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Evaluating the Impact of Flexibilities from Heating and Electromobility in Chile's Carbon Neutrality Pathway

Abhishake Kundu [1], Francisco Flores [1], Carlos A. A. Fernández Vázquez [2,3], Humberto Godoy [1], Sylvain Quoilin [2], Monica Castaneda [1] and Felipe Feijoo [1,*]

[1] School of Industrial Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso 2362807, Chile; abhishake.kundu@pucv.cl (A.K.); francisco.flores@pucv.cl (F.F.); humberto.godoy.c01@mail.pucv.cl (H.G.); monica.castaneda@pucv.cl (M.C.)

[2] Department of Aerospatial and Mechanical Engineering, Université de Liège, 4000 Liège, Belgium; caa.fernandez@uliege.be (C.A.A.F.V.); squoilin@uliege.be (S.Q.)

[3] Centro Universitario de Investigaciones en Energías, Universidad Mayor de San Simón, Cochabamba 00591, Bolivia

* Correspondence: felipe.feijoo@pucv.cl

Abstract: Chile's commitment to achieve carbon neutrality by 2050 underscores the need for robust decarbonization strategies across various sectors. Despite making progress in integrating renewable energy, sectors like transportation and residential heating, which are heavily reliant on fossil fuels, present significant opportunities for decarbonization. This study develops and evaluates pathways based on Chile's Long-Term Energy Plan for assessing the effect of flexibilities from the power-to-heat and power-to-transportation sectors. Using EnergyPLAN, we model different scenarios of Chile's 2050 energy plan that incorporate varying levels of individual heating and electromobility and assess their impacts on excess (surplus) electricity generation, different cost metrics, and renewable energy penetration. Findings indicate that increasing flexibility within the transportation sector through smart charging and vehicle-to-grid technologies can reduce excess generation, enhance grid stability, and lower operational costs. Flexibilities in individual heating, when coupled with more renewable energy capacity, show the potential to decrease reliance on fossil fuels significantly. The evidence of major efficiency gains in Chile's 2050 energy plan, which is achievable by investing in heating and transportation flexibilities and further augmented by the country's unique renewable potential, should interest stakeholders. Future work will focus on optimizing these technologies to address Chile's specific infrastructure and regulatory challenges.

Keywords: electromobility; individual heating; energy system analysis; carbon neutrality pathway; EnergyPLAN

Academic Editor: Amos Darko

Received: 3 December 2024
Revised: 22 December 2024
Accepted: 23 December 2024
Published: 28 December 2024

Citation: Kundu, A.; Flores, F.; Fernández Vázquez, C.A.A.; Godoy, H.; Quoilin, S.; Castaneda, M.; Feijoo, F. Evaluating the Impact of Flexibilities from Heating and Electromobility in Chile's Carbon Neutrality Pathway. *Buildings* **2025**, *15*, 68. https://doi.org/10.3390/buildings15010068

1. Introduction

In alignment with the Paris Agreement, countries worldwide have committed to ambitious climate goals to limit global temperature rise and mitigate climate change impacts [1]. The Nationally Determined Contributions (NDCs) outlined by the participating nations reflect these commitments, setting targets for greenhouse gas (GHG) reductions and carbon neutrality [2]. However, the pathways proposed in these NDCs often fall short of the required emissions reductions due to various challenges. These challenges include reliable electrification, effective dispatch systems, and overcoming technological and infrastructural barriers [3].

The introduction section provides a general overview of the Chilean context, focusing on a compilation of its main advancements in policy and the current regulation efforts regarding its pathways toward carbon neutrality. A short literature review is provided following this, as a benchmark for studies in other countries or regions that deal with heating and electromobility, particularly in Europe. The main objectives and contributions of this study are stated after that.

1.1. The Chilean Context

Chile presented its NDC to the United Nations Framework Convention on Climate Change in 2015, and in April 2020, Chile updated it, becoming one of the first countries to do so [4]. Carbon neutrality in Chile entails balancing the amount of emitted carbon with the amount removed from the atmosphere through sequestering [5], a goal requiring transformative changes across various sectors [6]. Chile aims to reduce its GHG emissions by 45% by 2030 compared to 2007 levels and achieve carbon neutrality by mid-century [7]. This ambitious target underscores the importance of reliable energy systems and effective decarbonization strategies.

Chile's energy sector, responsible for approximately 78% of the nation's total GHG emissions, will lead the way in this transition [8]. The country has made significant strides in integrating renewable energy into its power grid, with renewables accounting for 63% of electricity generation as of 2023, and aims to further convert 70% of its total energy consumption to renewables by 2030 [9].

To this end, Chile has enacted several laws and regulatory frameworks. The Climate Change Framework Law (Ley Marco de Cambio Climático), passed in 2022, sets the legal foundation for achieving carbon neutrality by 2050 and mandates the development of sectoral plans. The Energy Efficiency Law (Ley de Eficiencia Energética), enacted in 2021, aims to reduce energy consumption by 10% by 2030, focusing on sectors with high energy demand, including transport and industry. However, the transition to carbon neutrality presents a unique blend of challenges and opportunities, particularly in sectors such as transportation and heating, which together account for over 40% of the nation's energy consumption and remain heavily dependent on fossil fuels [6].

In 2020, residential heating accounted for about 40% of Chile's energy consumption, with the vast majority of homes, particularly in southern regions like Araucanía, Los Lagos, and Aysén, relying on firewood for heat [4]. These needs are mostly met through inefficient and highly polluting woodstoves or individual gas boilers. This widespread use of inefficient, traditional heating leads to serious air pollution problems [10], especially during the winter months, when particulate matter levels in cities like Temuco are five times higher than the standards recommended by the World Health Organization [11]. Firewood combustion is responsible for about 94% of the particulate matter ($PM_{2.5}$) emissions in south-central Chile [12,13]. The reliance on firewood also presents inefficiency in terms of energy use, with older stoves converting only around 40% of the energy contained in firewood into usable heat [14]. Moreover, the absence of strict regulations for non-certified firewood, which accounts for 70% of the firewood sold in southern cities, results in severe environmental and health risks [13,15].

Chile's National Strategy for Heating and Cooling, released in 2021, targets 80% of household heating and cooling to be powered by sustainable energy by 2050 [16]. It also highlights the importance of transitioning to low-carbon technologies, like electric heat pumps (HPs), and utilizing Chile's abundant renewable energy resources, particularly solar and geothermal energy. Given that Chile has the highest solar potential in the world, particularly in the Atacama regions [10,17], there is significant room for growth in using renewable energy to power both individual and district heating (DH) systems while reducing dependency on fossil-fuel-based generation.

Current regulations, such as the 2016 Thermal Insulation Standards, aim at implementing new efficiency standards for the construction of buildings. Despite the adoption of this and similar regulations being slow to date, the significant potential these could provide in conjunction with the transition of technologies in the power-to-heat (P2H) sector could greatly improve efficiency and reduce overall emissions in Chile [18]. For example, studies estimate that DH could reduce heating-related emissions by up to 75% compared to individual biomass stoves [14]. Moreover, if DH systems are powered by renewable energy, such as solar thermal or geothermal, Chile could reduce its carbon footprint even further.

Chile's transportation sector is another area that presents a significant opportunity to advance its carbon neutrality goals. Currently, transportation accounts for over 36% of the country's total energy consumption and contributes around a quarter of national emissions [6]. With increasing vehicle ownership and a dependency on fossil fuels, transport emissions in Chile have surged by over 200% in the past three decades [19]. The National Electromobility Strategy (Estrategia Nacional de Electromovilidad), launched in 2021, has set ambitious targets: by 2040, Chile aims to electrify 100% of its urban public transport—including buses, taxis, and *colectivos* (shared taxis)—and by 2035, all newly sold light and medium vehicles should be zero-emission [20].

On this front, Chile has already made substantial progress in electrifying its public transport system. Approximately 21% of Santiago's 7400 buses are electric [21], making it one of the leading cities globally—outside of China—in electric bus adoption. This shift has been facilitated by an innovative model where the public sector leases buses from private fleet providers, enabling affordable, long-term financing [22].

Nevertheless, Chile still has a long way to go in achieving widespread electrification. As of June 2023, only 6812 electric vehicles (EVs) were on the road [23]. By 2050, projections estimate this figure will reach approximately 5.6 million [24]. Reaching this target will demand targeted legislative support and significant investment in EV infrastructure, including charging networks and grid integration. As EVs grow, power-to-transport (P2T) technologies like smart charging infrastructure and vehicle-to-grid (V2G) technology can play a transformative role in balancing peak energy demands and ensuring grid efficiency [25]. Smart charging (V1G) optimizes EV charging during hours of excess electricity generation, while V2G allows vehicles to return power to the grid, stabilizing it during fluctuations in renewable energy generation [26].

