

# Synergies of electrical and sectoral integration: Analysing geographical multi-node scenarios with sector coupling variations for a transition towards a fully renewables-based energy system

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## ABSTRACT

The cost-optimal pathway for moving from the current fossil-fuel based energy system to 100% renewables is still an open question. This work presents the first study that analyses the transition towards a 100% renewable energy system under different spatial resolutions (1-node, 6-nodes electrically isolated and interconnected) and various coupling configurations for the power, heat, transport and desalination sectors. With the LUT Energy System Transition Model for the case of Chile, 12 scenarios were investigated in an hourly resolution and considering more than one hundred energy-related technologies. The results show that: (1) 1-node systems deliver too simplistic results for key metrics; (2) power sector simulations can lead to a strongly distorted resources allocation compared to scenarios that include other sectors; (3) a multi-node model better reflects transmission bottlenecks and local resources, and; (4) the lowest-cost solution is reached when power transmission lines are considered. Thus, it is concluded that a cost-optimal, balanced, and realistic solution to reach a fully defossilised energy system is transitioning towards a multi-node, interconnected, and fully sector-coupled energy system. This can be called, in short, the ‘Power-to-X economy’, which in the case of Chile would more accurately be a ‘Solar-to-X economy’, given the high solar share found in the simulations.

## 1. Introduction

The most feasible, sustainable and low-cost option to achieve the Paris Agreement target is transitioning towards a fully renewable-based energy system across all sectors [1–3]. This would be based on direct and indirect electrification across all energy-demanding sectors [4–6]. Moreover, such a transition has been reported to be an essential

socio-economic contributor to job creation at global and local levels [7, 8]. However, understanding the most cost-optimal pathway for going from the current fossil fuel-based energy system to an entire system based on 100% renewable energy (RE) by 2050 is still an open question [9]. This is seen to be even more challenging in developing countries [10].

Although the design of 100% RE systems has been studied at

**Abbreviations:** (A-CAES), Adiabatic compressed air energy storage; (BEV), Battery electric vehicle; (CO<sub>2</sub>), Carbon dioxide; (CDR), carbon dioxide removal; (DACCS), direct air captured carbon storage; (DH), District heating; (FT), Fischer-Tropsch; (GW), Gigawatt; (GHG), Greenhouse gas; (LCOE), Levelised cost of electricity; (LNG), Liquefied natural gas; (LT), Low temperature; (LUT-ESTM), LUT Energy System Transition Model; (MDV), Medium duty vehicle; (MT), Medium temperature; (MWh), Megawatt-hour; (PV), Photovoltaics; (P), Power; (PH), Power and heat; (PHT), Power, heat and transport; (PHTD), Power, heat, transport and desalination; (PTH), Power-to-heat; (PtX), Power-to-X; (PHES), Pumped hydro energy storage; (RE), Renewable energy; (SNG), Synthetic natural gas; (TTW), Tank-to-wheel; (TW), Terawatt; (TWh), Terawatt-hour; (TES), Thermal energy storage; (€), Euro.

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different scales (such as global, continental, national, etc.) and in all regions of the world, most of the research articles have focused on the power sector only [11]. It is also found a dominance of studies for Europe in particular and the Global North in general and a substantial research gaps for the Global South [9,12]. The past decade has shown an extension towards cross-sectoral analysis becoming state-of-the-art in the literature [9,11]. This trend of multi-sector planning started in the 2010s [13] and has been gaining ground ever since [9,11]. Reference [14] showed that out of the 30 peer-reviewed articles on 100% RE systems (with a share of solar photovoltaic (PV) in energy supply greater than 50% by 2050), 14 have included all sectors in the analysis.

However, the effect of different spatial resolutions (geographical multi-nodes isolated versus interconnected in electrical terms) with multi-sector scenarios have had less attention in the literature. For instance, Schlachtberger et al. [15] carried out a comparison of 30 nodes isolated and interconnected for the European power sector, and Barbosa et al. [16] and Aghahosseini et al. [17] have made a similar work considering 15 and 21 nodes for the case of Central–South America and the Americas, respectively. Recently, Galván et al. [18] studied for the case of South America, how a varying spatial resolution (from 1 to 16, 30, and 43 nodes interconnected) impact the energy system results throughout the transition period, but only for the power sector as well.

While a few studies [19–21] have analysed the energy transition of a multi-node fully-interconnected and multi-sector coupled system, different sectoral configurations were not considered. Only Brown et al. [22], for the case of Europe, have compared 30 nodes isolated and interconnected considering the power, heat and transport sectors under different sector-coupled variations. In summary, an analysis of the energy transition based on multi-sector coupled configurations under different spatial resolutions (different number of nodes isolated and interconnected), have not been discussed in the same work.

Therefore, with the objective to fill that research gap, and with the overarching motivation to understand the most cost-optimal solution of a transition to reach a 100% RE system, the aim of this work is to:

- Analyse the effect of the spatial resolution on the energy pathway. It will be looked at single-node versus multi-nodes isolated versus multi-nodes interconnected.
- Analyse the effect of different sector coupling configurations on the energy pathway. It will be studied in scenarios: the power sector alone, integrated power-heat sectors, integrated power-heat-transport sectors, and integrated power-heat-transport-desalination sectors.

This study is the first one that analyses various sector coupling configurations and compares single-node versus multi-node isolated and interconnected scenarios. Therefore, this is not only the first study of its kind globally but also the first one applied to the Global South and Chile. In terms of methods, the LUT Energy System Transition Model (LUT-ESTM) is applied in a full hourly resolution from 2015 to 2050 and considering more than one hundred energy-related technologies, on the case of Chile. Furthermore, a modelling experiment varying the spatial and sectoral resolutions is set up to study the questions above.

