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The role of hydrogen for deep decarbonization of energy systems: A Chilean case study

Francisco Ferrada [a], Frederic Babonneau [b,c], Tito Homem-de-Mello [d,f], Francisca Jalil-Vega [e,f,g,*]

[a] Faculty of Engineering and Sciences, Universidad Adolfo Ibáñez, Santiago, Chile
[b] Kedge Business School, Bordeaux, France
[c] ORDECSYS, Geneva, Switzerland
[d] School of Business, Universidad Adolfo Ibáñez, Santiago, Chile
[e] Electrical Energy Management Group, Faculty of Engineering, University of Bristol, Bristol, UK
[f] Center for Energy Transition (CENTRA), Universidad Adolfo Ibáñez, Santiago, Chile
[g] Instituto Sistemas Complejos de Ingeniería (ISCI), Santiago, Chile

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ABSTRACT

In this paper we implement a long-term multi-sectoral energy planning model to evaluate the role of green hydrogen in the energy mix of Chile, a country with a high renewable potential, under stringent emission reduction objectives in 2050. Our results show that green hydrogen is a cost-effective and environmentally friendly route especially for hard-to-abate sectors, such as interprovincial and freight transport. They also suggest a strong synergy of hydrogen with electricity generation from renewable sources. Our numerical simulations show that Chile should (i) start immediately to develop hydrogen production through electrolyzers all along the country, (ii) keep investing in wind and solar generation capacities ensuring a low cost hydrogen production and reinforce the power transmission grid to allow nodal hydrogen production, (iii) foster the use of electric mobility for cars and local buses and of hydrogen for long-haul trucks and interprovincial buses and, (iv) develop seasonal hydrogen storage and hydrogen cells to be exploited for electricity supply, especially for the most stringent emission reduction objectives.

1. Introduction

Over the last decade, many countries around the world have committed to reducing their carbon footprints by decarbonizing their energy systems. Hard-to-decarbonize energy end-uses include the transportation and heating sectors, responsible for more than 25% of global greenhouse gas (GHG) emissions (Rüdisüli et al., 2022). Proposed decarbonization pathways for heat and transport generally involve electrification or hydrogen uses (Ruhnau et al., 2019), with future expected uptakes of technologies such as combined heat and power (CHP), battery electric vehicles (BEVs), heat pumps, or fuel cells, among others (Narula et al., 2019). However, in order for electrification or hydrogen uses to lead to decarbonization of energy services, we must ensure that electricity and hydrogen supply chains – from production to end-uses – are low carbon (Rüdisüli et al., 2019), which is why it is essential to consider GHG emissions of the total energy system when developing decarbonization transition pathways.

Stringent global and national decarbonization targets – together with an exponential decline in investment costs for wind power, solar photovoltaics (PV), and battery energy storage – have encouraged a significant increase in variable renewable energy (VRE) penetration over time. From 2015 to 2020, solar PV installed capacity increased by 225% globally, while installed wind capacity increased by 76% (Hannah Ritchie and Rosado, 2020). However, one of the biggest challenges of energy systems with high VRE penetration is that their variability and intermittency (Kötter et al., 2016) require the existence of complementary storage technologies to allow for decoupling supply and demand at different timescales (hourly, daily or seasonal) (Chen et al., 2018).

The idea of incorporating hydrogen as an energy carrier in energy systems has gained momentum in recent years, and although there are still many techno-economic difficulties to implement this at scale, hydrogen is getting closer to being a cost-effective solution (Schmidt et al., 2017). Also, hydrogen is one of the few energy carriers that could potentially supply heavy-duty transport energy demands with near-zero emissions (Greene et al., 2020). Even in hard-to-decarbonize sectors such as long-haul freight transport, hydrogen may be one of the few viable low-carbon alternatives (FCH, 2019). There has also been recent

* Corresponding author at: Electrical Energy Management Group, Faculty of Engineering, University of Bristol, Bristol, UK.
E-mail address: f.jalil-vega@bristol.ac.uk (F. Jalil-Vega).

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interest in using hydrogen as storage for the power sector, producing it from renewable sources in times of excess electricity generation, and using it to generate electricity when renewable generation is insufficient (see for example Brey, 2021).

Long-term energy planning models have been proposed to understand possible decarbonization pathways of national energy systems, and to analyze hydrogen's role in energy systems and its possible supply chains at different scales and for diverse end-uses. In Ozawa et al. (2018), the authors implement the MARKAL model (Loulou et al., 2004) in order to evaluate the role of hydrogen in future energy systems in Japan. They find that hydrogen can play a functional role as long as it is synergistic with nuclear energy and CCS. However, the study does not model end-use sectors and does not consider local hydrogen production, but only its import from overseas—without considering transportation, distribution, and refueling costs after leaving the port. Contaldi et al. (2008) also implement the MARKAL model to evaluate the role of hydrogen when constraining CO_2 emissions in the Italian energy system. Under given CO_2 taxes and an exogenous assumption on the use of hydrogen, results show a decrease in total energy consumption, oil imports, and in CO_2 emissions – by about 11% – together with an increase in the share of renewables. In addition to the fact that the use of hydrogen is exogenously defined and not the result of a cost-effective decision, the authors do not consider hydrogen production via electrolyzers. Instead, they assume hydrogen production only from natural gas catalytic reforming and biomass and coal gasification with CCS. Choi et al. (2022) implement the TIMES model (Loulou et al., 2005) to evaluate the effects of hydrogen penetration for decarbonizing the Korean energy system. They assess the feasibility of possible hydrogen supply chains considering an exogenously determined hydrogen penetration level, based on official governmental targets. Results indicate that in order for carbon emissions from hydrogen produced via water electrolysis to be comparable to steam methane reforming with CCS, the share of renewable energy in the power sector must increase to 60%. In Vats and Mathur (2022), authors use the MARKAL model to analyze the implications of a net-zero emissions scenario for India in 2050. They incorporate a series of constraints to exogenously set the combinations of fixed technologies to meet energy service demands, in order to assess the impact of governmental energy planning policies over the energy system. Hydrogen is assumed to meet the whole energy demand for heavy road commercial vehicles by 2050, and used for the direct reduction process in iron and steel industries.

While most of the reviewed long-term energy planning models incorporate the deployment of hydrogen technologies in different sectors, they consider hydrogen demands as exogenous inputs. Hydrogen is considered as a final demand per-se, rather than as an energy carrier able to supply different energy service demands, and which can be evaluated from a cost-effective perspective. In other words, they do not allow for an analysis of the impact of hydrogen over the whole system. While hydrogen can be an alternative for decarbonizing hard-to-decarbonize sectors – such as heavy-duty road transport – these models do not show the indirect effects of hydrogen over other sectors when decarbonization initiatives are planned from a system's perspective. In the present paper we propose an integrated long-term multi-sector energy planning model for Chile, with the entire hydrogen supply chain being evaluated from a cost-effective perspective.

Among countries aiming to incorporate hydrogen as an energy vector, Chile is one of the cases whose high renewable potentials have led to an ambitious National Green Hydrogen Strategy (Ministry of Energy, 2021b). Chile has a combined wind and solar potential that accounts for more than 1800 GW, equivalent to 70 times its current installed capacity, Ministry of Energy (2020), and at very high capacity factors (Ministry of Energy, 2018; Molina et al., 2017). The country has been framed as potentially having the lowest hydrogen production costs globally by 2030—1.5 USD/kg according to Mckinsey and Company (2020), International Energy Agency (2019b). Additionally, in its updated Nationally Determined Contributions (NDCs), Chile has committed to carbon neutrality by 2050, along with meeting intermediate carbon budgets and reducing its black carbon emissions (Gobierno de Chile, 2020). Chile's long-term energy planning process uses a tool that performs a joint optimization of the investments and operations of the national power system (PELP, 2019). One of its main shortcomings is that the model minimizes costs based on exogenous energy-service electrification scenarios, as opposed to endogenously deciding optimal electrification and end-use technologies. Thus, external hydrogen deployment scenarios are incorporated without considering if they are cost-effective pathways or not. Ferrada et al. (2022) was the first (and only) Chilean study to date, where an integrated energy planning model – namely, ETEM *(Energy-Technology-Environment-Model)* – was applied for the energy system. It considered the capacity expansion of the power system together with commercial and residential sectors' demands, so that the model endogenously decides which are the lowest-cost end-use technologies to satisfy energy service demands. However, this study did not incorporate the transport sector, nor did it integrate hydrogen supply chains and end-uses.

The main contribution of this paper is thus the implementation of a long-term integrated model to assess the cost-effectiveness of incorporating hydrogen supply chains and uses into whole-energy systems, and to assess hydrogen's role for reaching deep decarbonization in a highly renewable energy system, such as Chile. To do so, we expand the previous implementation of the Chilean ETEM model (Ferrada et al., 2022) to the transportation and hydrogen sectors. In this extended version, hydrogen is considered as an alternative for supplying different energy service demands, and as an energy carrier for the power system, including its possible role as a storage technology. To the best of our knowledge, this is the first integrated long-term energy planning model that incorporates residential, commercial, and transportation sectors together with the electricity and hydrogen supply chains. The model enables competition among all viable technologies to meet energy service demands, thereby allowing us to evaluate, in particular, whether electrolytic hydrogen can be a competitive energy carrier in a highly renewable energy system. More globally, it enables an analysis of the direct and indirect policy implications of the use of hydrogen in different sectors under strong emission reduction policies to 2050.

The article is structured as follows: Section 2 presents the general description of the ETEM model, and the approach used to integrate the transportation sector, the modeling of hydrogen, and the technologies considered. Section 3 presents the results and discussions of the study, focusing mainly on decarbonization policies, and in Section 4 we present concluding remarks.

2. Methodology

The methodology of this study consists of the implementation of the ETEM model in the Chilean energy system – considering the work previously carried out by Ferrada et al. (2022) – and expanding it to incorporate the transportation sector, together with hydrogen supply chains and end-uses. The objective is to determine if hydrogen could be a competitive way to satisfy consumption when synergies between sectors are possible. In this section, we first describe briefly the ETEM model and its previous application to Chile. Then we detail the procedure carried out to model and calibrate the transportation and hydrogen sectors. It is important to observe that the methodology carried out by this study follows a structure that can potentially be applied in other energy systems for the assessment of deep decarbonization, especially when high potential variable renewable energy sources are observed. Of course, in order to use the model in a different setting (say, a different country) it would be necessary to properly calibrate all the parameters such as investment costs, operating costs, demand, installed capacity, etc.

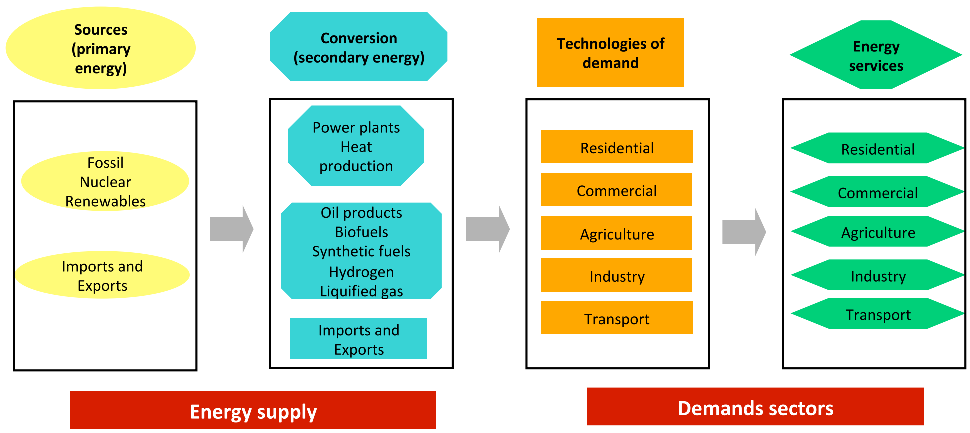


Fig. 1. Reference energy system.

