3.2). This phenomenon shows the effect of OC in “flattening” demand, thereby requiring less capacity. In the V2G scenario the difference is starker, as the installed capacity is significantly lower, not only because of demand management (as in OC), but also because of the contribution of V2G to the system’s reserve capacity. It is also worthwhile observing that in the CaU and OC scenarios the model invests in hydrogen power plants to achieve high levels of emissions reduction (84% and 100%) as the use of hydrogen as a power source provides stable generation and contributes to the system’s reserve. In contrast, when V2G is implemented the power system relies on electricity stored in the vehicle batteries to provide stability and reserve. Thus, in the V2G scenario there are no hydrogen power plants, and PV capacity significantly increases for the 84% and 100% emissions reduction targets. As expected, there is a desirable synergy between V2G and PV penetration.

Finally, Fig. 5 also shows that when distribution costs are considered, the model slightly decreases the power system’s installed capacity (and ultimately the electrification of the system), except for the 100% emissions reduction objective. In this scenario, the stringent target enforces a high level of electrification. On the other hand, when distribution costs are not considered, we observe a higher system electrification (e.g. heating and transport), which translates into a higher power system’s installed capacity, particularly through investments in PV.

3.2. Evolution of the transportation sector

In this section we discuss the differences in the evolution of vehicle technologies for the various scenarios of charging methods, emissions reduction policies and distribution costs, as shown in Fig. 7.

Fig. 7 shows that as the emissions constraint is tightened, electric cars replace plug-in and non-plug-in hybrid cars — and even hydrogen fuel cell cars for the 100% reduction scenario — in 2050. For the latter, we observe that not considering distribution costs tends

to overestimate the share of electric cars, as it underestimates the associated charging costs. One interesting point to note is that, in the scenario with 84% emissions reduction (in all charging scenarios), there is a larger penetration of electric vehicles when distribution costs are considered, compared to the cases with no distribution costs. At first sight such a result is counter-intuitive; however, an explanation can be obtained by looking at the activity of the entire electric sector in the cases with and without distribution costs, shown in Fig. 8 for the CaU scenario. The figure shows that the total installed electric distribution capacity is larger in the case without distribution costs (which is expected) — resulting in the electrification of other sectors and fewer electric vehicles. In the case without distribution costs, the benefit of electrifying residential heating is larger than that of fully electrifying the vehicles, resulting in a higher residential heat electrification in the 84% reduction scenario. This phenomenon does not occur in the 100% scenario, where the system reaches a higher level of electrification. In this scenario, when distribution costs are included the model chooses to increase the share of hydrogen fuel cell vehicles, as can be seen in Fig. 7 by examining the bars corresponding to the 100% reduction scenario in 2050. More generally, we see an optimized and more rational use of the available distribution capacity among seasons when distribution costs are considered, as illustrated in Fig. 8.

We can also see in Fig. 7 the competitive advantage that optimal charging strategies (OC and V2G scenarios) offer to electric vehicles, whose share increase in 2050 in detriment of hydrogen fuel cell vehicles, compared to the CaU scenario. It is important to observe that these results correspond to an optimized evolution of the transportation sector; we do not attempt to predict what the actual evolution will be, as in Bloomberg NEF (2023). Still, it is interesting to notice that the overall trends described in that report — such as the overwhelming penetration of electric vehicles by 2050 under a no-emissions scenario, with a small portion of hydrogen fuel cell vehicles — agree with our results, which are also in line with Chile’s National Strategy for Electromobility (Ministerio de Energía, 2021). We emphasize that the discussion in this paper revolves around *light* vehicles. As shown in Ferrada et al. (2023), the model recommends the use of green hydrogen for long-haul trucks and interprovincial buses in the emission reduction scenarios.