1.2. Literature Review

Outside of the Chilean context, European studies provide valuable insights into the transition expectations for their corresponding energy system, particularly by exemplifying the potential benefits of P2H and P2T technologies [27,28].

Regarding the analysis of heating-related scenarios or measures in energy systems, several studies have utilized EnergyPLAN to demonstrate its capability in simulating and optimizing energy systems to achieve energy goals. This tool can model and simulate complete energy systems, with hourly resolution, encompassing the electricity, heating, cooling, and transport sectors [29] (for more details, see Section 2.1). Relevant studies show that coupling power and heating demands could improve the operation of the system at the continental level [30]. At national/subnational levels, studies for Denmark [31,32] and Finland [33] highlight how DH technologies such as combined heat and power (CHP) and heating storage, when paired with renewable energy sources, can significantly reduce carbon emissions.

Similarly, several studies also focus on the effects of the introduction of EVs into the energy system. At the continental level, a technical analysis was made regarding the potential use of EVs for providing short-term storage to the power grid, which showed that even with conservative estimates of EV integration, the flexibility requirements of the grid should be covered by 2030 [34]. When considering the European energy system, a scenario-based analysis of the implementation of alternative EV management strategies was considered to better comprehend the impacts of differences between dumb charging (sometimes referred to as uncontrolled charging in the literature), smart charging, and V2G in the system [35]. A high-resolution model to simulate EV mobility and charging patterns across 28 European countries is presented in [36]. The findings reveal that dumb charging increases peak demand by 35–51%, while smart charging strategies (like night charging or variable electricity charging) can reduce this to 30–41%.

When tackling country-level analysis, other relevant studies evaluate the impacts that the inclusion of EVs in the grid would have in northern European countries (Denmark, Finland, Germany, Norway, and Sweden) considering the V2G potential of the vehicles [37]. This particular case considers that shares of EVs would reach up to 53% by 2030, which would in turn allow the system to reduce curtailment of RE technologies and cover peak demands without the need to install new fossil-based generation powerplants. On the other hand, a social study based on questionnaires conducted in the Netherlands focused on exploring the potential and willingness of EV drivers to adopt V2G schemes [38]. Results show that based on the characteristics of the scheme (fast charge and remuneration), a large majority (up to 63%) of drivers would consider a V2G scheme, showing that currently there is a big potential for the deployment of this management strategy and its potential benefits for grid operation.

Other authors have also focused on analyzing both DH and EVs in their energy systems, e.g., the impact of efficiency measures in heating and cooling sectors, with a focus on Croatia [39]. Another study [40] evaluates the flexibility of energy systems under different sector-coupling scenarios (transport, heating, hydro) for 2050. Results highlight the cumulative flexibility benefits of combined sector coupling, enabling higher renewable integration (up to 15% for solar) and reduced curtailment. Furthermore, studies on the impact of electromobility integration with the grid have also been conducted to assess impacts on the electricity markets [41–43] and its role in reducing emissions [44–46].

A relevant takeaway from all these studies is that there is a large sample of potential modeling tools available that are currently being used. While the models can be chosen based on the type of system, the approach of the study, or the objectives to be met, EnergyPLAN seems to be a widespread and accepted option when analyzing these topics (impacts of DH and EVs on the energy system). Currently, there is a large sample of peer-reviewed articles (over 315) that have implemented the tool in their particular case studies and applications, from which a large focus is given to the relevance of DH in energy systems and the integration of variable renewable sources [47].

These experiences provide valuable insights for Chile as it undertakes its energy transition. Based on the conducted literature review, most studies on Chile's power systems primarily focus on sectoral integration as Chile's abundant renewable potential allows for massive decarbonization in the near future. For example, the authors of [48] developed the Global Change Analysis Model (GCAM)-Chile model and studied the feasibility of carbon neutrality under different mitigation policies. The authors of [49] integrate the GCAM-Chile with the Highway to Renewable Energy Systems model to consider intermittency and study the impact of flexible technology in Chile's carbon neutrality transition under an hourly resolution of generation, dispatch, and storage. The authors of [50] show that a net-negative system for Chile is feasible because of Chile's high potential for renewables but needs economic incentives to boost green energy deployment into hard-to-decarbonize sectors. In another study [13], the authors develop a long-term energy planning model to study the feasibility of Chile reaching the goal of zero emissions by 2050. Using the LUT Energy System Transition model, the authors of [10] study the transition of Chile to a 100% renewable-based energy system by 2050 by integrating four different sectors. They conclude that Chile could reach carbon neutrality as early as 2030. Another study in [51] that looks at supplying electricity using only renewable sources combines a multi-period model with an economic dispatch model and reports on the cost metrics to achieve it.

In terms of assessing the impact of sectoral flexibilities on Chile's power system, ref. [14] focuses on the role of DH technology in air pollution decontamination and decarbonization. Another article [11] conducts a rapid assessment of DH implementation to decarbonize the power and focuses on the city of Temuco in south Chile. They report on the cost and emissions metrics. Sectoral integration is evidently crucial for achieving Chile's carbon neutrality targets, but understanding the impact of technological flexibilities within these sectors is equally important for enhancing the system's performance. This understanding can guide policymakers in making informed capacity investment decisions. Beyond DH, the impact of such flexibilities has yet to be thoroughly studied in Chile. With significant upgrades needed in the country's heating and transport sectors, this article explores how integrating general heating and electromobility flexibilities could enhance the efficiency of Chile's power system by 2050. Chile's DH scenario, as presented in [14], is taken as a reference for this study with modifications that incorporate storage and adjusted photovoltaic (PV) capacity while integrating flexibilities from the P2H and P2T sectors.

1.3. Objective

We aim to evaluate the system efficiencies offered through the integration of technological flexibilities for individual heating and electrification of the transportation sector in the context of Chile's 2050 Long Term Energy Planning (LTEP) [24] and determine the effects of coupling it with Chile's high PV potential. We use an hourly simulation model, EnergyPLAN, to generate scenarios combining individual heating with the flexibility offered through smart technology integrations within the transportation sector. Thereafter, we evaluate the impact of the different scenarios on the technology mixes for excess (curtailed) electricity, annual costs, and generation profiles.

2. Materials and Methods

This section describes the step-by-step development of the scenarios considered in this study. The structure of these scenarios is based on those presented in the Heat Roadmap Chile (HRCL) report [14], which incorporates the LTEP assumptions established by the Chilean Ministry of Energy in 2016 [24]. The scenario was developed using the EnergyPLAN simulation tool described in the following section.

2.1. EnergyPLAN

EnergyPLAN simulates the hourly operation of energy systems for a specific year, covering sectors such as electricity, heating, cooling, industry, and transportation [52]. Figure 1 provides an overview of the technologies considered, and the connection processes involved in the single-node EnergyPLAN model for Chile. The main objective of EnergyPLAN is to analyze the energy, economic, and environmental impacts of energy strategies. It uses a deterministic model that optimizes the operation of a given energy system based on user-defined factors. EnergyPLAN has been widely used for energy system simulations [47], where it has been applied in 315 articles between 2003 and 2022. The articles in review [47] were identified through a systematic search process combining

Scopus, the Directory of Open-Access Journals, and full-text search engines. The articles were categorized into three groups: application (39%), where EnergyPLAN was used for case studies; characterization (42%), which evaluated or compared EnergyPLAN as an analytical tool; and referencing results (19%), which cited EnergyPLAN results without detailed usage. The authors note that 136 articles focus on Europe at the national level, while 72 address local-scale studies within Europe, collectively representing approximately 70% of the total articles.

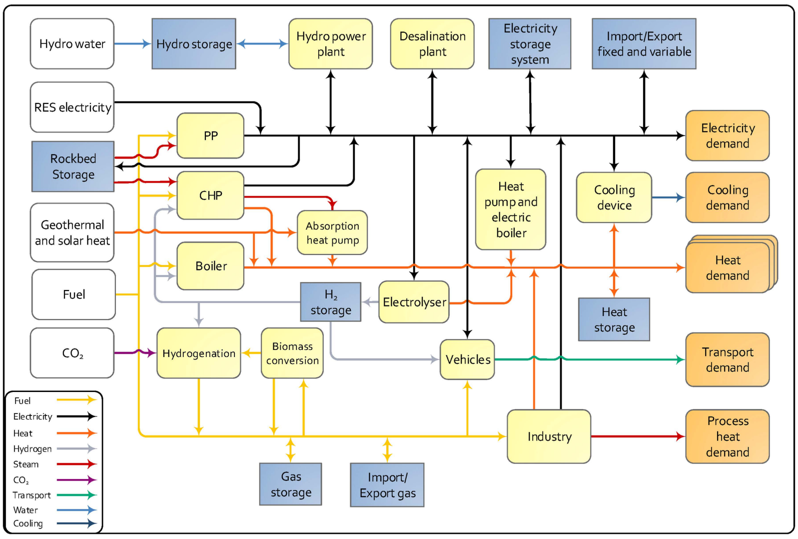

Figure 1. Schematic diagram of the overall technology and flow of EnergyPLAN (adopted from [53]).