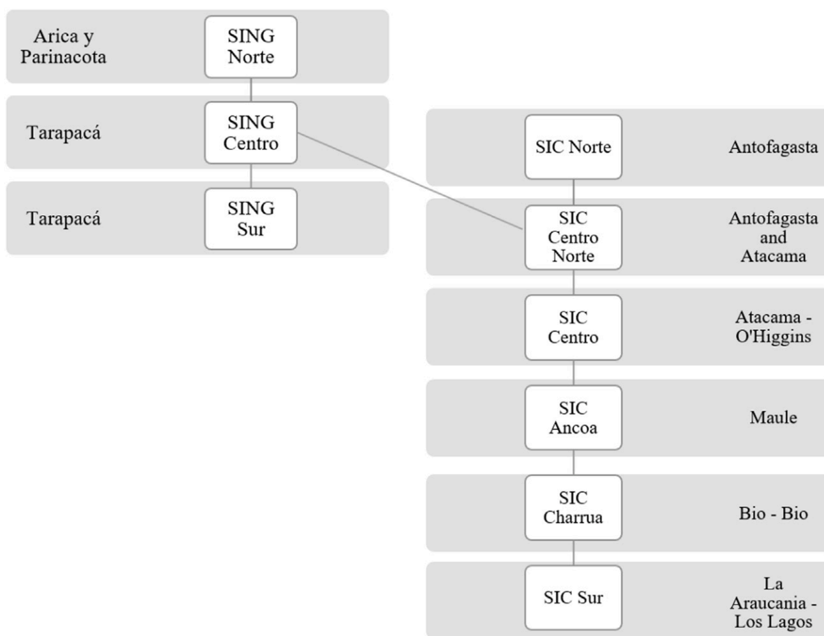


Fig. 2. Diagram of transmission lines and representative nodes from Babonneau et al. (2021). White boxes represent the nodes that simplify the national electricity system, while the names in the gray rectangles represent the approximate geographic location in Chile's regions covered in this study.

2.1. ETEM description in brief

ETEM is a multi-sector, multi-energy, technology-rich model specifically designed to analyze the energy transition at a regional or national level. While a full description of the ETEM model is provided in Babonneau et al. (2017b), power flow constraints and nodal marginal prices representation can be found in Babonneau and Haurie (2019), and a presentation of the possibility to represent demand and distribution constraints and options in ETEM in a smart energy system is given in Babonneau et al. (2017a). ETEM is a linear programming model related to the MARKAL-TIMES family of models (Berger et al., 1992; Fragnière and Haurie, 1996; Loulou and Labriet, 2008).

As shown in Babonneau et al. (2017b), the ETEM model, in its standard version, is driven by exogenously defined energy service demands and commodities prices. Fig. 1 illustrate the representation of the energy transformation processes considered in the model, where technologies are used always as resource transformers and are defined with techno-economical parameters such as efficiencies, inputs and outputs, availability factors, lifetime and capacity limits, among others.

The ETEM model is usually applied within a time horizon of 20 to 50 years, with the objective of evaluating the energy system in a time frame that is likely to be sufficient to change the entire technology mix. The time horizon is divided into periods of one to five years. In this work, 5-year investment periods are used. Typical days are also considered within each period. These were chosen in this work as weekdays and weekends, for each season of the year, in order to represent energy services demand profiles in more detail.

Our work extends the previous implementations of the ETEM model for the Chilean energy system presented by Babonneau et al. (2021) and Ferrada et al. (2022), to integrate the transport sector and hydrogen technologies. In Babonneau et al. (2021), the authors implement the ETEM-Chile model specifically for the national electricity system to assess the impact of strict decarbonization policies, taking into consideration an exogenous electricity demand predicted by the Ministry of Energy, which considers electrification assumptions for all of the country's energy service demands. They simplify the national electricity system into 9 nodes and 8 transmission lines, where the installed capacity potentials of each technology are calibrated in each node. Fig. 2 depicts the nodes' geographical distribution.

Ferrada et al. (2022) extend the work in Babonneau et al. (2021) to include energy services related to the commercial and residential sectors across nodes—specifically, heating, cooling and sanitary hot

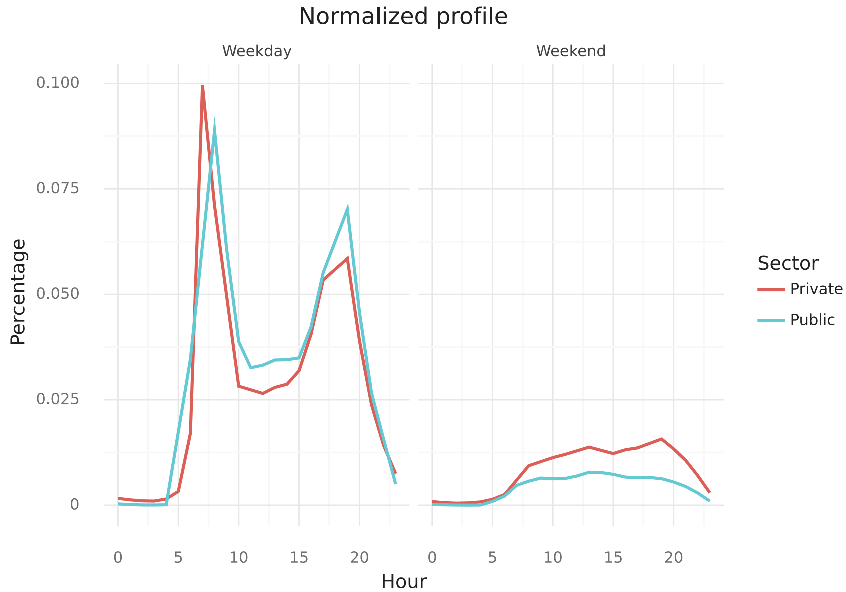


Fig. 3. Percentage of annual demand for public and private urban transport, corresponding to each hour on each typical day.

water. The model in Ferrada et al. (2022) is based mainly on governmental data on demand projections up to 2050. Installed capacities of the current system are considered as a starting point and the model chooses after the first period which technologies are going to be part of the mix of each energy service.

Note that important modeling assumptions are made in Ferrada et al. (2022) and Babonneau et al. (2021):

- The work carried out by Babonneau et al. (2021) considers the decommissioning of coal-fired plants by 2040 as part of the commitments made by the Chilean government (Ministerio de Energía, 2020).
- Ferrada et al. (2022) assume that the rate of change of end-use technologies between consecutive periods to meet demands is no more than 25%, so that the transition of technologies has a realistic and achievable behavior (European Commission, 2017).

2.2. Modeling the transport sector

2.2.1. Transport demand projections

To include transport into the model, we rely on governmental demand projections of different transport energy service demands. Specifically, we consider freight, public urban passenger, private urban passenger, and inter-provincial public passenger demands. Annual demands for each service are shown in Table 1. The demands associated with the transportation sector are in millions of passengers-KM (denoted Mpkm) and millions of tons-KM (denoted Mtkm), as the technologies we consider in the model have different conversion factors.

To calibrate transportation demands across nodes, demand projections developed by the Ministry of Energy are disaggregated into regions. However, our study adopts a simplification of the national electricity system, which results in a different geographical distribution. An approximation to obtain the percentage of total demand assigned to each node is to consider that both distributions – nodal and regional – can be described by municipalities, which are the smallest administrative divisions in the country. In order to disaggregate the regional demand into municipalities, we consider the number of vehicles by sector owned by each municipality as a weighting factor. For this purpose, we used the database of vehicle registration permits of the National Institute of Statistics (2020). Finally, municipal demands per sector are added-up into nodes.

The ETEM model is calibrated with typical days; each year is represented by 192 h according to a weekday and a weekend day per season of the year. To obtain the demand profiles per energy service in the transport sector we consider two different sources. On the one hand, we utilize the Origin Destination Survey developed by the Ministry of Transportation (SECTRA, 2017), to describe the demand profile on urban private transport. On the other hand, we use the Transport Ministry's records for bus and subway boarding transactions in the Metropolitan Region (Ministry of transportation and Chile, 2018), in order to obtain hourly profiles of public transport occupancy on different days of the year. We assume that there are no differences between the hourly profiles corresponding to different seasons of the year and nodes. Fig. 3 shows the demands profiles for public and private urban transport.

2.2.2. Technologies and calibration

We discuss now how we define the technologies used to meet demand. For current technologies, we rely on the vehicle circulation permit database (National Institute of Statistics, 2020), which contains details on the type of vehicles, and other characteristics such as years and fuels. As the database is populated by municipalities, we can know precisely the number of vehicles and type of fuels used in each node.

Possible technologies included in the model consider hydrogen deployment in heavy-duty trucks, inter-provincial buses, urban public buses and private cars considering fuel cell applications. Battery Electric Vehicles (BEV) are also included to satisfy private transport, public urban transport and last mile fraction of freight transport. Economic parameters of each technology considered to satisfy transportation energy services can be found in Table 4 presented in Appendix A. Technical parameters per technology considered per sector can be found in Table 5 in Appendix A, where the conversion factors and the activity multipliers are presented in detail, indicating the average cargo (in persons or tons) carried by each vehicle type. Vehicle efficiencies follow a trend that considers expected improvement potentials (National Renewable Energy Lab. U.S Department of Energy, 2020).

Regarding freight transportation, it is important to observe that we do not include long-haul electric trucks as a technology to meet demand, considering that to date there are no effective technologies to reduce battery charging times, and it is not feasible in practice to manage a transport fleet with such long waiting times for refueling (FCH, 2019; Fuell Cells and Hydrogen joint undertaking, 2019). Electric trucks can only satisfy last mile freight transportation, which does not

Table 1
Chilean total demands per energy service up to 2050.

Demand	2020	2025	2030	2035	2040	2045	2050	Units
Exogenous Demand								
Electricity	761497	800193	814910	806885	885022	895465	931266	GWh
Residential Demand								
Heating	232720	276882	329424	391938	466314	595455	660087	GWh
Sanitary Hot Water	102416	115037	124965	131740	136227	139741	141798	GWh
Commercial Demand								
Cooling	775	1013	1249	1481	1715	1949	2178	GWh
Sanitary Hot Water	6765	7758	8688	9523	10404	11281	12072	GWh
Heating	19809	25690	31538	37244	43035	48828	54483	GWh
Transport Demand								
Public	63368	72879	81960	91950	102556	114348	125212	Mpkm
Interregional	37412	44031	50432	57487	65032	73069	80753	Mpkm
Private	65955	75853	85305	95703	106742	119015	130323	Mpkm
Freight	81270	99566	117136	137023	158833	182096	205138	Mtkm

Table 2
Techno-economic assumptions for PEM electrolyzers in H_2_High and H_2_Low scenarios.

Parameter PEM electrolyzer	2020	2025	2030	2035	2040	2045	2050
H_2_High							
CAPEX (USD/KW)	1100	875	650	537.5	425	312.5	200
Stack lifetime (Thousand Hours)	90	90	90	105	120	135	150
Electrical Efficiency (%)	60	64	68	69.5	71	72.5	74
H_2_Low							
CAPEX (USD/KW)	1800	1650	1500	1350	1200	1050	900
Stack lifetime (Thousand Hours)	30	45	60	70	80	90	100
Electrical Efficiency (%)	56	59.5	63	64	65	66	67

Table 3
Average nodal marginal costs in 2050 for electricity and hydrogen (before and after storage) by scenario for SIC_Centro and SIC_CentroNorte.