Detailed activity electric sector

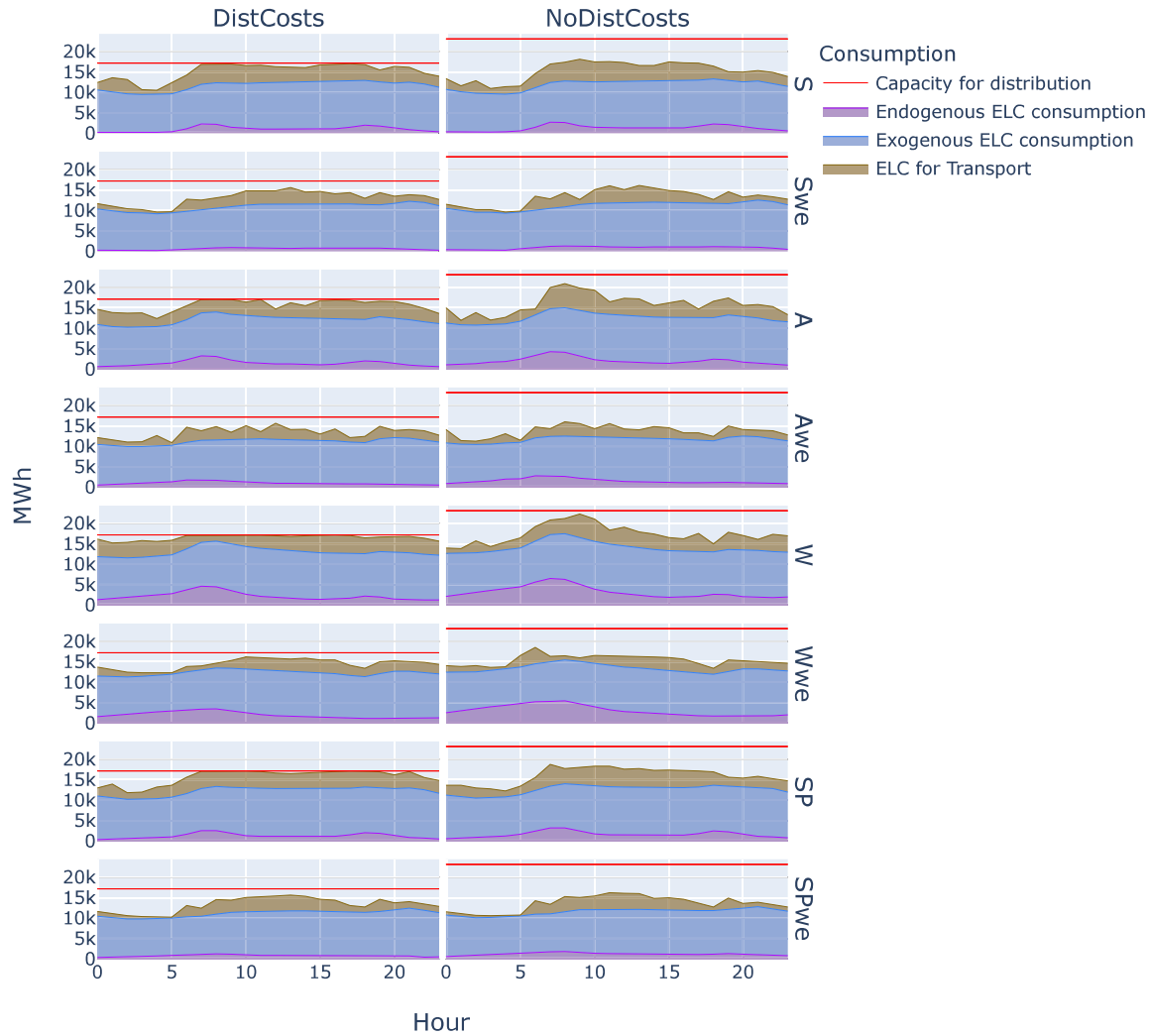


Fig. 8. Total electricity consumption and distribution capacity in 2050 for the 84% emission reduction scenario with CaU strategy. The red line represents the distribution capacity of the system which is constant over the typical days.

In order to account for the uncertainty in the estimate of the distribution costs, we conduct a sensitivity analysis on the share of each type of vehicle where the distributions costs are 50% higher than the nominal value and when they are 50% lower. Fig. 9 displays the results for the V2G scenario with no-emissions. We observe that, for higher distribution costs, there is lower penetration of EVs and higher penetration of hydrogen and LPG (Liquified Petroleum Gas) cars, the latter only until 2045.