2.2. *District Heating Scenarios: Heat Roadmap for Chile*

The HRCL scenarios as defined in [14] clarify the role of different elements in the energy system mix by modeling their gradual implementation and analyzing their contributions through multiple scenarios. The generated scenarios are the product of four stepwise considerations of different technologies as discussed next.

- Step 1 introduces DH infrastructure by simulating incremental increases in thermal distribution networks for heat for residential and tertiary heat demand, initially supplied solely by boilers. GIS-based inputs, accounting for local climate and building conditions, estimated distribution costs, losses, and geospatial variability, are integrated into the national energy model.
- Building on the boiler-only setup from Step 1, Step 2 introduces different technologies, including industrial excess heat, renewable energy, and CHP/HP capacity, to enhance the district heating system. Excess industrial heat, estimated at 11% of total DH production, was generalized using prior studies in the European context [54]. Potentials for CHPs and HPs were set based on system operational needs rather than geographic limitations, enabling them to balance heat and electricity while responding to intermittent generation.
- Step 3 increased intermittent renewable electricity that is integrated with the flexibility provided to the power system by the use of CHP and electric heating. Building on Step 2, this phase induces expansions in geothermal, onshore wind, and solar capacities. For solar thermal and geothermal DH plants, potential estimations were derived from PELP inputs, assuming half of the total defined potential available for heat, with the remainder allocated to electricity generation.
- Step 4 (HRCL) represents the final adjustments to ensure energy system balance and alignment with government targets, such as phasing out coal by 2040 and capping biomass use. This step incorporates considerations of boiler capacity and short-term

storage for district heating, providing a 10% supply buffer for peak demand. Production capacities are also adjusted to minimize excess and ensure demand coverage.

In the modified HRCL scenario which we consider for this case study, the evaluation focuses on how smart and V2G loads are affected. To achieve this, the load profile used in the HRCL scenario is modified by incorporating the profiles of dumb and V2G, represented by [55,56], respectively. This modification transitions the load profile from a constant to specific profiles for each behavior. A heat storage capacity of 13,602 MWh is included, which corresponds to the peak heat demand in the HRCL scenario. Additionally, the battery storage capacity and the capacity of the grid-to-battery connection are determined based on a fleet of 5.6 million electric vehicles. Finally, to assess the impact of the sectoral flexibilities under intermittent renewable generation, we allow the PV capacity to increase from its base of 17,508 MW in Step 4 up to 43.6 GW [57] to match Chile's renewable potential. The next section provides detailed considerations in the case study.

2.3. Transportation Scenarios: EnergyPLAN Applied to Chile

To model the transport sector, it is necessary to define the annual demand for each type of fuel, such as jet fuel, diesel, petroleum/methane, natural gas, and liquified petroleum gas (LPG). The HRCL report [58] and the work developed in [14] are used as baselines in this context. Similarly, the electricity demand associated with electric vehicles must be explicitly defined, including dumb charging, smart charging, and V2G. Consequently, different scenarios are developed to account for the various demands, considering the behavior of EVs, which adopt patterns categorized as dumb charging and smart charging. These profiles (behaviors) have been used in previous research such as Yuan et al. [56], Lund and Kempton [55], and Bartolini et al. [59].

Additionally, it is necessary to define the technical parameters associated with EVs, such as grid connection capacity (MW), charging distributions, and the maximum number of vehicles parked during peak hours. For this purpose, a total of 5.6 million vehicles are considered, in line with the expected number of EVs in Chile in 2050 [24]. This closely aligns with the predictions from other reports of 5 million and between 2.9 and 7.8 million [60]. An average charging/discharging capacity of 7 kW per vehicle and an average storage capacity of 50 kWh per vehicle is assumed.

As mentioned above, EnergyPLAN uses an annual hourly resolution; therefore, distribution profiles associated with renewable resources, such as wind and solar, are applied. Similarly, hourly profiles are considered for hydroelectric technologies, such as run-of-river plants and reservoirs, as well as for geothermal energy, based on data from the HRCL report [58].

For the scenarios evaluated in EnergyPLAN, we used the 2050 scenario presented in the HRCL report [58] that considers demands such as those of the transport, industry, and power sectors. Our baseline scenario assumes that 100% of EV demand (i.e., 100% of EVs) follows a dumb charging profile. To perform a sensitivity analysis, we consider a gradual increase in adopting the smart charging profile until reaching 100% of EVs under the smart charging profile. The objective is to assess the impact of both charging behavior (dumb charging vs. smart charging) and technological advancement (dumb charging vs. V2G).

These scenarios consider a variation in the number of vehicles that follow a behavior defined as dumb charging or smart charging or that have access to V2G technology, motivated by the study conducted for Chile in [61]. As previously mentioned, the benchmark scenario considers that 100% of vehicles follow a dumb charging profile. From this scenario, three scenarios are generated where the number of vehicles that switch from dumb to smart charging behavior is gradually increased by 50%, which results in the comparison between dumb charging and smart charging (see Table 1 for more details).

Table 1. Summary of the scenarios considered in terms of charging type.

Charging	0% Smart	50% Smart	100% Smart
Dumb (%)	100%	50%	0%
Smart (%)	0%	50%	100%

In addition, three additional scenarios are created from the base scenarios to analyze V2G technology. The same percentage of growth from smart towards V2G is considered. In other words, the amount of V2G increases by 50% until reaching 100%, where all vehicles are V2G eligible. The scenarios are detailed in Table 2 and an overview of the pathway for the scenario development is presented in Figure 2.

Table 2. Scenario definition and EV-based measures implementation.

Scenario	General Details and Characteristics	Smart Charging Profiles (% SC)	Available Vehicle-to-Grid Shares (% V2G)
Step 4 (HRCL)	Coal phase-out and DH were assumed to be able to provide a supply security buffer	0% *; 50%; 100%	0%; 50%; 100%

* 0% smart charging scenarios have no V2G availability.

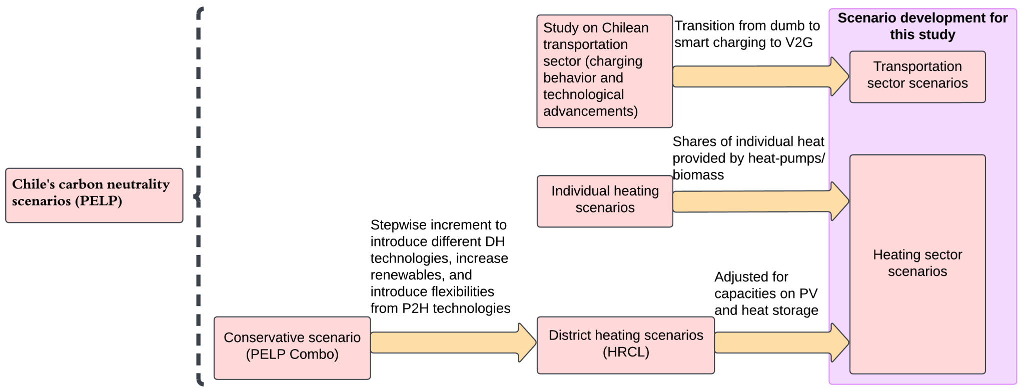

Figure 2. Overview of the pathway for generating Chile's 2050 carbon neutrality scenarios. The modified DH scenarios are developed from [14] and Chile's 2050 carbon neutrality pathways [24]. The transportation scenarios are developed from the study in [61].

3. Case Study

This section provides a compilation of details, data, and characteristics linked to the Chilean energy system (case study), the relevant considerations taken for the modeling process, and the particularities of each of the proposed scenarios.

3.1. Overview of Chilean Data in the Energy Sector

This section introduces the current state of the Chilean energy system, thereby providing a context for the development of scenarios for the case study. When describing Chile's power sector, it was primarily composed of fossil fuel technologies, such as coal, gas, and liquids, which accounted for approximately 48.9% of the power installed capacity in 2020. However, by 2023, the installed capacity of renewable technologies like wind, solar, and concentrated solar power (CSP) had increased by 129%, reflecting an increase from 2527 MWto 4628 MW in wind technology and from 3575 MW to 9343 MW in combined solar and CSP technologies [62]. Additionally, a reduction in coal plant capacity is observed in line to phase out coal plants by 2040 [4], as outlined in the plan developed by the Ministry of Energy [63]. This reduction is approximately 19%, which allows for reducing, in general terms, the installed capacity of fossil sources to 33%. As previously described in the introduction, Chile has significant renewable energy potential, both in the Atacama Desert in the north and the high wind energy potential in the south. This is reflected in Chile's estimated renewable energy potential, which includes 40.5 GW for wind energy, 2193 GW for solar energy (1640 GW for PV and 552.9 GW for CSP), and 12.5 GW for hydroelectric energy [64,65].