Emission reduction objective	Scenario	Electricity (USD/KWh)	Hydrogen production (USD/Kg)	Hydrogen after charging station (USD/Kg)
SIC_Centro				
Free	H_2_High	0.079	3.62	5.76
	H_2_Low	0.070	3.97	6.22
60%	H_2_High	0.079	3.62	5.75
	H_2_Low	0.088	4.85	7.41
84%	H_2_High	0.084	3.81	6.01
	H_2_Low	0.091	5.02	7.63
100%	H_2_High	0.088	4.04	6.32
	H_2_Low	0.097	5.29	8.00
SIC_CentroNorte				
Free	H_2_High	0.058	2.68	2.58
	H_2_Low	0.048	2.83	4.22
60%	H_2_High	0.058	2.69	2.44
	H_2_Low	0.058	3.37	4.15
84%	H_2_High	0.059	2.76	2.18
	H_2_Low	0.063	3.59	3.95
100%	H_2_High	0.062	2.89	2.24
	H_2_Low	0.068	3.83	3.88

exceed 10% of total freight transportation (Comisión de Transporte, 2019).

For electric vehicles, the capital costs associated with charging stations are defined as follows. We consider 3 different types of stations: (i) Level 1, 7 kW AC, are those that would be placed in houses, with installation costs including electrical junction increase and hardware (1100 USD and 1000 USD respectively). (ii) Level 2, 22 kW AC for public stations, considers installation costs and hardware costs (2700 USD and 3200 USD respectively). (iii) Level 3, 80 kW DC for commercial purposes, which consider installation and hardware costs (26,964 USD and 30,000 USD respectively). Cost data is obtained from Nicholas (2019), where hardware costs follow a trend of decreasing prices at a rate of 3% per year.

2.3. Modeling hydrogen deployment

Hydrogen in this work plays the role of an energy carrier. According to Chile's National Green Hydrogen Strategy (Ministry of Energy, 2020), all of the Government's plans regarding hydrogen production and uses involve electrolytic hydrogen produced from renewables, or "green" hydrogen, given the high potential for cheap wind and solar energy in the country. Such a strategy aligns with the country's stated goals of achieving net zero greenhouse gas emissions by 2050. Hence, in this work we only consider hydrogen production through electrolysis, and not from other sources such as fossil fuels. It is also worth noting that Chile has no national fossil fuel production and relies entirely on imports. Once it is generated by electrolyzers, hydrogen is stored and distributed for one of the following purposes: to satisfy the transportation sectors; to be used as storage for electricity generation; or to be blended into natural gas pipelines. Important assumptions about hydrogen in the model are: (i) Hydrogen cannot be imported; if we consider the national hydrogen generation potential, local generation is the only way to supply it. (ii) There is unrestricted generation potential in all nodes; Chile is a country with coastline

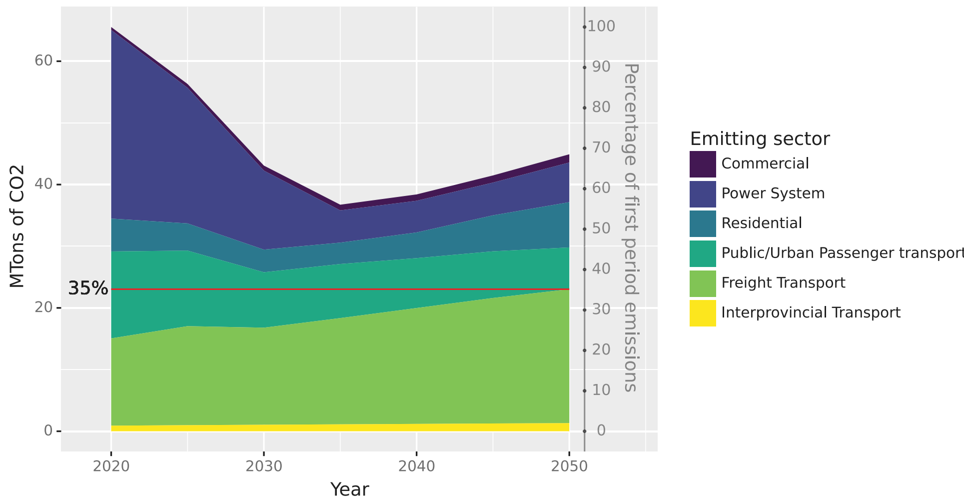


Fig. 4. Total CO_2 emissions for H_2_No scenario without emission constraints. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

presence throughout the territory, and the operating and investment costs consider water desalination. (iii) Based on Semeraro (2021), we assume that it is less costly to install electricity transmission lines than hydrogen pipelines to transport it for an operation normally expected in the Chilean case, in terms of amount of energy and distances. Thus, the model can deliver electricity from one node to another, but hydrogen transmission is not possible. That is, all the hydrogen produced in one node is consumed within the same node.

Liquefied gas storage tanks are thus the selected technology for the Chilean case study. An investment of 26.75 USD/kg of hydrogen is considered for the tanks, plus a compressor with a 50 $t/H_2 - day$ capacity and 112 million dollars investment, at an efficiency of 78% and plant availability factor of 0.91. Operating and maintenance costs are equal to 3% of investment costs (Emonts et al., 2019).

Hydrogen is assumed to be distributed by trucks, as there are significant potentials for hydrogen production throughout the country, and it is estimated that plants can be relatively close to any major demand. International Energy Agency (2019a) shows that the levelized costs of pipelines for distances under 300 kms are only competitive (compared to trucks) when a strongly centralized distribution is in place, which is not the case of Chile. Natural gas (NGA) pipeline refurbishment is not considered as an alternative, but hydrogen can be mixed with NGA up to 20% in volume. Refueling stations for Fuel Cell Electric Vehicles (FCEV) are considered to have an average capacity of 850 kg/day of hydrogen supply (Emonts et al., 2019), with an investment of 1.819 million dollars per station, an efficiency of 95.2%, plant availability factor of 91%, and lifetime of 20 years (Perna et al., 2022).

Sectors assumed to consume hydrogen are: (i) Commercial and Residential sectors that use NGA (only up to 20% of the mix in volume), (ii) the transport sector, by means of fuel cells in long distance road freight transport, inter-provincial passenger transport, public transport and private transport, and (iii) electricity generation, where hydrogen power plants – with the same techno-economic parameters as natural gas combined cycle power plants (Ozawa et al., 2018; Chiesa et al., 2005) – and fuel cells are considered.

In the modeled energy system, hydrogen can be produced using surplus electricity, and used on an inter-seasonal basis to meet energy service demands of the described sectors. In the next section, we analyze the direct and indirect implications of the presence of hydrogen to satisfy demands, how it affects the transition of technologies when the system is exposed to strict emission reduction policies, and its potential environmental and economic benefits.

3. Numerical analysis and discussion

In this section, we first describe the analyzed scenarios and then we discuss the results. The detailed evolution of technology choices by sectors for the different scenarios are given in Appendix B.

3.1. Scenarios definition

To assess the potential role of hydrogen in Chile's future energy system, we analyze a set of scenarios considering different techno-economic assumptions for hydrogen production, and different emission reduction objectives. For hydrogen production, we define the three following scenarios:

- The H_2_No scenario where hydrogen is not deployed in the energy system.
- The H_2_Low where hydrogen can be produced with unfavorable techno-economic parameters as defined in Table 2.
- The H_2_$High$ scenario where hydrogen can be produced with favorable techno-economic parameters as defined in Table 2.

Favorable and unfavorable techno-economic parameters for PEM *(polymer electrolyte membrane)* electrolyzers are defined in Table 2, based on International Energy Agency (2019a). Favorable scenario, H_2_$High$, reflects the emergence of more efficient PEM electrolyzers and economies of scale in hydrogen production.

Regarding emission reduction objectives, we consider the following targets:

- A 0% target corresponds to an unconstrained emission reduction scenario. The emissions profile for the H_2_No scenario is displayed in Fig. 4. The figure shows that without any constraints and without hydrogen, the energy system reduces its emissions by almost 30% in 2050 compared to 2020, by incorporating more competitive and efficient technologies mainly in the power system.
- A 60% target that corresponds to the maximum feasible decarbonization without hydrogen deployment. This 60% limit can be explained by the difficulty in decarbonizing freight and interprovincial transport without hydrogen. We can observe in Fig. 4 that these two sectors account for nearly 35% of total emissions in 2050, compared to 2020 levels (see the red line). As a reminder, only 10% of this demand, corresponding to the last mile, can be electrified.

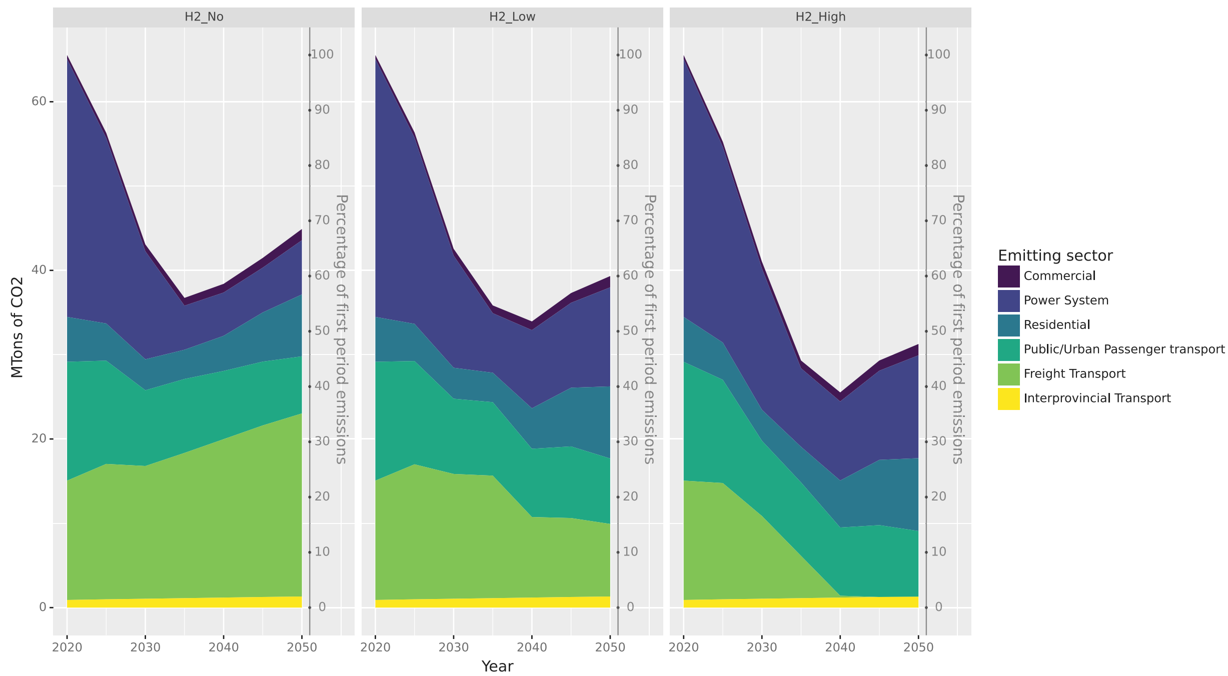


Fig. 5. Total CO_2 emissions for all hydrogen scenarios without emission constraints.

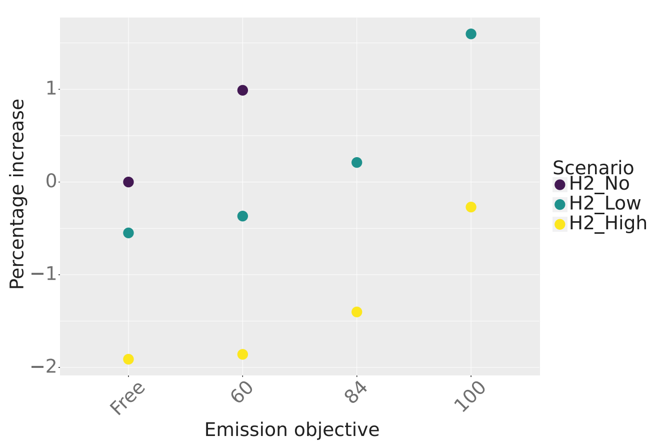


Fig. 6. Variation of the discounted system's cost as a percentage of the H_2_No scenario without emissions constraints.