Fig. 10 shows the charging strategy of electric cars in a representative 2050 summer day for the 100% emissions reduction scenario. In the CaU scenario, the charging profile shown in the figure corresponds to the current charging profile of the users, as the system does not interfere in the charging. For the OC and V2G scenarios, we observe again the synergy between PV generation and electric cars, with charging optimized during sunshine hours in public areas. Compared to the OC scenario, in the V2G scenario charging is anticipated during the early morning hours, and its duration is reduced in the afternoon, mainly due to the potential contribution of V2G activity as system reserve during the morning and evening demand peaks.

Note that the model invests mainly in Public chargers in the OC and V2G scenarios, because of the economies of scales of public chargers. This result is somehow unrealistic but leads to the optimal solution

from a cost-effective perspective. It provides us with a lower bound for a more realistic mix strategy between residential and public. Finally, since the share of electric cars is higher without distribution costs, we have a higher associated charging activity in these cases.

The detailed seasonal charging and V2G activity is shown in Fig. 11 for the V2G scenario. We see from the figure that the model uses solar power during the day to charge the EV, so they can supply energy at night. For instance, in Summer and Spring, this amounts to a net value of about 5000 MWh of V2G activity on a typical day. It is worthwhile noticing that in 2023 Chile had a total curtailment of about 2600 GWh (Coordinador Eléctrico Nacional, 2023). This is wasted energy that can be harnessed by further increasing the storage capacity, which can be significantly aided by EV batteries in the V2G scenario as the electric vehicles are used for that purpose. Indeed, as discussed in Section 3.1, the V2G scenario requires overall less installed capacities in the power sector than the CaU and OC scenarios.

We conclude this section by mentioning that, in previous work (Ferrada et al., 2023), we have observed that hydrogen plays a major role in meeting the demand for freight transport, even when CO₂ emissions restrictions are not very stringent. For the most ambitious carbon-reduction target, hydrogen is used in inter-provincial buses, which appears to be one of the most difficult transport sectors to decarbonize,

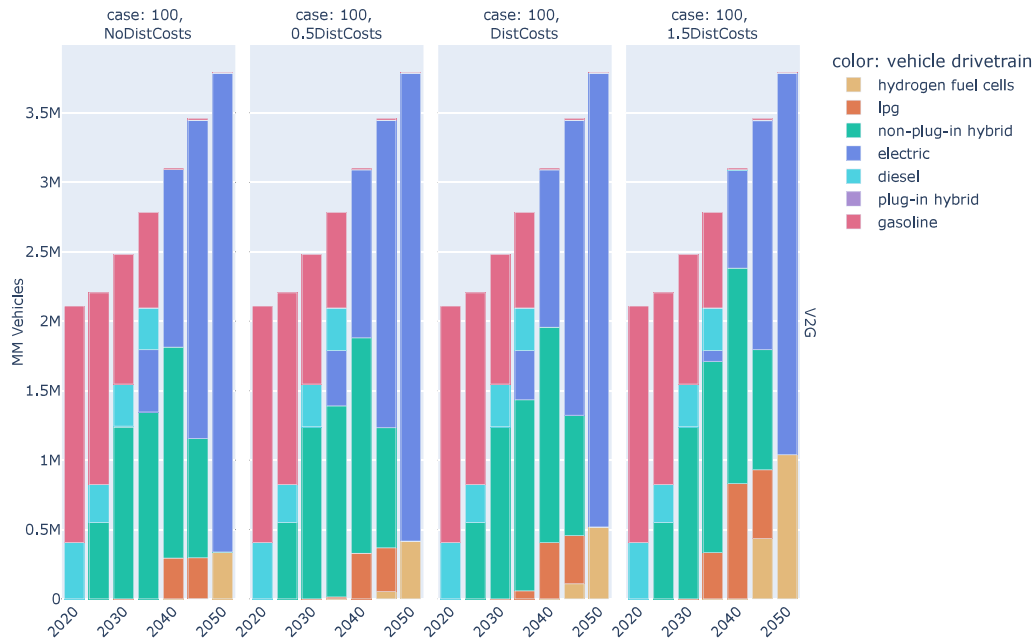


Fig. 9. Sensitivity analysis on share of vehicle technologies with higher and lower distribution costs.