Figure 3 shows how electricity generation was affected by investments in renewable technologies in 2020 and 2023. It is important to note that hydroelectric generation accounted for nearly 27% of total annual generation in 2020. The share of renewable electricity generation (wind, PV, and CSP) in 2020 was 16.9%. By 2023, while hydropower generation remained similar to the 2020 levels (28.4%), renewable electricity generation reached 31%, demonstrating significant development over just three years. Additionally, Figure 3 shows a reduction in coal-fired generation, which declined to 17.2% in 2023, lower than the combined PV and CSP generation at 19.7%.

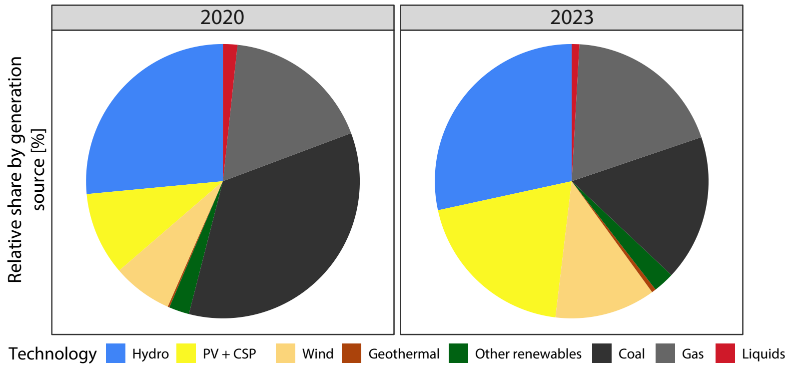

Figure 3. Composition of generation in 2020 and 2023 for each technology (data available at [62], accessed on 25 September 2024).

When analyzing GHG emissions in Chile, it is observed that 77.4% come from the energy sector. Within this sector, 38% is attributed to power generation, while the transportation sector accounts for 33% of energy-related emissions [66] (see Figure 4). This is due to the predominant use of fossil fuels, such as coal and natural gas, in both the electricity generation and transportation sectors. Furthermore, the electricity generation sector emits 29,841.6 kT of CO2e, while the transportation sector contributes 26,114.2 kT of CO2e [66].

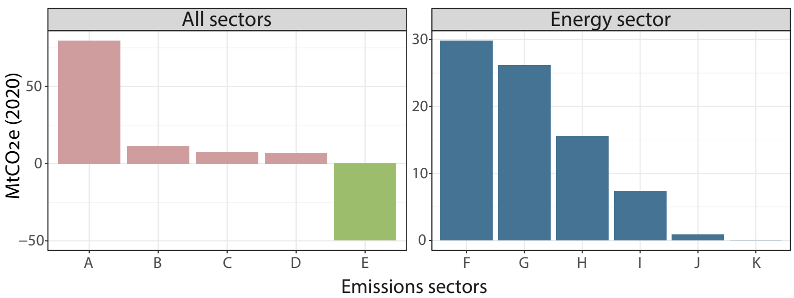

Figure 4. Total emissions in Chile in 2020. A: Energy, B: Agriculture, C: Waste, D: Industrial processes, E: LULUCF, F: Electricity, G: Transportation, H: Manufacturing and construction industries, I: Other sectors, J: Fugitive emissions, K: CO_2 transport and storage.

In terms of electricity projections, Chile, according to LTEP [20], expects that by 2050, 86% of electricity generation will come from renewable technologies (wind, PV, and CSP), with only 1.5% coming from fossil fuel technologies. The remaining percentage is expected to be sourced from other renewable energy sources and storage. Regarding investment in installed capacity, wind capacity is projected to increase 14 times, while the combined PV and CSP capacity is expected to increase 8.1 times compared to 2020. This difference in installed capacity is explained by a 70-time increase in CSP capacity, which also includes battery storage.

3.2. Considerations in the Case Study

In this study, the power demand for 2050 in each scenario is considered to be the same at 182.095 TWh. The transport demand (electricity) for the transport sector is consistent across scenarios, estimated at 21.62 TWh. Regarding heating demand, the scenario considers a district heating demand of 42.38 TWh and an individual heating demand of 63.6 TWh, supplied by biomass and heat pumps. In the industrial sector, coal consumption is estimated at 7.63 TWh, oil at 105.08 TWh, natural gas at 20.59 TWh, and biomass at 49.56 TWh. Similarly, in the transport sector, consumption is estimated at 17.19 TWh for jet fuel, 49.74 TWh for diesel, 46.51 TWh for oil, 17.5 TWh for natural gas, and 0.3 TWh for LPG. These are consistent with the HRCL scenario.

The installed capacity considered for various technologies includes PV and CSP (17,508 MW and 139.71 MW, respectively), wind (20,000 MW), river and dam hydropower (4556 MW and 3502.4 MW, respectively), geothermal (848 MW), and fossil fuels, totaling 19,422 MW, which includes gas and biomass liquids.

3.3. Scenario Development

To analyze the potential impact of flexibility on the heat and transportation sectors, several scenarios are evaluated, and a matrix is generated. Specifically, three heat scenarios are developed: In the first scenario, half of the individual heating demand is met by heat pumps. This scenario corresponds to the final HRCL scenario from the report in [58], which we consider as our business-as-usual (BAU) scenario. In the second scenario, 75% of the individual heating demand is supplied by heat pumps. This represents an increase of 15.9 TWh in heat pump demand (totaling 47.7 TWh) from the BAU scenario, which accounts for a demand of 31.8 TWh from both heat pumps and biomass. Finally, in the third scenario, heat pumps meet the entirety of the individual heating demand of 63.6 TWh.

On the other hand, the transportation sector is analyzed under three scenarios related to demand. In the first scenario, all demand follows a dumb profile. In the second scenario, demand is equally distributed between the dumb and smart profiles, with 50% of demand following the dumb profile and the other 50% following the smart profile. Finally, the third scenario assumes that all demand adopts a smart profile. In addition, when considering the smart profile, three sub-scenarios are introduced. In the first sub-scenario, V2G interaction is not considered. The second sub-scenario assumes that half of the vehicles within the smart demand can inject electricity into the grid. Finally, the third sub-scenario assumes that all vehicles with a smart profile can supply electricity to the grid. A 3×7 matrix (as shown below) is generated that evaluates the impact of flexibility in both sectors. Each scenario is further coupled with different PV capacity considerations with 0%, 50%, 100%, and 150% increase from its baseline of 17,508 MW to align with Chile's maximum PV potential of 43.6 GW [57]. The BAU scenario, adapted from the modified HRCL scenario in [14], represents a baseline with no flexibility in either the individual heating (shared equally between biomass and HP) or transportation sectors and a PV capacity of 17,508 MW. These scenarios were developed to create a flexibility comparison matrix for the two technologies, which can be represented as follows.

$$\text{Scenario}_{HP,Charging} = \begin{bmatrix} a_{50,0\text{smart}} & a_{50,50\text{smart}} & a_{50,100\text{smart}} & a_{50,50\text{smart}/50\text{V2G}} & a_{50,100\text{smart}/50\text{V2G}} & a_{50,50\text{smart}/100\text{V2G}} & a_{50,100\text{smart}/100\text{V2G}} \\ a_{75,0\text{smart}} & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{100,0\text{smart}} & a_{100,50\text{smart}} & a_{100,100\text{smart}} & a_{100,50\text{smart}/50\text{V2G}} & a_{100,100\text{smart}/50\text{V2G}} & a_{100,50\text{smart}/100\text{V2G}} & a_{100,100\text{smart}/100\text{V2G}} \end{bmatrix}$$

4. Results and Discussion

This section presents key insights into the individual and combined effects of flexibility across sectors in Chile's energy scenario for 2050, focusing on P2H flexibility (individual heating demand met by heat pumps in %) and flexibility provided through the P2T sector through smart charging and V2G capabilities. The effects of such flexibilities are studied in conjunction with PV capacity expansion from its baseline. Of the 84 scenarios, barring the BAU scenario, the remaining ones incorporate varying flexibility levels across one or multiple sectors. As outlined in the previous section, these scenarios include three levels each for percentage of individual heat demand met through heat pumps and smart charging profiles with different V2G availability levels, coupled with four levels of PV capacity increase (0% to 150% increase from its baseline capacity).