- An 84% target that would be equivalent to carbon neutrality for Chile. According to the National Greenhouse Gas Inventory (INGEI, 2021), total CO_{2eq} production in 2018 is 112.3 Mt, of which 63.4 Mt (56.43%) correspond to all the sectors covered in this study. In addition, land-use, land-use change and forestry sectors induce net negative emissions of 64.0 Mt of CO_{2eq}, having a positive national balance equivalent to 48.3 Mt. Assuming (i) a growing trend of CO_{2eq} emissions equivalent to the one from 1990 to 2018 in the sectors not considered in this study, and (ii) that negative emissions remain constant, we will have a balance of −10.4 Mt of CO_{2eq} in 2050. Thus if the emissions of all sectors considered in this study are greater than this number (positive value) in 2050, Chile will not be able to reach carbon neutrality (83.6% effective emission reduction target).
- A 100% target corresponding to a stringent complete decarbonization of the Chilean energy system.

3.2. Hydrogen: A cost-effective low-carbon option

We first discuss the evolution of emissions in the unconstrained scenarios with and without hydrogen. Fig. 5 shows that the system's emissions are reduced by 40% in the unfavorable hydrogen cost scenario, and by more than 50% in the favorable scenario, compared to a 30% reduction in the scenario without hydrogen. Emissions increases in the power sector are largely offset by the evolution of the freight transport towards hydrogen. "By considering the scenario free of CO_2 constraints, we observe that although hydrogen's presence increases CO_2 emissions in the power sector, in the whole system it appears to be a cost-effective low-carbon commodity. This suggests that public policies should be oriented to foster the development of hydrogen supply chains and end-uses.

From an overall energy system cost perspective, it can be seen in Fig. 6 that the scenarios with hydrogen (H_2_Low and H_2_High) are less costly than the H_2_No scenario, for all the emission reduction objectives considered. Results show that, with an emission reduction target of 60%, H_2_High and H_2_Low scenarios would be 2.91% (21.73 billion USD) and 1.38% (10.3 billion USD) cheaper than the H_2_No scenario respectively (as a point of reference, Chile's national GDP is equivalent to 317 billion USD).

3.3. Impact on residential and commercial sectors

The detailed results on the residential and commercial sectors are shown in Figs. 13 and 14 respectively. They show an indirect impact of hydrogen development on these sectors. Early decarbonization of other sectors (e.g., transportation) using hydrogen allows for natural gas to remain as the preferred energy vector for commercial and residential heating during the transition, showing hydrogen's synergistic effects across sectors.

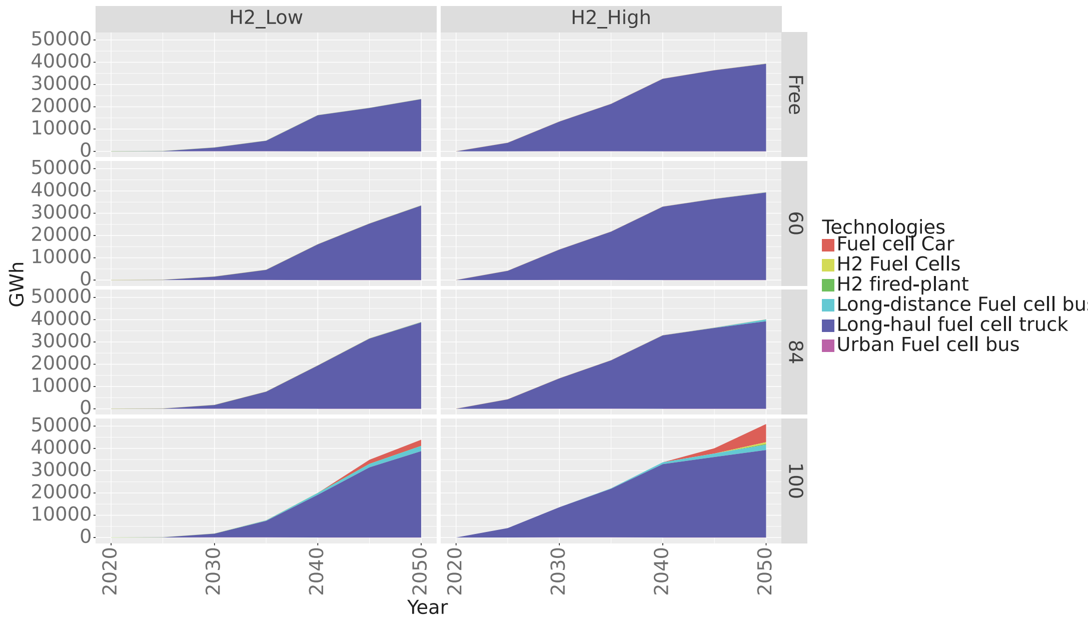


Fig. 7. Hydrogen consumption per vehicle type for all hydrogen and emission scenarios.

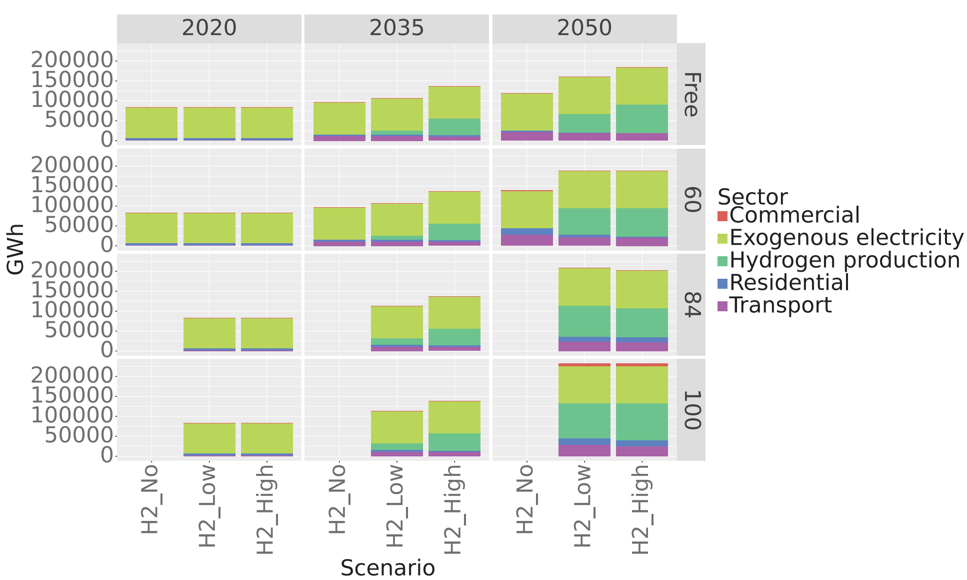
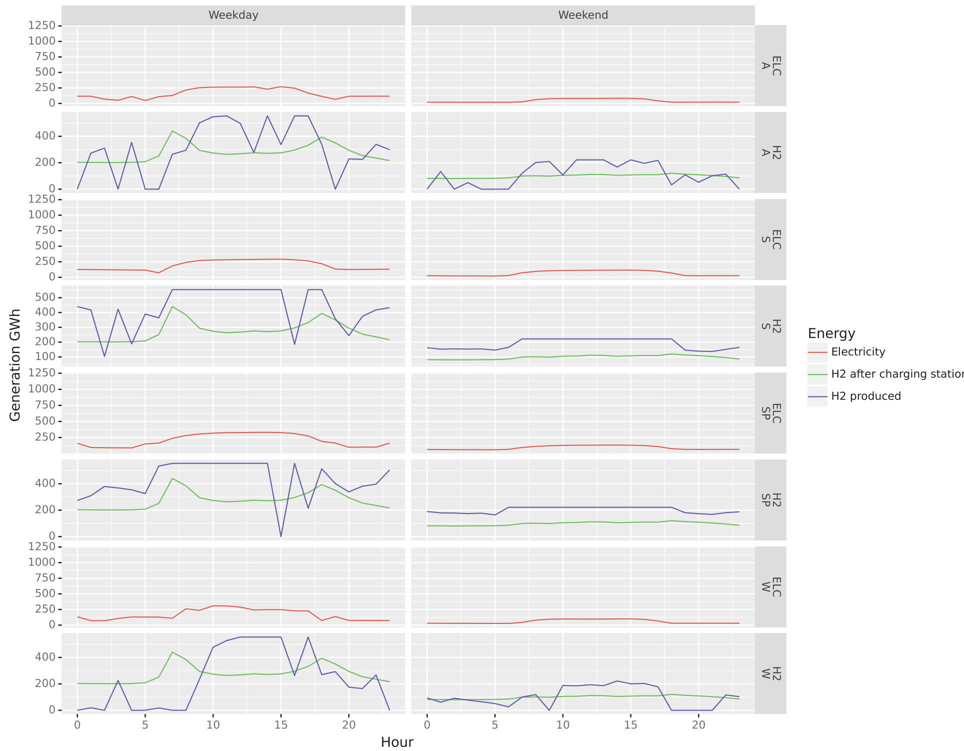


Fig. 8. Electricity consumption across hydrogen and emission scenarios.

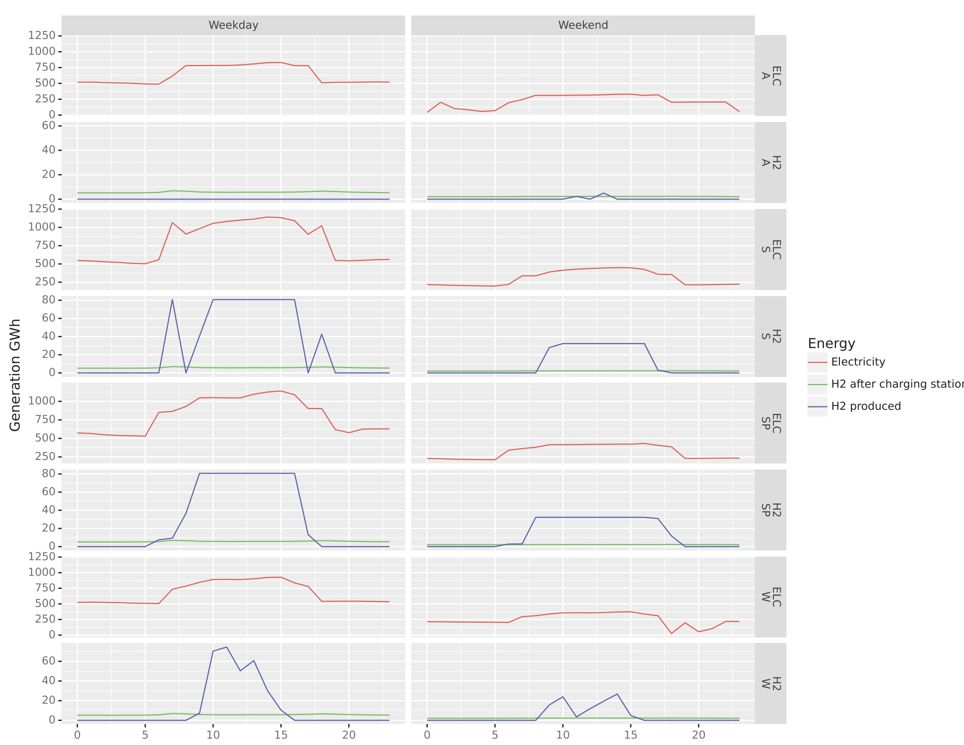
3.4. Impact on transport activities

Transport is probably the sector most impacted by the development of hydrogen. Fig. 7 shows hydrogen consumption per technology for all hydrogen and CO_2 scenarios. Hydrogen plays a major role in meeting the demand for freight transport, even when CO_2 emission restrictions are low. Only for the most ambitious carbon-reduction target, hydrogen is used in private transport and inter-provincial buses. The latter is one of the most difficult transport sectors to decarbonize, mainly because it requires a large autonomy, which seems incompatible with electric mobility (FCH, 2019).