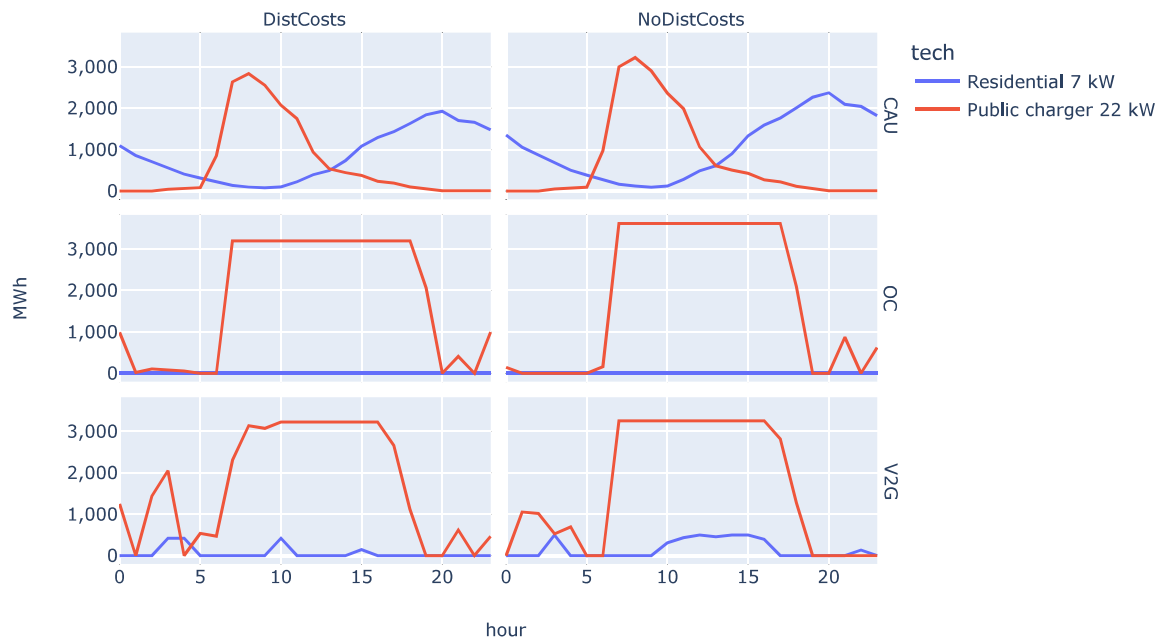


Fig. 10. Charging profiles of private electric vehicles in a 2050 summer day for the 100% emissions reduction scenario.

mainly because in Chile they require a large range (considering the country's long geography), which seems incompatible with electric mobility under our model assumptions.

3.3. Economic benefit of advanced charging methods

In this section we analyze the economic advantages of integrating advanced charging scenarios into the system. The total discounted system costs for the CaU scenarios are shown in Fig. 12. We see that, regardless of the emissions scenario considered, distribution costs represent an increase in around 6% of the total system cost, compared to the case where distribution costs are not included in the analysis. As expected, the more stringent the emissions target, the higher is the system cost.

Fig. 13 depicts the economic benefits of integrating advanced charging strategies into the system for each distribution cost case, relative to the corresponding case in the CaU scenario. The figure shows that the incorporation of V2G technology results in significant cost benefits for the system, even when distribution costs are considered. As discussed earlier, such savings result from the use of V2G both for demand management and as system reserve.

With regards to OC, in the absence of emissions restrictions, the economic benefits of OC are higher when no distribution costs are considered. This is expected, and occurs because in the "Free" scenario, the benefit consists only in being able to use the most economical hours to charge the vehicles. Hence, when distribution costs are included, the penetration of plug-in vehicles is smaller, and therefore the economic benefit of OC is reduced. On the other hand, when emissions restrictions increase (to 84%) the economic benefits of OC are lower when