The following subsections examine the impact of P2H and P2T flexibility, as well as their combined effect on Chile's energy generation efficiency in 2050. For analyzing the isolated impacts of the P2H and P2T sectors, the system metric under study is averaged across the different levels of flexibility from the other sector.

4.1. Effect of Power to Heat

The P2H sector is characterized by three levels of flexibility, in which individual heating demand is met by a combination of heat pumps and biomass boilers. In the BAU scenario, heating demand is equally divided between heat pumps and biomass boilers, with no added flexibility from the transport sector with the PV capacity remaining fixed at its baseline of 17,508 MW, resulting in a surplus electricity production of 10.73 TWh.

Figure 5 shows that as PV capacity increases, excess electricity production rises too. This outcome aligns with expectations that a greater volume of non-dispatchable energy is generated, particularly during the summer months in Chile, which cannot be stored or allocated to other demands. Mean excess electricity increases from 2.8 TWh at a 0% PV to 53.6 TWh at a 150% increase. Conversely, a higher share of individual heating demand met by heat pumps reduces surplus electricity due to the added flexibility through storage, as shown in Table 3. It is seen that when the heat pump share rises to 75% and 100% from 50%, average excess electricity decreases by 7.14% and 13.84%, respectively. Concurrently, the average renewable energy generation in 2050 will remain similar for the three cases, ranging between 219.1 TWh and 223.7 TWh.

Annual costs are divided into investment, operational, and variable costs. The present values of annual costs are calculated using a discount rate of 10%, reflecting the short-term nodal price discount rate in the electrical system [23]. Investment costs are expected to increase with higher PV and heat pump capacities. As PV capacity rises from 0% to 150% of its baseline, investment costs increase from 17,593 mUSD to 18,805 mUSD on average. Similarly, as heat pump usage rises from 50% to 100%, investment costs increase from 17,050 mUSD to 19,348 mUSD, as indicated in Table 3. Operational costs, which are lower in comparison to other costs, show a slight decrease with greater heat pump penetration.

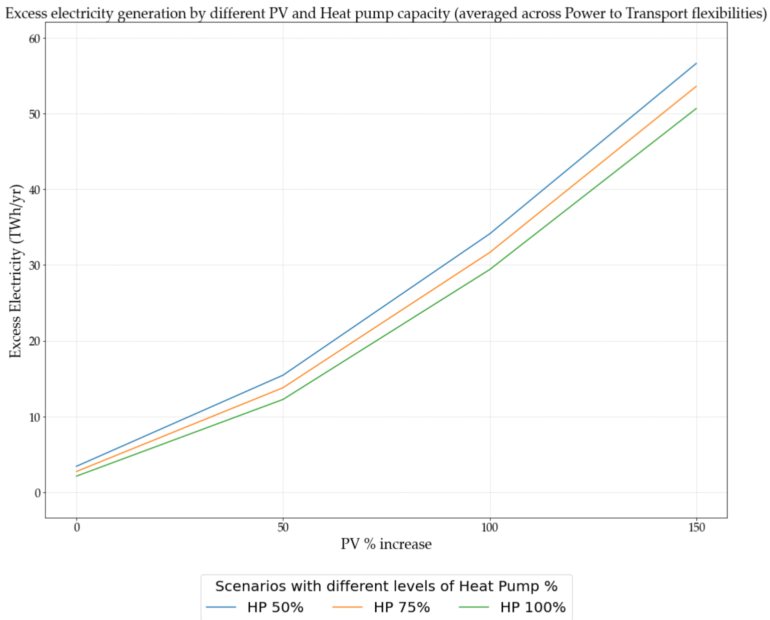

Figure 5. Excess electricity generated under Chile's 2050 energy plan under different P2H and PV flexibilities averaged across flexibilities from the transportation sector.

Variable costs, in contrast, do not exhibit a linear trend with changes in PV capacity, as shown in Figure 6. While variable costs decrease with added PV capacity, the rate of decrease slows, falling from 24,033.2 mUSD to 22,949.9 mUSD on average as PV capacity rises from 0% to 150%. Similarly, as indicated in Table 3, increased heat pump penetration reduces operational costs, which decrease from 23,695.0 mUSD to 22,983.8 mUSD as heat pump usage increases from 50% to 100%.

Table 3. Impacts of individual heating demand met by HP on system metrics averaged out across transport sector and PV capacity flexibilities.

Metric	Penetration % of Heat Pumps		
	50%	**75%**	**100%**
Excess electricity	27.4	25.4	23.6
Investment costs	17,050.0	18,199.0	19,348.0
Operational costs	3700.5	3691.0	3681.5
Variable costs *	23,695.0	23,334.8	22,983.8
Total annual costs	44,445.3	45,224.8	46,013.2

Note: The cost unit is mUSD, and the excess electricity unit is TWh. * annual variable costs are identified as cost per unit times production.

The combined effect of the opposing trends in investment and variable costs results in low overall costs when heat pump penetration is lower (see Table 3). Total annual costs initially decrease as PV capacity increases from 0% to 50%, before rising again beyond a 50% PV increase. The lowest annual costs, averaging 44,201.0 mUSD across transportation flexibility scenarios, are achieved when heat pumps meet 50% of individual heating demand and PV capacity is increased by 50% from its baseline.

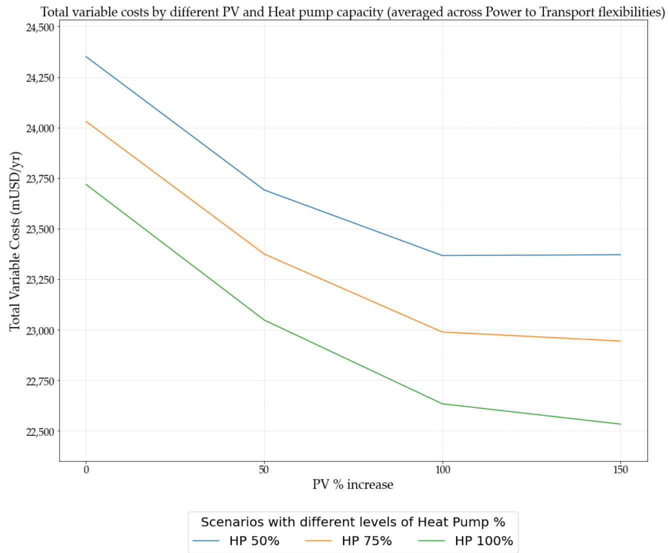

Figure 6. Variable costs under Chile's 2050 energy plan under different P2H and PV flexibilities averaged across flexibilities from the transportation sector.

4.2. Effect of Power to Transport

The transport sector provides flexibility through the combination of smart charging profiles and V2G availability. As discussed before, there are three levels of flexibility for each, except for V2G being unavailable when following a 100% dumb charging profile.

Figure 7 shows that average excess electricity production is consistently the highest when there is no flexibility from the transport sector (0% smart charging), ranging from 9.4 TWh to 74.2 TWh as PV capacity increases. Introducing transport sector flexibilities reduces excess electricity production. In the absence of V2G availability, excess electricity remains high, as V2G enables the reintegration of excess electricity into the grid during peak demand periods. Without V2G flexibility, excess electricity ranges from 4.0 TWh to 65.4 TWh with 50% smart charging and from 1.4 TWh to 56.7 TWh with full smart charging profile.

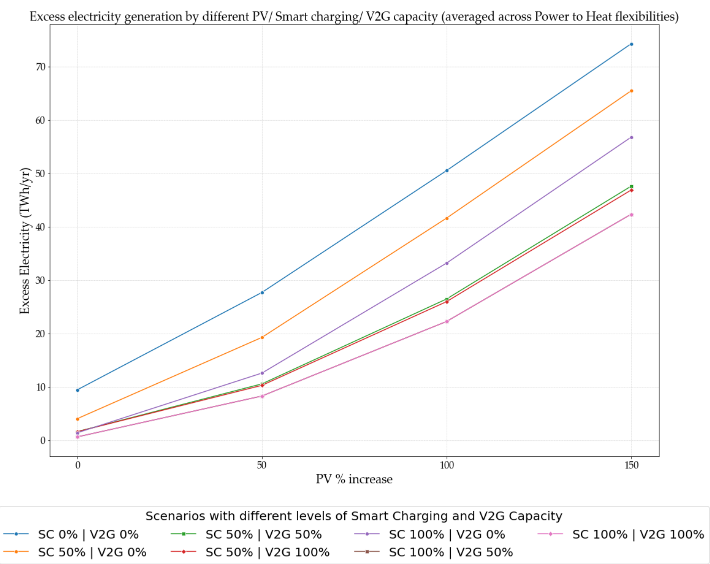

Figure 7. Excess electricity generated under Chile's 2050 energy plan under different P2T and PV flexibilities averaged across flexibilities from the individual heating sector.