Urban public transport is the only sector of the entire system whose activities are not affected by the presence of hydrogen. Public transport is almost completely electrified by 2035 in all scenarios, and remains so in the long term.



(a) SIC_Centro node.



(b) SIC_CentroNorte node.

Fig. 9. Production in SIC_Centro and SIC_CentroNorte nodes for electricity (ELC) and hydrogen (H2) in two points of the supply chain.

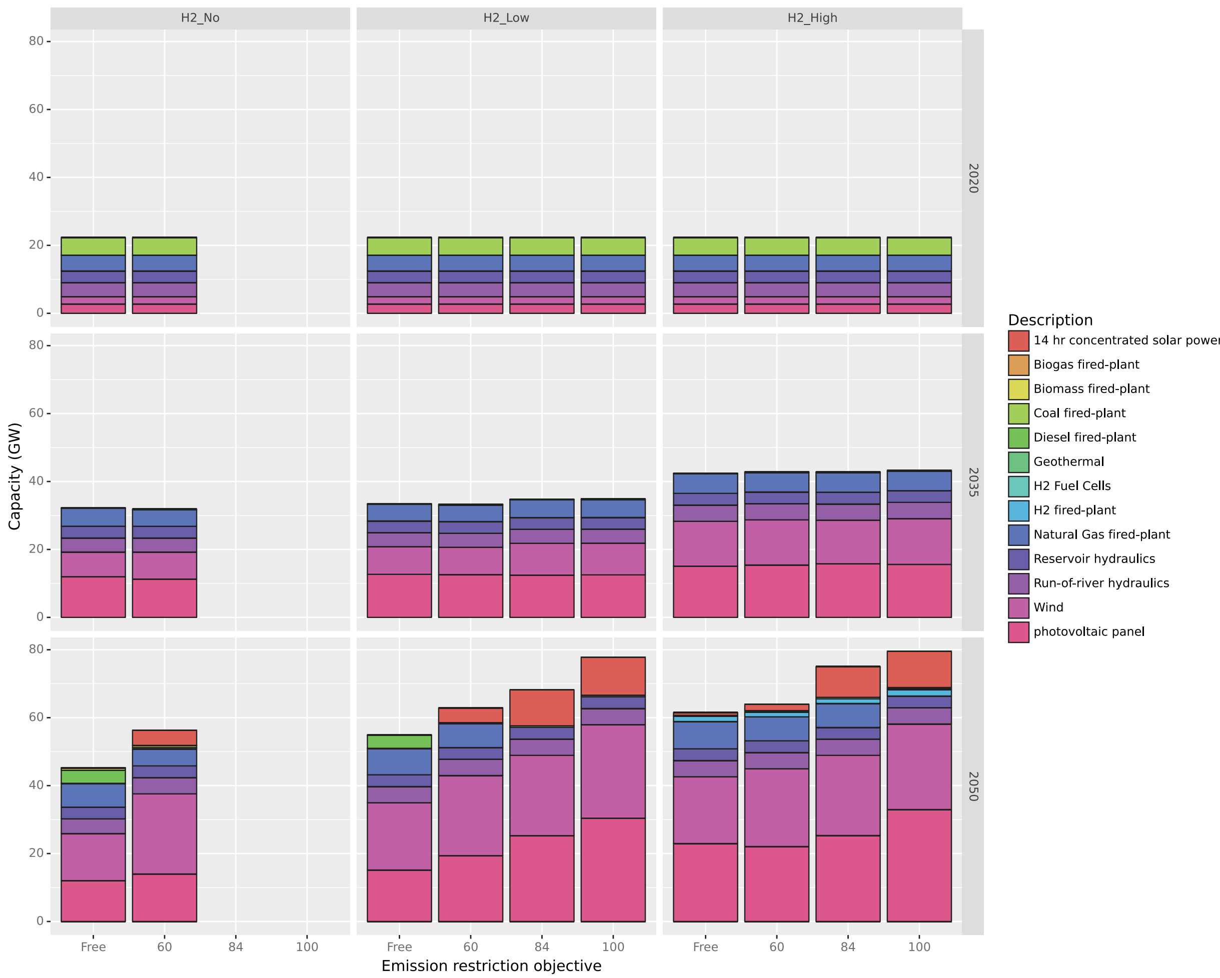


Fig. 10. Global installed capacity of power sector by year, scenario and emission restriction objective.

Based on our results, we would expect public policies to promote the development of hydrogen supply chains and refueling stations, along with the reinforcement of the electric vehicle network, including chargers and commercial charging stations.

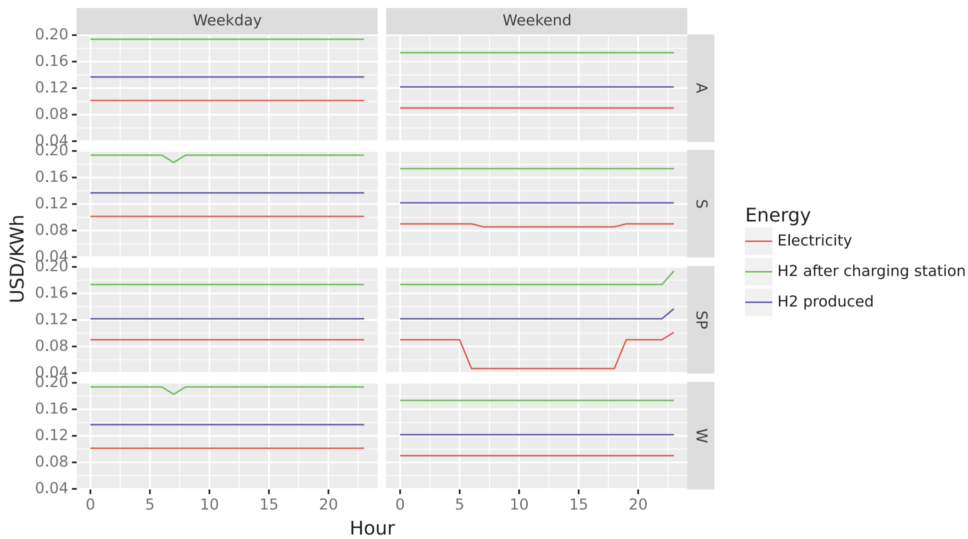
3.5. Hydrogen and electricity generation

Fig. 8 shows a clear trend of increased electricity consumption as hydrogen conditions become more favorable and emission reduction targets are more ambitious. Globally, there is about a two- to four-fold increase between the 0% and 100% reduction targets. When hydrogen development is not allowed (H_2_No), we see a higher electrification of the transportation, residential and commercial sectors in 2050 than in the hydrogen scenarios (for the 0% and 60% emission scenarios).

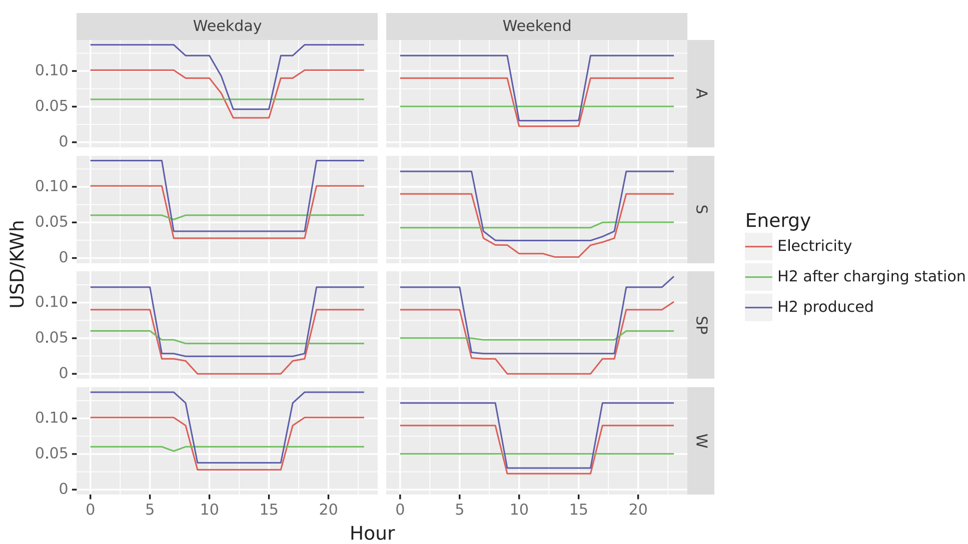
In Fig. 9, we focus on hourly production of electricity and hydrogen on typical days for two specific and connected nodes, namely, SIC_Centro and SIC_CentroNorte. These two nodes are of particular interest as SIC_CentroNorte satisfies a large part of the electricity consumption of SIC_Centro, which is the main Chilean demand node. We can see the synergy between electricity and hydrogen, especially in the midday hours, with the abundance of low-cost solar energy in the SIC_CentroNorte node, from both PV and CSP. As only electricity can flow between nodes, we observe that generated electricity in the SIC_CentroNorte node is used to produced hydrogen in the SIC_Centro node.

Regarding the installed capacity of the system, in all scenarios results show that it is more cost-effective to invest in CSP than in other types of storage (see Fig. 10). Although it is a substantially more expensive technology than 10-hour batteries (5300 USD/KW vs 3900 USD/KW respectively), it allows generation without having to be coupled to an additional technology. In the case of batteries, these are directly dependent on the availability of higher capacities of solar PV and wind power. Also, results show that in the case of 100% emissions reduction, hydrogen fuel cells contribute to electricity supply capacity in about 2 GW. The presence of hydrogen fuel cells has a seasonal behavior for supplying electricity. Hydrogen fuel cells' activity is concentrated in winter and autumn months, while the main production of hydrogen occurs in summer and spring, taking advantage of the PV load factors. Such behavior validates the role of hydrogen as a storage option.

An important factor to take into consideration is the difference in generation potential and nodal consumption. Most electricity is consumed in the SIC_Centro node, which has the highest productivity and population density in the country. However, the highest generation



(a) SIC_Centro node.



(b) SIC_CentroNorte node.

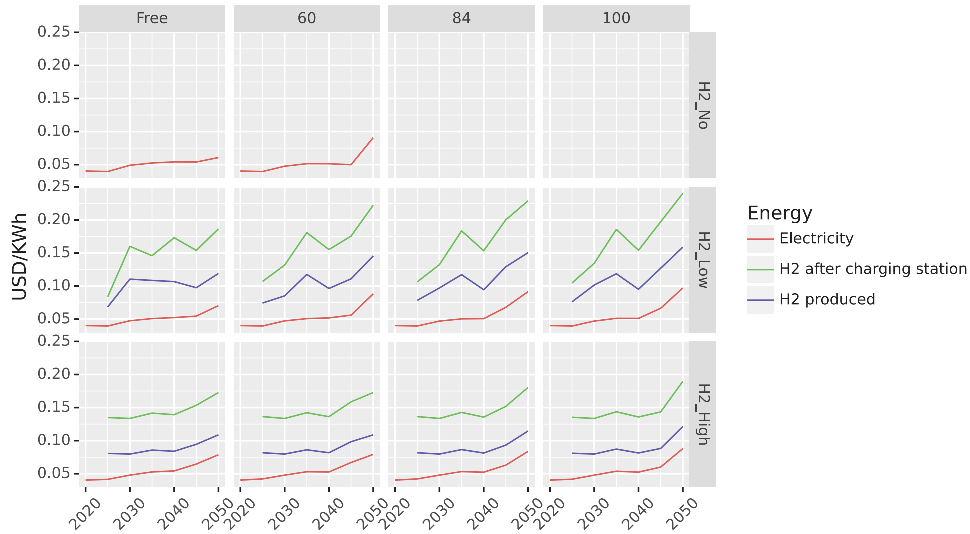
Fig. 11. Detailed marginal cost in 2050 by emission and hydrogen scenarios at the SIC_Centro and SIC_CentroNorte nodes.

potentials, which satisfy the electricity consumption of SIC_Centro, are found in the southern nodes and in SIC_CentroNorte (see Fig. 19 in Appendix C). As hydrogen consumption increases, so does the need for stable and secure transmission lines. Since no hydrogen is transmitted between nodes, only electricity is considered as an inter-nodal energy carrier.