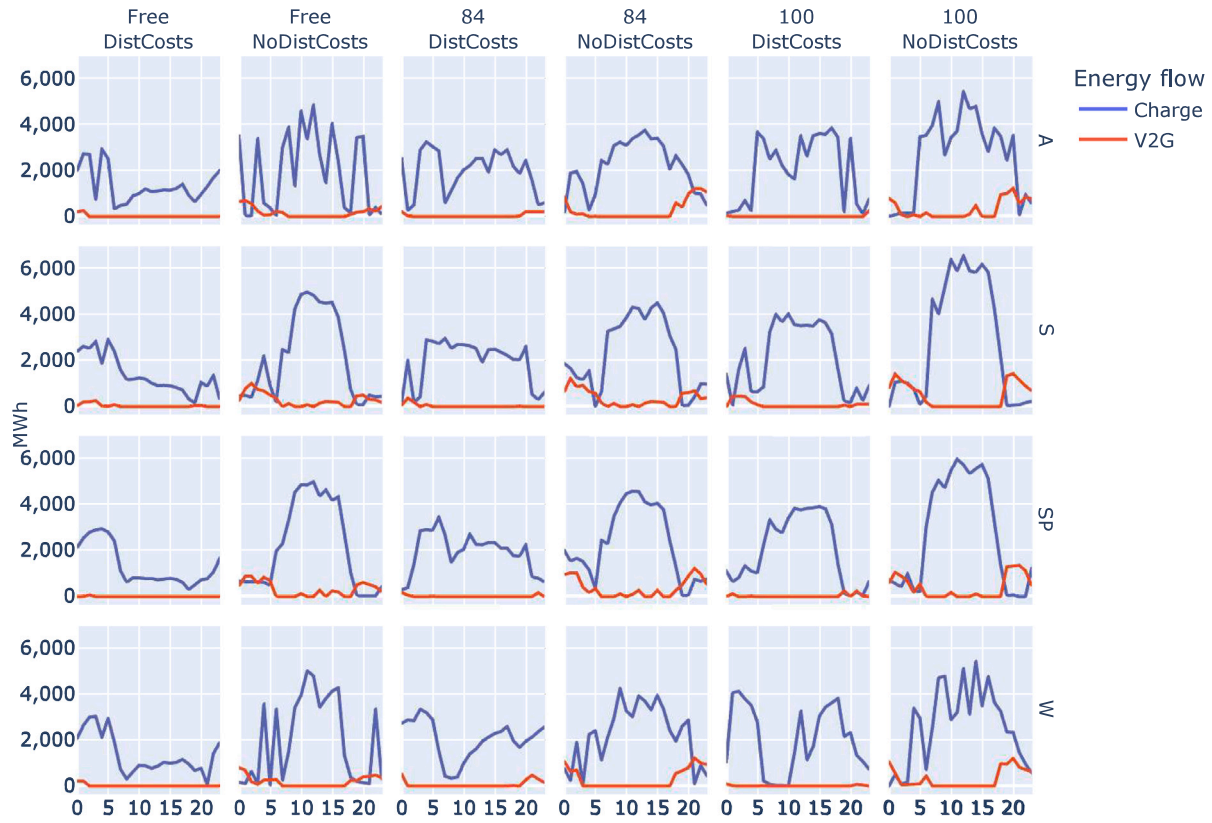


Fig. 11. Charging and V2G hourly activity for the V2G scenario.