As indicated in Table 4, when smart charging capability increases, excess electricity decreases, indicating improved management of peak generation levels. With 50% smart charging, the impact of V2G beyond 50% capacity on excess electricity is minimal, ranging from 1.6 TWh to 47.6 TWh for 50% V2G, and from 1.6 TWh to 46.8 TWh for full V2G. At the full smart charging profile, V2G availability beyond 50% has no additional impact on excess electricity (as indicated by the overlapping brown and purple trend lines in Figure 7), which ranges between 0.6 TWh and 42.3 TWh. Thus, the combined effect of smart charging and V2G shows that while having V2G significantly reduces excess electricity, this effect is less pronounced at higher smart charging levels.

For cost components, average investment and operational costs are unaffected by transport sector flexibilities, increasing only with higher PV capacity. Investment costs range between 16,444 mUSD and 19,954 mUSD, and operational costs from 3565 mUSD to 3817 mUSD as PV capacity increases from 0% to 150% above baseline. However, transport sector flexibilities do affect variable costs, as highlighted in Figure 8. Without V2G flexibility, variable costs remain consistently high. The availability of smart charging lowers these costs. With no V2G flexibility, variable costs range from 23,844 mUSD to 24,822 mUSD for a 100% dumb charging profile, and between 22,817 mUSD and 24,262 mUSD with a full smart charging profile.

Table 4. Impacts of smart charging and V2G flexibilities on system metrics averaged out across individual heating sector and PV capacity flexibilities.

Metric	Smart Charging (%)			V2G (%)		
	0%	50%	100%	0%	50%	100%
Excess electricity	40.4	25.1	20.9	33.0	19.9	19.6
Variable costs *	24,341.4	23,333.4	23,007.8	23,864.0	22,950.5	22,936.1
Total annual costs	46,231.4	45,223.3	44,897.8	45,753.8	44,840.3	44,826.1

Note: The cost unit is mUSD, and the excess electricity unit is TWh. * annual variable costs are identified as cost per unit times production.

When some V2G flexibility is available, variable costs decline with increasing PV capacity. At the 50% smart charging profile, raising V2G capacity from 50% to 100% results in a marginal 0.2% decrease in average variable costs. At full smart charging, increasing V2G capacity beyond 50% does not affect variable costs (as indicated by the overlapping brown and purple trend lines in Figure 8).

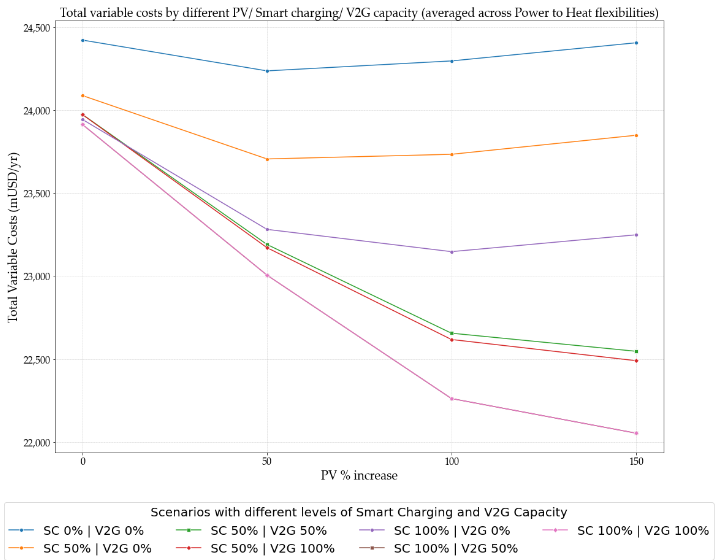

Figure 8. Variable costs under Chile's 2050 energy plan under different P2T and PV flexibilities averaged across flexibilities from the individual heating sector.

The combined effect of investment, operational, and variable costs leads to an overall decrease in total costs as both V2G availability and smart charging profile rise, as shown in Table 4. The influence of V2G flexibility is most pronounced at lower levels of smart charging but diminishes beyond the 50% smart charging profile. With an increase in PV capacity from baseline, opposing trends in investment and variable costs cause total annual costs to initially decrease with PV capacity flexibility before rising beyond a 100% increase from baseline.

4.3. Combined Effect of Power to Heat and Power to Transport

In this subsection, the combined effect of P2H and P2T are analyzed. Figure 9 presents the excess electricity generation for different HP and smart charging settings. The boxplots illustrate that the excess electricity reduces as the percentage of individual heating demand met by HP increases. For instance, scenario HP 100%/SC 0% (100% of individual heat demand met by HP with no smart charging) has a lower median value for the excess of electricity at 36.9 TWh/yr, compared to scenario HP 50%/SC 0% (individual heat demand equally shared between HP and biomass with no smart charging), which has a higher median value of 41.2 TWh/yr—a difference of 10%. In addition, the scenario with the least excess electricity corresponds to 100% of the individual heating demand met by HP and with full smart charging with a median value of 15.5 TWh/yr. Additionally, as highlighted in Figure 9, the range of excess electricity is lower when both individual HP share and smart charging profile exceed 50%. This indicates that the combined effect of flexibilities from the P2H and P2T sectors beyond 50% reduces the excess of electricity significantly, which encourages the integration of non-dispatchable technologies such as solar PV.

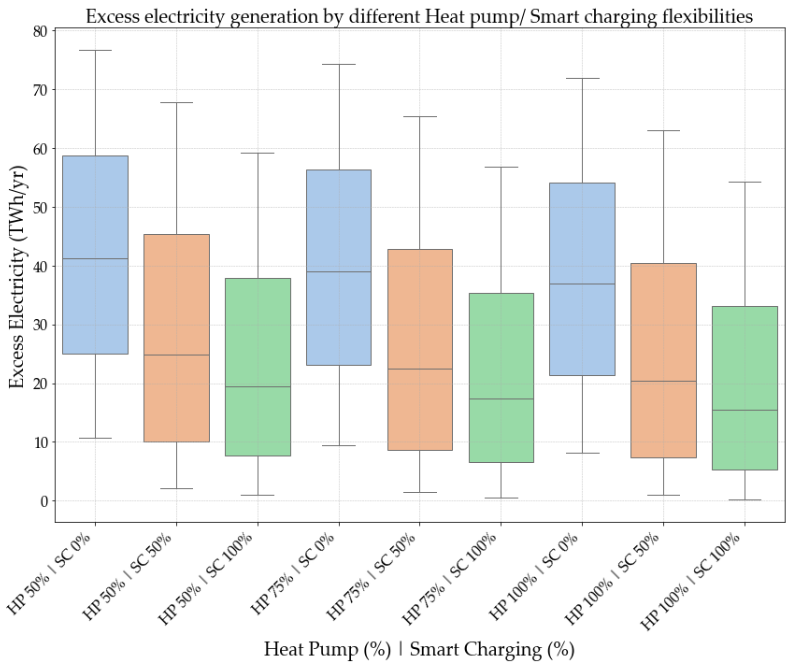

Figure 9. Excess electricity generated under Chile's 2050 energy plan with different P2H, P2T, and PV flexibilities.

Figure 10 illustrates the effect of varying smart charging levels on the variable costs that Chile will incur in 2050. When charging follows a 100% dumb profile, the total variable cost values tend to show little variation over the ranges of PV capacity. For example, in the scenarios with HP 50%, HP 75%, and HP 100% with no smart charging, the median values of total variable costs reach 24,740.5 mUSD/yr, 24,351.5 mUSD/yr, and 23,941 mUSD/yr, respectively. Additionally, under these scenarios, the variable costs are higher due to the increased gap between generation and demand, which reaches its maximum. The total variable costs are the lowest when HP corresponds to 100% and both smart charging and V2G correspond to 100%, reaching a median value of 22,755 mUSD/yr.

Table 5 summarizes the mean values of metrics such as critical excess of electricity produced, variable costs, and annual costs for different levels of transportation and individual heating flexibilities, averaged across PV capacities. The lowest average value of surplus electricity is associated with the scenarios with 100% HP and 100% V2G, at 17.8 TWh/yr. The same scenario is associated with the lowest average variable cost of 22,594.4 mUSD/yr. However, in the case of the average total annual costs, the minimum corresponds when HP is 50% and V2G is 100%. This combination leads to an average total annual cost of 44,033 mUSD/yr. This is because, beyond 50% HP, the increase in investment costs cannot be offset by the decrease in operational costs.