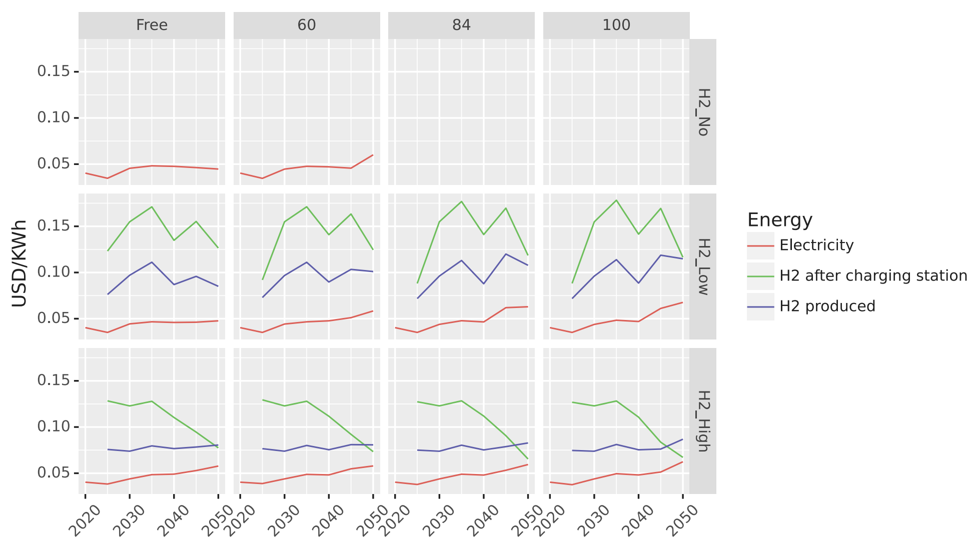
3.6. Nodal marginal costs of electricity and hydrogen

Our observations above on nodal generation (SIC_Centro and SIC_CentroNorte) reflect directly into marginal costs as shown in Fig. 11. During the middle of the day, the marginal costs of electricity and hydrogen production drop considerably. As expected, hydrogen storage helps to smooth out the marginal cost of hydrogen. In the case of SIC_Centro, for example, being highly dependent on the generation of SIC_CentroNorte, the marginal generation costs do not vary much during the day, as transmission levels the costs. Therefore we see a constant hydrogen generation during the year (see Fig. 9), making a more efficient, but more expensive, use of the installed capacity of electrolyzers in relation to SIC_CentroNorte. Depending on the composition of the power generation portfolio, the system will require more or less installed capacity of electrolyzers and storage.

Fig. 12 shows the evolution of the annual average marginal costs at the SIC_Centro and SIC_CentroNorte nodes. Again marginal costs of electricity and hydrogen production follow similar patterns. Hydrogen storage allows decoupling of the two marginal costs mainly in 2040



(a) SIC_Centro node.



(b) SIC_CentroNorte node.

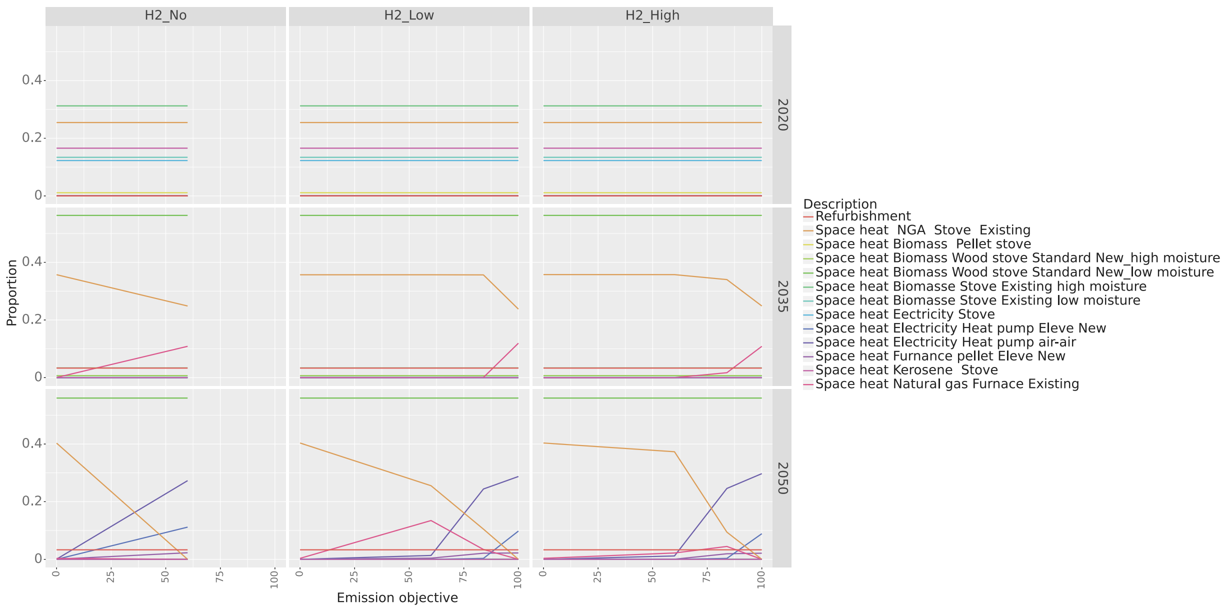
Fig. 12. Average marginal cost per year for emission and hydrogen scenarios at the SIC_Centro and SIC_CentroNorte nodes.

and 2050 when the high level of renewable production leads to high volumes of cheap and stored hydrogen (see Table 3).

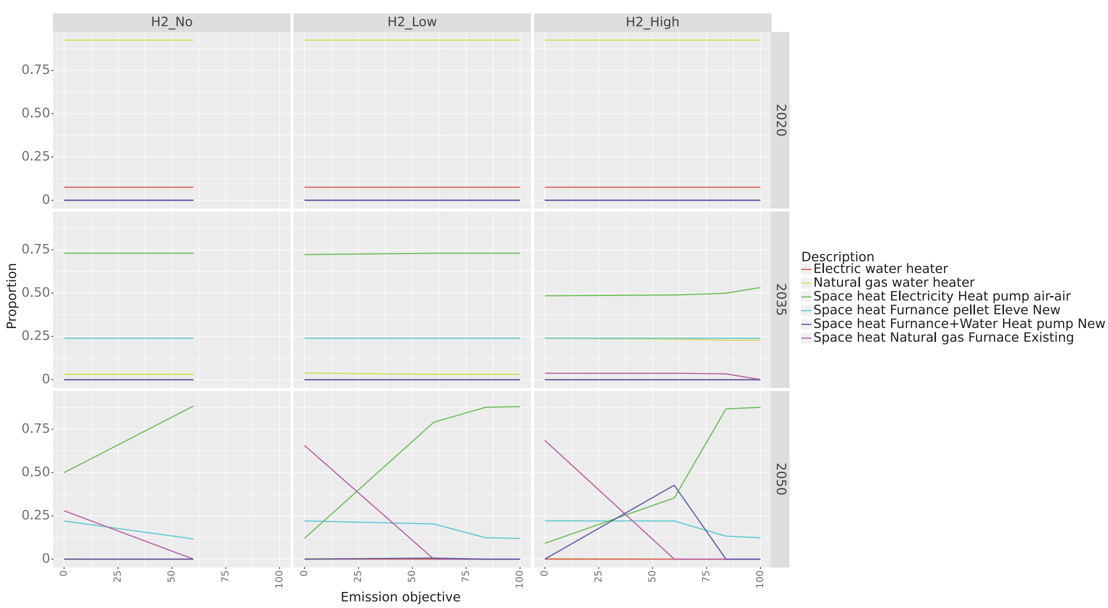
Regarding the marginal costs of hydrogen production, results shows that hydrogen will have marginal production costs at the SIC_Centro node between 3.62 and 4.04 USD/Kg in 2050 (for unconstrained and 100% emission constrained, respectively) in the H_2_High scenario. Note that the SIC_Centro node represents about 70% of the national freight transportation demand. The observed marginal cost of hydrogen after charging stations by 2050 is 5.7 USD/Kg and 6.31 USD/Kg in the H_2_High scenario, and 6.21 USD/Kg and 8 USD/Kg in the H_2_Low scenario—for a 0% and 100% emission constraint, respectively. The increase in the marginal cost of production in 2050 is related to the level of stress on the power generation system. As hydrogen-based technologies are integrated to meet transportation consumption, more electricity demand is needed, which means an increase in the marginal cost of electricity. According to the technologies considered in the model, if hydrogen reaches a marginal cost above 6.16 USD/Kg (0.185 USD/KWh), it is no longer considered a cost-effective fuel and additional measures are needed for its implementation.

4. Conclusion and policy implications

In this paper, we develop the bottom-up multi-sectoral energy planning model ETEM-Chile, and use it to assess the role of hydrogen under different emission and techno-economic hydrogen scenarios through 2050. Our results suggest that for a country with a high renewable potential – like Chile – and under our model calibration, hydrogen



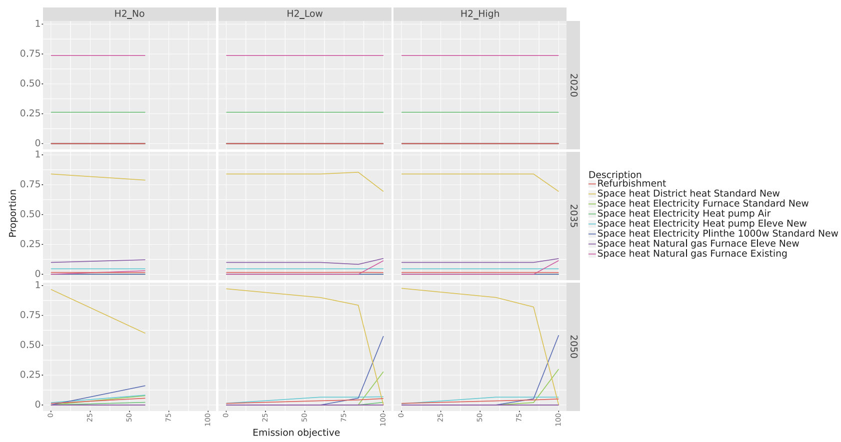
(a) Heating



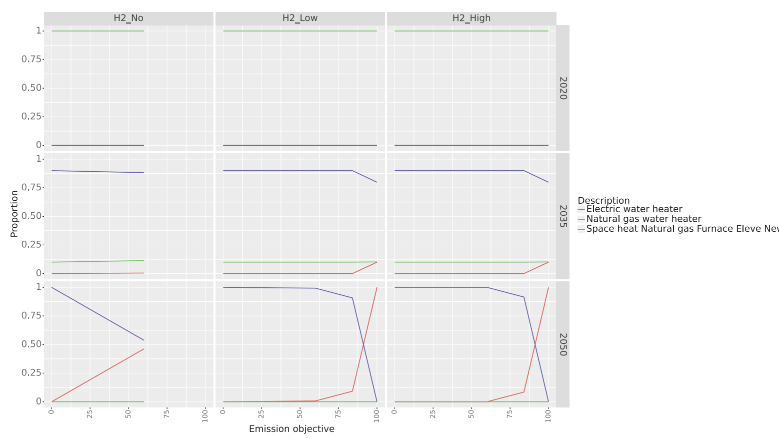
(b) Sanitary hot water

Fig. 13. Residential sector. Proportion of each demand been satisfied by technology at different emission objectives at the end of the time horizon, scenario comparison.