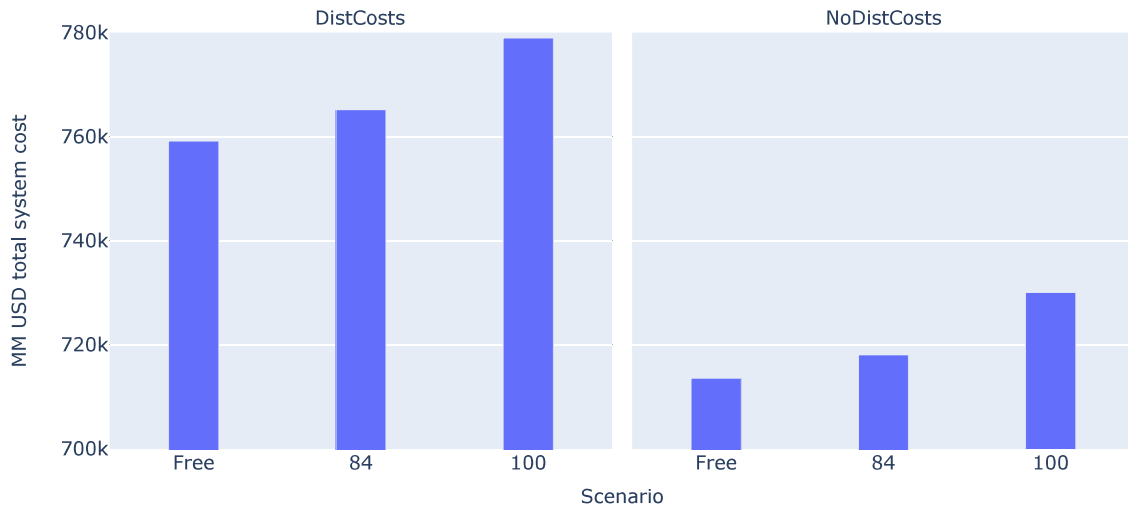


Fig. 12. Total system costs for all CaU and emissions reduction scenarios, for cases with and without distribution costs.

no distribution costs are considered. The reason is that in the scenario with no distribution costs there is a higher electrification of residential heating and hence a lower penetration of electric vehicles, as discussed previously. Finally, in the 100% emissions reduction scenario the economic benefits of OC are similar with or without distribution costs. This is because there are no reserve benefits as in the V2G scenario and, most importantly, because in the 100% reduction scenario a large portion of the vehicle fleet is electrified regardless of distribution costs. Hence the difference between the *DistCosts* and *NoDistCosts* cases amount to the difference in distribution costs, which is approximately USD 3 million — a small percentage of the total benefit. When distribution costs are not considered, the economic benefits of all OC scenarios are similar, regardless of the emissions constraint. This occurs because

in all emissions reduction scenarios the model chooses mostly either plug-in hybrid vehicles (in “Free” and 84% reduction scenarios), or full electric vehicles (100% reduction scenario) for the private transport sector — and both technologies have the option of demand shaving.

4. Conclusion

In this paper, a bottom-up multi-sectoral model ETEM-Chile is developed and used to assess electric mobility, vehicle-to-grid technologies, and their synergy with renewable generation under different emission objectives in 2050 for Chile. The ETEM-Chile model as developed in Babonneau et al. (2021) and Ferrada et al. (2022, 2023) is

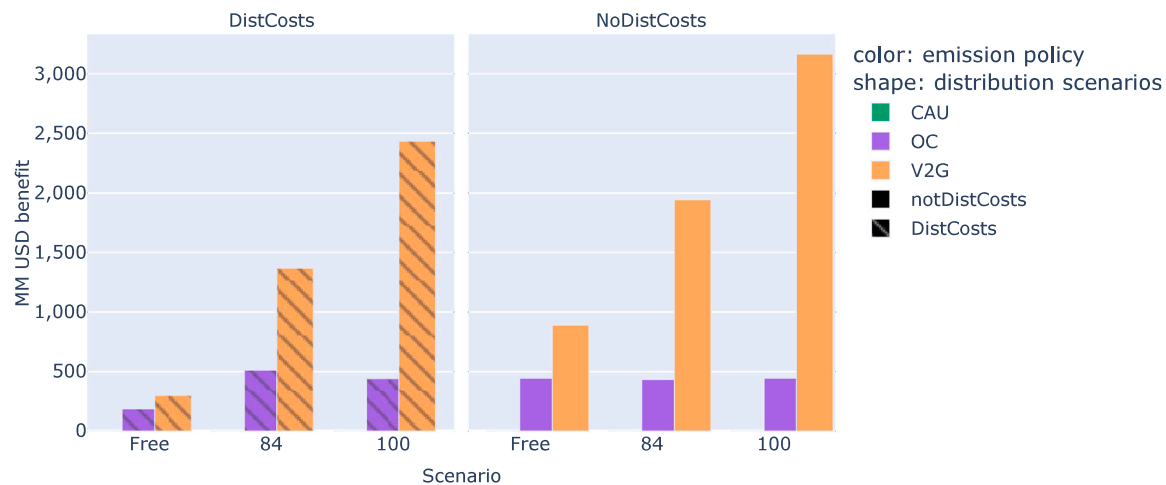


Fig. 13. System costs benefits of the three charging strategies under each emission reduction scenario, for the cases with and without distribution costs.

extended to include vehicle-to-grid mechanisms, optimal electric vehicle charging strategies, and the necessary power distribution upgrading costs resulting from a high level of system electrification. The novelty of this work is the inclusion of vehicle-to-grid technologies and power distribution costs and capacities into a long-term energy planning model, accounting for multiple end-use technologies connected to these networks, and modeling their potential impacts at a national scale while simultaneously trading-off multiple energy vectors and sectors.