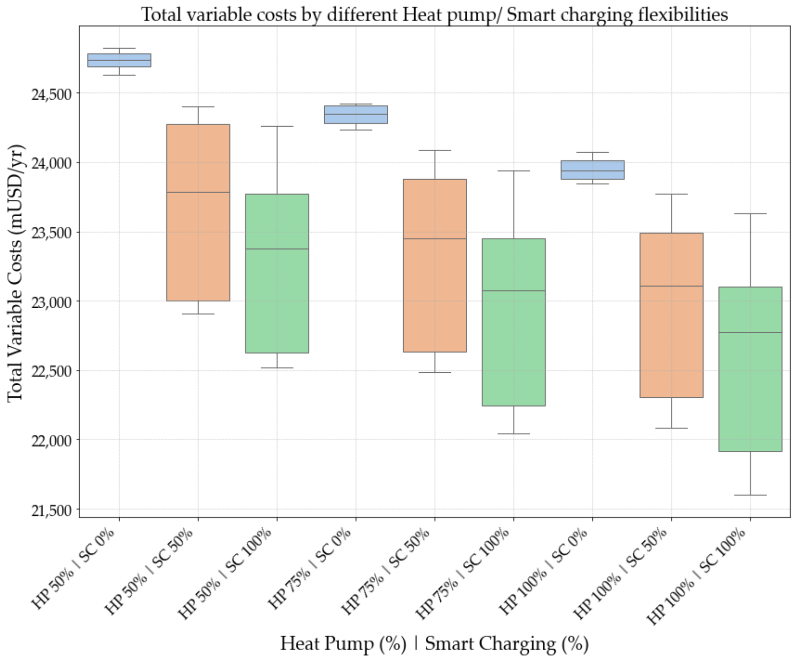

Figure 10. Variable costs under Chile's 2050 energy plan with different P2H, P2T, and PV flexibilities.

Table 5. Impacts of individual heating demand met by HP, smart charging, and V2G flexibilities on system metrics averaged out across PV capacities.

Heat Pumps	Smart Charging (%)			V2G (%)		
	0%	50%	100%	0%	50%	100%
			Excess electricity (TWh)			
50%	42.5	27.0	22.8	34.8	21.9	21.7
75%	40.4	25.0	20.8	32.9	19.8	19.7
100%	38.5	23.2	19.1	31.2	18.0	17.8
			Variable costs * (mUSD)			
50%	24,734.0	23,668.7	23,355.1	24,235.3	23,296.6	23,282.0
75%	24,339.8	23,330.4	23,004.2	23,863.4	22,945.6	229,131.0
100%	23,950.5	22,981.3	22,664.2	23,493.2	22,609.1	22,593.4
			Total annual costs (mUSD)			
50%	45,484.3	44,438.9	44,105.3	44,985.5	44,046.9	44,033.4
75%	46,228.8	45,220.4	44,894.2	45,753,4	44,835.5	44,821.1
100%	46,979.5	46,010.7	45,693.8	46,522.6	45,638.6	45,623.9

* annual variable costs are identified as cost per unit times production.

4.4. Comparison of Monthly Generation Profiles: BAU vs. Full Sectoral Flexibility

Figure 11 illustrate monthly electricity generation profiles from various technologies across two scenarios: A: the BAU (HRCL with no flexibilities from P2H or P2T and no PV capacity increase from baseline) and B: full sectoral flexibility (HRCL with 100% P2H and P2T flexibility and a 150% increase in baseline PV capacity). While the generation patterns are generally similar month to month, notable differences emerge between these scenarios.

It is observed that the renewable resource availability in Chile is highly seasonal, with distinct periods of increased renewable generation throughout the year. From September to December, for instance, renewable resources, such as wind, river, and PV, peak, allowing renewable generation to cover most of the electricity demand. In the BAU scenario, seasonality has a more pronounced effect, with renewable sources meeting around 60% of demand during most of the year and over 80% during peak months. The remainder is met by fossil fuel-based technologies, which provide the necessary flexibility, particularly from April to September when the demand is relatively higher.

Between these two scenarios, PV generation shows the most substantial increase, rising from a range of 2985–7094 TWh in the BAU to 7463–17,736 TWh under the full sectoral flexibility, reflecting that the flexibilities from the heat and transport sector allow better integration of solar energy under additional PV capacity. This shift reduces seasonal fluctuations, with PV becoming the dominant renewable technology in the full flexibility scenario.

Several technologies remain constant across both scenarios: river (1509–3910 TWh), hydro (2124–2192 TWh), wind (6409–10,321 TWh), CSP (94–116 TWh), industrial combined steam heat and power (CSHP) (2095 TWh), and geothermal (848 TWh). Heat pumps show modest differences between the two scenarios, with generation ranging from 226 to 550 TWh in BAU and 132 to 514 TWh under full flexibility. In the full flexibility scenario, heat pump generation is slightly higher from April to August, while the BAU scenario sees higher levels in other months. CHP also shows minimal variation, ranging from 1340 to 4226 TWh in BAU and 1434 to 3776 TWh in full flexibility. It shows an opposing effect to that of HP generation, with the CHP generation being slightly higher in full flexibility from April to August.

Powerplant generation sees a decrease due to the sectoral flexibilities provided in the scenario in Figure 11B. The system becomes mostly free of fossil fuels to cover the national demand. While the power plant generation ranges between 930 and 4273 TWh in the BAU scenario, the generation in the full sectoral flexibility scenario remains non-existent for most of the months, except April to July, reaching a peak generation of 1321 TWh in May. In the full sectoral scenario, the inclusion of flexible technologies, such as HP, geothermal, and CHP in addition to the increase of PV generation, allows for the generation of surplus energy during the peak generation season, which could allow exports.

Lastly, unlike district heating-linked technologies, smart charging and V2G measures will not have a representative effect over monthly demand requirements, as shown in the nearly constant demand lines, with only slight elevation during winter months. This is explained as the main effect of smart charging and V2G is to provide short-term flexibility on an hourly basis, which, when aggregated in larger periods, is balanced out.

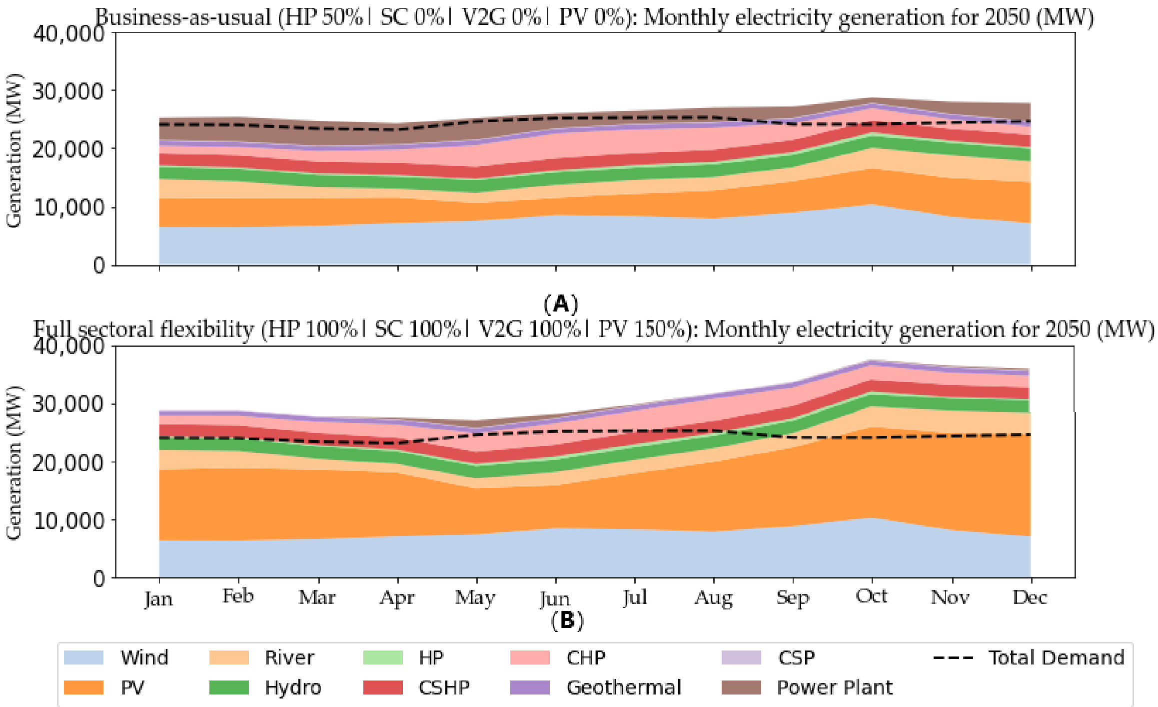

Figure 11. Monthly dispatch expected in renewable generation in Chile's 2050 power system for the (**A**): BAU and (**B**): full sectorial flexibility scenarios.