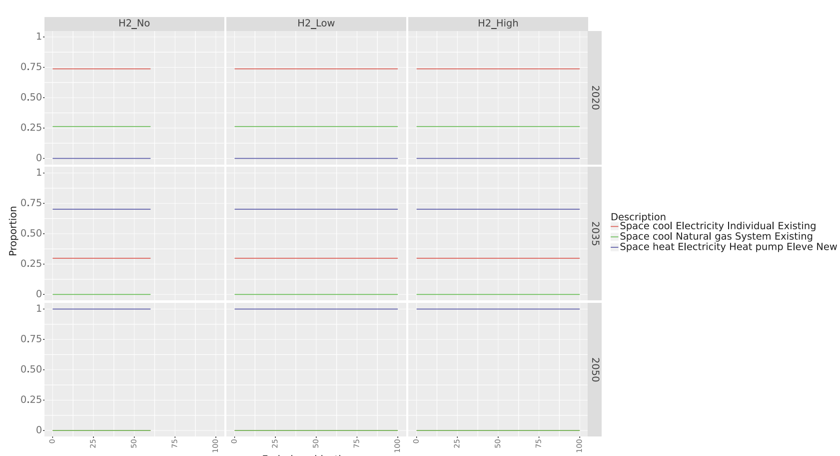
is a cost-effective and low-carbon route for transportation and electricity sectors, for all the modeled future hydrogen techno-economic scenarios. In scenarios without carbon emission reduction targets, the introduction of hydrogen contributes to an additional 50% reduction in emissions (compared to the scenario without hydrogen), with an economic gain of about 1.4 to 3%. Moreover, hydrogen appears to be the only viable solution to effectively decarbonize part of the transport sector, particularly long-haul freight transport and inter-provincial buses. For more ambitious carbon emission targets, hydrogen is also used by the electrical system as a seasonal storage option to complement hydraulic dams. Specifically, in order to reach ambitious carbon emissions reduction targets, Chile should (i) start immediately to develop hydrogen production through electrolyzers all along the country, (ii) keep investing in wind and solar generation capacities,



(a) Heating



(b) Sanitary hot water



(c) Cooling

Fig. 14. Commercial sector. Proportion of each demand been satisfied by technology at different emission objectives at the end of the time horizon, scenario comparison.

Table 4
Economic parameters transport technologies, information gathered mainly from U.S. Department of Energy (2018), Transport & Environment (2020), National Renewable Energy Laboratory (2022).

Sector	Detail	Investment (Thousand USD/Vehicle)							Var. Cost (USD/MKm)
		2020	2025	2030	2035	2040	2045	2050	
Private Transport	Gasoline Car	17.0	17.0	17.0	17.0	17.0	17.0	17.0	60.2
	Diesel Car	19.5	19.5	19.5	19.5	19.5	19.5	19.5	72.5
	GLP Car	20.9	20.9	20.9	20.9	20.9	20.9	20.9	72.5
	Non-plugin Hybrid Car	28.5	27.6	26.7	25.8	24.8	23.9	23.0	50.9
	Plugin Hybrid Car	38.3	35.7	33.2	30.6	28.1	25.5	23.0	50.9
	Electric Car 55 KWh	45.0	42.2	39.3	36.5	33.7	30.8	28.0	46.4
	Fuel-Cell Car	49.5	27.5	23.1	23.1	23.1	23.1	23.1	46.4
Public Transport	Electric Bus 250KWh	390.0	383.1	376.2	369.3	362.3	355.4	348.5	101.3
	Diesel Bus	240.0	244.1	248.2	252.2	256.3	260.4	264.5	337.5
	Gasoline Bus	204.0	215.0	226.0	237.0	248.0	259.0	270.0	286.9
	Subway Wagon	1530.0	1530.0	1530.0	1530.0	1530.0	1530.0	1530.0	127.8
	Fuel-Cell Bus	670.0	510.0	350.0	325.0	325.0	325.0	325.0	286.9
Interregional Transport	Diesel Bus	220.0	223.7	227.5	231.2	235.0	238.7	242.4	96.0
	Fuel-Cell Bus	650.0	490.0	330.0	305.0	305.0	305.0	305.0	108.6
Freight Transport	Fuel-Cell Truck	180.8	155.4	130.0	130.0	130.0	130.0	130.0	154.8
	Electric Truck	244.1	191.0	137.9	137.9	137.9	137.9	137.9	118.7
	Diesel Truck	130.0	132.2	134.4	136.6	138.8	141.1	143.3	96.0

ensuring a low cost hydrogen production, and reinforce the power transmission grid to allow for nodal hydrogen production; (iii) foster the use of electric mobility for cars and local buses, and of hydrogen for long-haul trucks and inter-provincial buses (This includes building charging/refueling infrastructure); and (iv) develop seasonal hydrogen storage and hydrogen fuel cells to be exploited for electricity supply, especially for the most stringent emission reduction objectives.

The numerical results show also, as expected, the synergy that exists between variable renewable generation and hydrogen production. This synergy is directly reflected in the average marginal costs of electricity and hydrogen production, which follow similar trajectories. However, hydrogen storage makes it possible to some extent to decouple these costs. It is also observed that when the carbon constraint is stronger, the electrification of the system is more important, leading to an increase in the marginal costs of electricity and thus hydrogen. This could be a problem for the competitiveness of hydrogen in the long run if the electrification of other sectors and energy services is considered, or if Chile decides to export hydrogen. Indeed we can find that hydrogen may not be a cost effective solution when the marginal cost exceeds 6.16 USD/kg.

The limitations of this study drive several directions for future work. First, because of the long-term horizon of ETEM-Chile, there are many sources of uncertainty that might affect the results and conclusions. It is interesting to explicitly consider uncertainty in our analysis. Demands, fuel and technology prices, technology efficiency and nodal hydrogen potentials are among these uncertain parameters. For example, for both electric vehicle chargers and hydrogen refueling stations, fixed and investment costs are considered constant, which is not realistic. Second, given the lack of information on the installation potentials of nodal hydrogen plants, the model could propose capacities that exceed the actual potentials. Therefore, it is necessary to do research in this direction in order to have more reliable data. Thirdly, Magallanes region – Chile's southern-most region – has not been considered within the study, as it is not connected to the national electricity system. However, due to its average inter-annual wind power plant factors of 50%, it would arguably be able to produce more than 10 million tons of H_2 per year (Ministry of Energy, 2021a). Future work could consider importing H_2 as a commodity from Magallanes. Finally, the model could include the possibility to transmit hydrogen between nodes as an alternative of producing locally, and thus analyze the trade-offs with power grid reinforcement.

Table 5
Technical parameters per technology considered per transport sub-sector, based on SECTRA (2017) and Ministry of transportation and Chile (2018).

Sub-sector	Description	Conversion units	Conversion factor 2050	Annual Kilometers
Private transport	Gasoline car	MWh → MMPKm MWh → KgPM2.5 MWh → TonCO2	0.00272 0.00425 0.279	21500
	Diesel Car	MWh → MMPKm MWh → KgPM2.5 MWh → TonCO2	0.0032 0.003 0.28	21500
	GLP Car	MWh → MMPKm MWh → KgPM2.5 MWh → TonCO2	0.00296 0.003 0.2	21500
	Non-plugin Hybrid Car	MWh → MMPKm MWh → KgPM2.5 MWh → TonCO2	0.004 0.00425 0.279	21500
	Plugin Hybrid Car 10 KWh	MWh → MMPKm MWh → KgPM2.5 MWh → TonCO2	0.00696 0.0021 0.279	21500
	Electric Car 55 KWh	MWh → MMPKm	0.0092	21500
	Fuel-Cell Vehicle	MWh → MMPKm	0.0064	21500
Public Transport	Electric Bus 250 KWh	MWh → MMPKm	0.01	66700
	Diesel Bus	MWh → MMPKm MWh → KgPM2.5 MWh → TonCO2	0.0022 0.0021 0.28	66700
	Gasoline Bus	MWh → MMPKm MWh → KgPM2.5 MWh → TonCO2	0.00196 0.001312 0.279	66700
	Subway Wagon	MWh → MMPKm	0.011	117000
	Fuel-Cell Bus	MWh → MMPKm	0.00905	66700
Interregional Transport	Diesel Bus	MWh → MMPKm MWh → KgPM2.5 MWh → TonCO2	0.0017 0.0079 0.28	240000
	Fuel-Cell Bus	MWh → MMPKm	0.0343	240000
Freight Transport	Fuel-Cell Truck	MWh → MMTonKm	0.017	118000
	Electric Truck	MWh → MMTonKm	0.0247	118000
	Diesel Truck	MWh → MMTonKm MWh → KgPM2.5 MWh → TonCO2	0.0086 0.0079 0.28	118000

CRediT authorship contribution statement

Francisco Ferrada: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Frederic Babonneau:** Conceptualization, Methodology, Project administration, Funding acquisition. **Tito Homem-de-Mello:** Conceptualization, Project administration, Funding acquisition, Supervision, Writing – review & editing. **Francisca Jalil-Vega:** Conceptualization, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Parameters of the transport technologies considered.

See Tables 4 and 5.

Appendix B. Mix share of technologies

See Figs. 15–18.

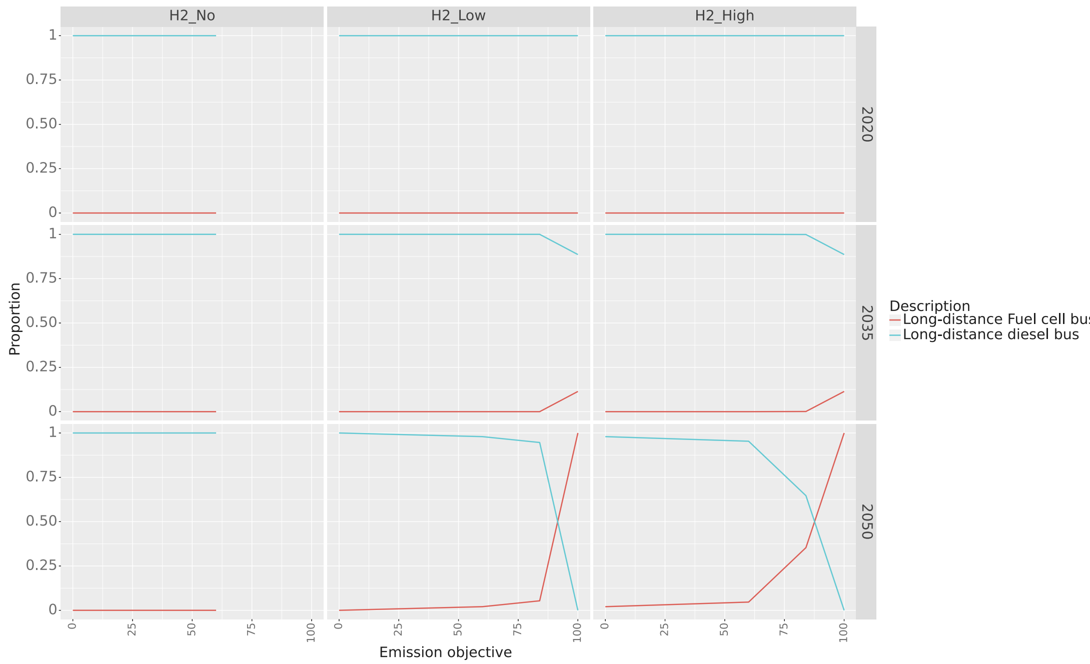


Fig. 15. Interprovincial transport sector. Proportion of each demand been satisfied by technology at different emission objectives at the end of the time horizon, scenario comparison.