Our results suggest that for a country with a high renewable potential, like Chile, and under our model calibration, electric mobility combined with vehicle-to-grid mechanisms is a cost-effective and environmentally friendly policy. It also has a very desirable synergy with solar photovoltaic deployment as it allows the system to optimally use electric vehicle batteries to charge intermittent production during the day using mainly public charging stations. In addition, the incorporation of vehicle-to-grid technology results in significant system cost benefits from the use of vehicle-to-grid for both demand management and as system reserve. By enabling a better use of electricity generation, vehicle-to-grid introduction leads to reduced installed capacity in the electricity sector (compared with other scenarios without vehicle-to-grid), partly with the disappearance of green-hydrogen-based power plants. Under stringent climate objectives, the transportation sector is almost completely electrified, leaving a small market share to hydrogen mobility. These results are consistent with the Chilean National Electromobility Strategy (Ministerio de Energía, 2021), which aims to achieve 100% of electric vehicle sales by 2035 for light and medium vehicles and public transport, and 100% of sales of emission-free freight transport and intercity buses by 2045. Regardless of the emissions target considered in each scenario, distribution costs represented an increase in around 6% of the total system cost, compared to the cases where distribution costs were not included. Not including them may lead to an over-electrified system with under-estimated system costs.

Several policy implications can be drawn from our study to accompany the transition and the profound changes expected in the transport, electricity and hydrogen sectors. First and foremost, it is essential for Chile to expand its infrastructure for electric vehicles, to accommodate an increasing share of these technologies. A proactive policy of installing charging stations is needed. These should be located mainly in public areas and shared car parks, to enable the consumption of solar-generated electricity during the day. Such expansion must be accompanied by advances in the distribution network so as to allow for the implementation of optimal charging strategies at an initial stage, and for vehicle-to-grid mechanisms later on. Although the cost of implementing a V2G mechanism can be high, our study demonstrates that V2G plays an essential role as system reserve and reduces system costs significantly—in fact, V2G allows for a cost reduction of about

five times as much as the scenario with only optimal charging, even when distribution upgrading costs are considered. Moreover, V2G contributes to absorb excess production from variable renewable energies, an issue that is quite relevant considering that in 2023 Chile had a total curtailment of about 2600 GWh. The government should also foster the use of electric mobility for cars and local public buses by providing incentives — for example for gasoline vehicle owners and urban authorities — to switch to plug-in hybrids and fully electric vehicles in order to reach the optimized path to net zero emissions by 2050. Further research and studies are needed on the design of efficient public incentive policies and new business models for optimal charging and V2G user participation.

Although the focus of this paper is not hydrogen, it is important to highlight the synergy that could exist between electric mobility, renewable generation and hydrogen development in terms of energy policies. Regarding electricity generation, Chile must keep investing in wind and solar capacities to be able to meet a rapid and significant growing demand, ensure a low-cost hydrogen production, and ensure a decarbonized fleet of electric vehicles. Reinforcement of the power transmission grid allowing for hydrogen production and renewable electricity to charge electric vehicles all along the country, must be anticipated. Future research is needed to better understand the interaction between electric mobility, V2G and the deployment of the green hydrogen sector.

Lastly, the upgrading costs for the distribution networks under electric mobility and V2G penetration were found to be a critical element for the optimal energy transition. It is important for the Chilean government to conduct new studies and research to better estimate these. These costs should be included in the long-term energy planning model (PELP) used by the government to assess energy scenarios and define the long-term energy policies.

CRedit authorship contribution statement

Francisco Ferrada: Visualization, Methodology, Formal analysis, Data curation. **Frederic Babonneau:** Writing – original draft, Supervision, Conceptualization. **Tito Homem-de-Mello:** Writing – original draft, Supervision. **Francisca Jalil-Vega:** Writing – original draft, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.jclepro.2025.146381>.

Data availability

Data will be made available on request.

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