4.5. Discussion and Comparison with European Studies

The results of the P2H scenarios indicate that integrating heat pumps can significantly reduce curtailed electricity, improve the integration of intermittent renewables, and improve system efficiency. This effect is most pronounced in scenarios with high solar generation, where storage and demand management via heat pumps enable more effective utilization of generated energy. However, achieving this integration requires increased investment in heating infrastructure and thermal distribution networks (if used for district heating), particularly in densely populated urban areas. European studies support these findings, demonstrating that district heating flexibility improves system efficiency while reducing operational costs [30] and reliance on imported fossil fuels [28]. Individual heating with heat pumps, on the other hand, when combined with solar energy requires higher investments but results in better diversification and does not require fuel energy consumption [67]. Another study on the Danish power system that considers flexibilities from both district and individual heating shows that combining district heating with individual heat pumps could replace a quarter of homes currently reliant on gas or oil boilers [32].

In the P2T sector, adopting smart charging and V2G technologies provides flexibility to balance supply and demand. The evaluated scenarios show that smart charging and V2G effectively reduce electricity surpluses and enhance system stability during peak demand periods. By enabling electric vehicles to function as distributed storage, these technologies align demand management with the intermittency of renewable sources (particularly solar) and contribute to overall cost reductions. Similar European case studies also demonstrate that higher flexibility levels from the transport sector improve the integration of intermittent renewables [35], such as solar [46] and wind in northern European countries [37], while reducing reliance on coal and natural gas capacities. Additionally, combining smart charging and V2G flexibilities has been shown to reduce overall system costs by 17% [35]. The work in [36] further highlights the significant role of different smart charging strategies in managing peak demand and synchronizing energy use with renewable availability.

The combination of P2H and P2T flexibilities compounds the benefits for Chile's power system by substantially reducing energy curtailment and improving demand coverage during critical periods. System efficiency metrics show greater sensitivity to P2T flexibilities compared to P2H. Notably, the reduction in surplus electricity is most effective when V2G capacity is prioritized, as it facilitates intermittent energy reintegration during high-demand periods while complementing the flexibility offered by heat pumps. However, the impact of V2G diminishes with higher smart charging profiles. This indicates that even without full flexibility across all sectors, Chile can achieve significant improvements in its power system efficiency.

Similar findings from European studies underscore the vital role of sectoral flexibility in enhancing power system efficiency. The study in [40] highlights the benefits of sectoral coupling—spanning hydro, heating, and transportation sectors—which leads to better renewable energy utilization and reduced GHG emissions. Among the three sectors, the transport sector shows the greatest reduction in curtailed electricity, followed by the heating sector.

5. Conclusions

This study aims to evaluate the impact of electrification in Chile's heating and transportation sectors within the context of the nation's carbon neutrality pathway. Scenarios were generated and analyzed to combine individual heating with the flexibility provided by smart technologies in transportation, assessing their impact on the technology mix, excess electricity, annualized costs, and generation profiles. The findings offer both academic and practical value by exploring the integration of P2H and P2T technologies to support Chilean carbon neutrality goals by 2050. Academically, it contributes to the growing body of work on energy system modeling and sectoral integration, emphasizing the role of smart charging, V2G technology, and heat pumps in enhancing system efficiency and enabling higher renewable energy penetration. Practically, the findings provide valuable insights for policymakers in Chile and similar countries, offering cost-effective strategies for reducing fossil fuel dependence, improving grid stability, and reducing operational costs through the electrification of heating and transportation.

Integrating P2H and P2T flexibilities offers significant benefits for Chile's power system by reducing energy curtailment while improving system efficiencies and integration of intermittent renewable energy. Heat pumps in the P2H sector enable better management of excess electricity but require substantial investment in heating infrastructure and thermal distribution networks if used for district heating. Meanwhile, smart charging and V2G technologies in the P2T sector provide flexibility by reducing electricity surpluses and enhancing stability during peak demand periods. The combination of flexibilities from the heating and transport sector has a cumulative effect in curtailing excess energy and improving other system efficiencies. The combination of these flexibilities is most effective when V2G technology is available. Although the impact diminishes with higher smart charging profiles, even partial adoption of these measures can significantly enhance system efficiency. This provides policymakers with pathways to balance sectoral costs, as P2T flexibility reduces overall costs, while HP flexibility can slightly increase them. Additionally, Chile's substantial PV capacity reduces reliance on fossil fuels, restricting their use to mid-winter months. Studies conducted in Europe lend support to our findings in the Chilean context. These findings underscore the importance of integrated flexibility measures for Chilean policymakers to maximize renewable energy utilization and stabilize costs while addressing socio-economic and climatic factors. Results obtained in this research can also be extrapolated to countries with similar conditions, where solar or wind-based generation can be better integrated with the availability of sector coupling. Examples include regions such as California, China, or Australia, where excess electricity has increased significantly. Hence, insights found in this research can be useful for international policy guidelines.

However, the authors acknowledge the shortcomings of the study conducted. Simulation models like the EnergyPLAN do not allow endogenous optimization of technology investment or generation of intermediate pathways over the horizon. This provides opportunities for refinement. Soft-linking with optimization models could enhance the accuracy of technology sizing and system metrics and can be a possible direction for extending this study. Furthermore, the simplified representation of grid infrastructure and the transportation sector module may overlook localized variations and limit our usage in vehicle types and charging behaviors. The usage of complementary tools and broader empirical data across diverse heating, transportation, and other hard-to-decarbonize sectors (like industry) could also provide more context about sectoral flexibilities in Chile. This is even more important for industrialized countries like China, Mexico, the United States, or India, countries that also have large renewable potential. Additionally, EnergyPLAN's deterministic nature limits its application for uncertainty analysis, making it less suitable for scenarios requiring probabilistic assessments.

As discussed in the introduction, Chile has a long way to go in altering its current dependency on firewood, implementing current insulation standards in households, and improving infrastructure that would allow the electrification of its transportation sector. Understanding social behavior regarding the willingness to adopt [38] (e.g., concerns about battery degradation risks with V2G) or its evolution over time in which flexible infrastructure is more widespread is complex and can significantly influence the dynamics. That being said, this study meets the objective of evaluating the feasibility of these technologies under Chile's LTEP, providing a pathway for policy and investment decisions that can drive effective decarbonization in Chile's energy system.

Author Contributions: Conceptualization, F.F. (Felipe Feijoo), F.F. (Francisco Flores), C.A.A.F.V. and A.K.; methodology, F.F. (Felipe Feijoo), F.F. (Francisco Flores), C.A.A.F.V. and A.K.; software, F.F. (Francisco Flores) and A.K.; validation, F.F. (Felipe Feijoo), F.F. (Francisco Flores), C.A.A.F.V., M.C., A.K., H.G. and S.Q.; formal analysis, F.F. (Francisco Flores), F.F. (Felipe Feijoo), A.K. and C.A.A.F.V.; investigation, F.F. (Felipe Feijoo), F.F. (Francisco Flores), C.A.A.F.V., A.K., H.G., S.Q. and M.C.; resources, F.F. (Francisco Flores) and F.F. (Felipe Feijoo); data curation, F.F. (Francisco Flores) and F.F. (Felipe Feijoo); writing—original draft preparation, A.K., F.F. (Francisco Flores), M.C., C.A.A.F.V. and H.G.; writing—review and editing, A.K., F.F. (Felipe Feijoo), F.F. (Francisco Flores), M.C., C.A.A.F.V., S.Q. and H.G.; visualization, A.K.; supervision, F.F. (Felipe Feijoo), M.C. and S.Q.; project administration, F.F. (Felipe Feijoo), S.Q. and M.C.; funding acquisition, F.F. (Felipe Feijoo) and M.C. All authors have read and agreed to the published version of the manuscript.

Funding: A.K., F.Fl., and F.F. were funded by the Agencia Nacional de Investigación y Desarrollo (ANID) of Chile by the grant FONDECYT regular 1221894, and M.C. by the grant FONDECYT regular 1241548. All authors were funded by the ANID Project Fomento a la Vinculacion Internacióńal FOVI230228.

Data Availability Statement: The EnergyPLAN and result files supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BAU	Business-as-Usual
CHP	Combined Heat and Power
CSHP	Combined Steam Heat and Power
CSP	Concentrated Solar Power
DH	District Heating
EV	Electric Vehicle
GCAM	Global Change Analysis Model
GHG	Greenhouse Gas
HP	Heatpump
HRCL	Heat Roadmap for Chile
LPG	Liquified Petroleum Gas
LTEP	Long-Term Energy Planning
NDC	Nationally Determined Contribution
P2H	Power to Heat
P2T	Power to Transport
PV	Photovoltaic
V2G	Vehicle to Grid

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