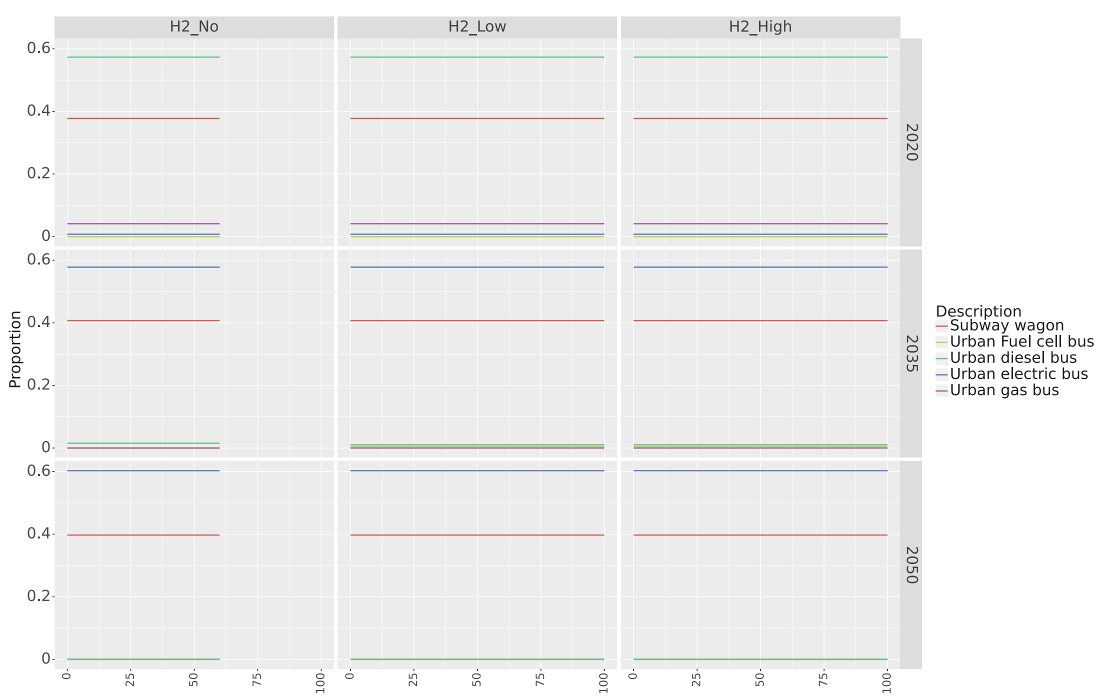


Fig. 16. Public transport sector. Proportion of each demand been satisfied by technology at different emission objectives at the end of the time horizon, scenario comparison.

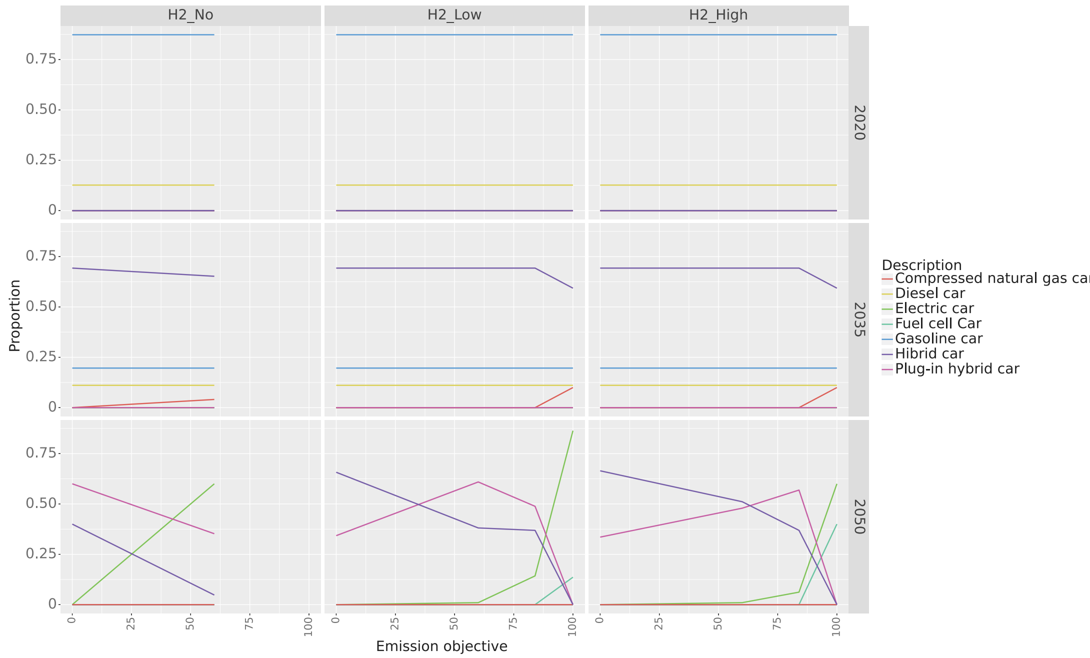


Fig. 17. Private transport sector. Proportion of each demand been satisfied by technology at different emission objectives at the end of the time horizon, scenario comparison.

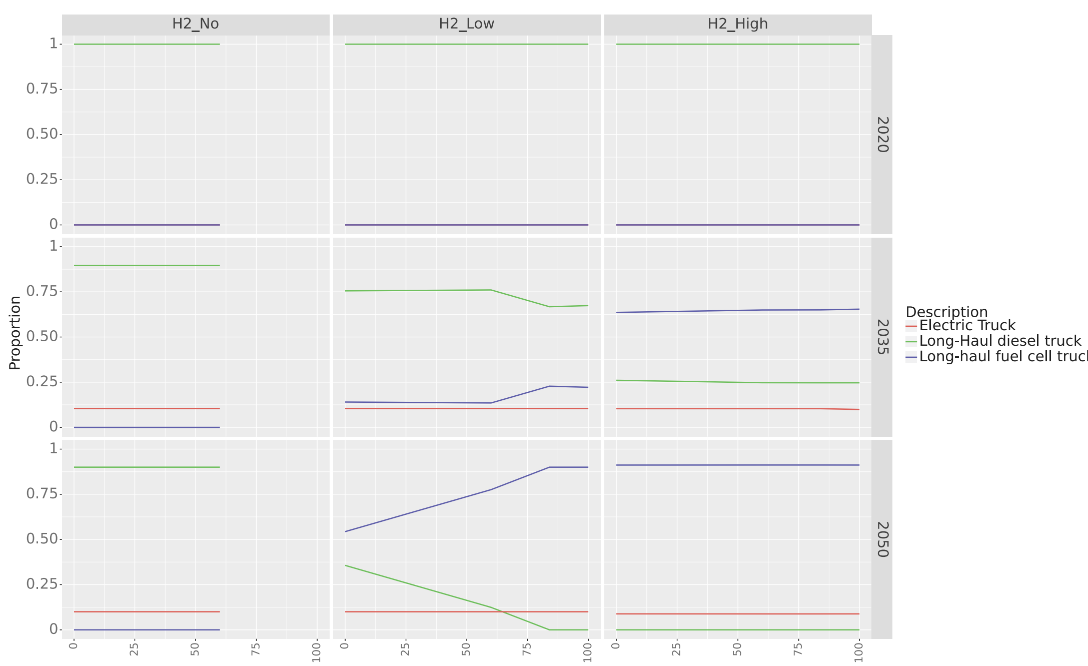
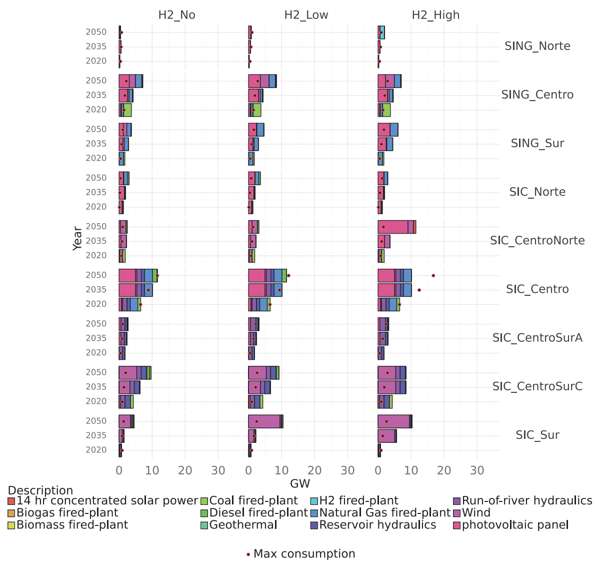
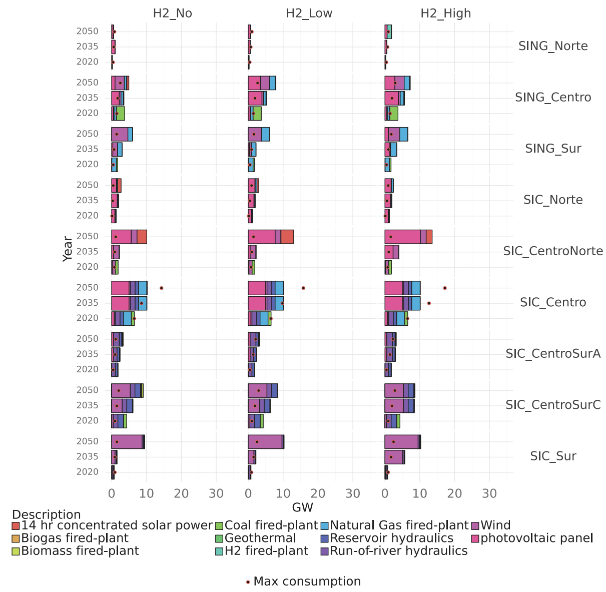


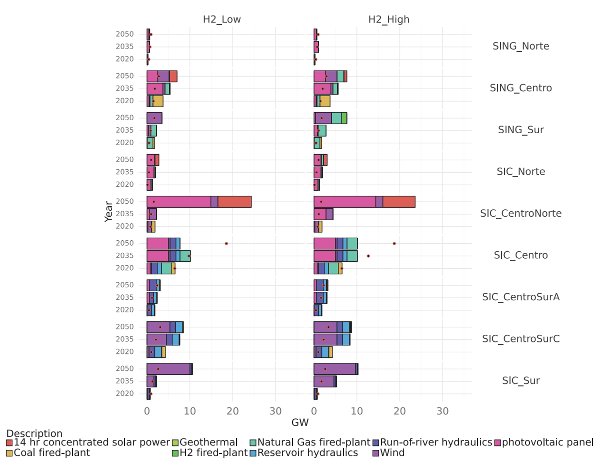
Fig. 18. Freight transport sector. Proportion of each demand been satisfied by technology at different emission objectives at the end of the time horizon, scenario comparison.



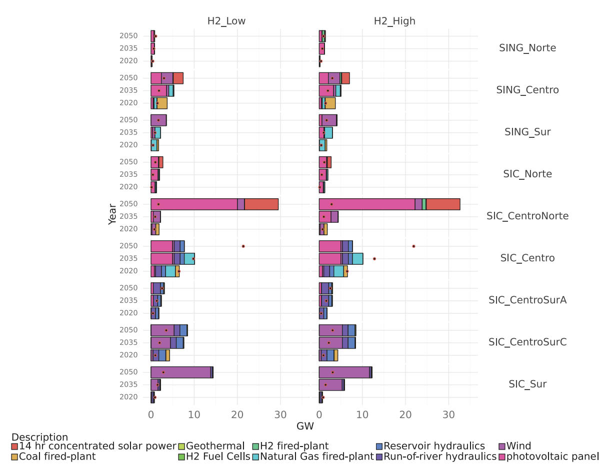
(a) 0% emission reduction target.



(b) 60% emission reduction target.



(c) 84% emission reduction target.



(d) 100% emission reduction target.

Fig. 19. Nodal installed capacities for all hydrogen and emission scenarios. Marked with a dot is the hourly maximum power demand over the timeslices.

Appendix C. Installed capacity results

See Fig. 19.

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