In Section 2, a brief literature overview on sector coupling research is presented. In Section 3, the energy system modelling tool and the defined scenarios are described, including input data and assumptions. Then, the results are presented and explained in Section 4. In Section 5, the results are compared to the literature and the limitations of the study are discussed; and the conclusions are drawn in Section 6.

## 2. Literature overview on sector coupling research

Sector coupling is a key concept in the research field of 100% RE systems [11,23] and is closely linked to the terms ‘smart energy systems’ [24–26] or ‘multi-energy systems’ [27–30]. The smart energy systems concept has been more studied, in particular, to understand the role of

energy storage [31] and the integration of heat [32] and transport [33] sectors to the smart energy system. In general terms, sector coupling refers to the purposeful planning, connection and interaction of at least two energy-intensive sectors, such as power, heat, cooling, gas, transport, industry, desalination and buildings. The focus is on counteracting challenges of variable RE sources with two technical goals: increasing flexibility between energy supply and energy demand, and the application of storage technologies [34–36]. As a consequence, this has an impact on the cost-optimal solutions of energy scenarios [22], as well as on early CO<sub>2</sub> emissions reductions [37–39].

Research on sector coupling started with the integration of the sectors power and heat, often for cogeneration power plants, to deal with the variable supply of RE sources [34,40]. For strengthening the coupling of these two sectors, different power-to-heat [41,42] and power-to-gas (the use of electric power to produce a gaseous e-fuel, such as hydrogen or methane) [43,44] approaches have been applied, as well as a mix of them [45]. Also, the coupling of the power and transport sectors started to appear in the scientific literature during the last decade [46], firstly, under the smart energy systems concept [33], and then, for evaluating its technical and economic impacts [47–49]. This has been based on direct electrification of transport analysing the interaction between electric vehicles and the grid [50–52], the value of flexibility in electricity consumption [53], and electric vehicles as a virtual power source [54], but also based on power-to-hydrogen and power-to-liquids [55,56]. These three pillars, electricity, heat and transport were the first sectors to adopt a multi-sector perspective, also called cross-sectoral coupling [22,57,58]. Later, the integration of the desalination [59] and industry sectors [19], and the power-to-gas-to-power concept [60] were introduced. In summary, according to Hansen et al. [11], the sector coupling approach has been included in about 40% of the research works on 100% RE systems. However, the literature on business models from a sector coupling approach is still in an incipient stage [61,62].

The multi-sector perspective, where at least three sectors are coupled into one energy system, has been applied at different scales. For instance, research works have been carried out to: continental level, such as those by Brown et al. [22,63], Victoria et al. [38,64,65], Pavičević et al. [66], Connolly et al. [48], and Rodrigues et al. [67], all for the case of Europe; sub-continental level, also for the case of Europe [68,69]; national level, applied to Kazakhstan [19], Chile [21], Germany [58], Brazil [70], Denmark [71], and Belgium [72]; sub-national level, using island communities [73], local alpine regions [74], and an Italian province [75] as study cases; megacity level [76]; city level [77–79], and; urban level [80–84]. However, most of these studies have been applied to Europe, and, the impact of various sector coupling configurations under different spatial resolutions have not been discussed in the same work. Therefore, as mentioned in the introduction, this research work is not only the first study of its kind globally but also the first one applied to the Global South and Chile.

## 3. Methods

With the aim to analyse the impact of various sector coupling configurations under different spatial resolutions and electrical connections in a transition towards a fully renewables-based energy system, 12 scenarios were simulated using the case of Chile. In the following subsections, an overview on the used modelling tool applied for that purpose is provided, the scenario setup is described, and the input data and assumptions are presented.

### 3.1. Model description

The simulated scenarios were performed with LUT-ESTM, which is a linear optimisation tool to obtain cost-optimised scenarios for a whole energy system. It has a full year of hourly temporal resolution, geographical multi-node design, dispatch optimisation methodology, and single objective investment optimisation [85]. The model has been

gradually developed from the power sector [86,87] to the integration of power and heat [88], transport [89] and desalination [90] sectors. In the case of industrial fuels, the model simulates the production of e-fuels (gaseous: hydrogen and methane, and liquids: liquefied hydrogen, liquefied methane, gasoline, diesel, marine and kerosene jet fuels) [91,92] based both on green e-hydrogen [93] and CO<sub>2</sub> from direct air capture units [94], which is part of the power-to-X (PtX) concept [95], but based on biomass as well. A description of how the model is designed in more detail with all sectors integrated and the key equations involved can be found in Bogdanov et al. [1].

The objective function of the model is the minimisation of the total annualised costs of an energy system. The costs of the entire system are calculated as a sum of the annualised capital expenditures including the weighted average cost of capital, operational expenditures (including ramping costs), fuel costs and cost for CO<sub>2</sub> emissions for all available technologies. LUT-ESTM reproduces the entire legacy system for the starting period. Then, the age structure of the power plants and infrastructure is considered and triggers a respective reinvestment. The model is constrained by the hourly-nodal energy balance, participation and/or phase-out of a specific technology and the percentage of RE generation during the transition period, among other technical system parameters. The results of the model are provided in five-year time intervals.

The model includes more than 108 technologies to describe the energy transition across all sectors, which can be classified into six main categories: i) electricity generation (RE, fossil and nuclear technologies); ii) heat generation (RE and fossil technologies); iii) transportation modes (road, rail, marine and aviation); iv) energy storage (electricity, heat and fuels); v) energy sector coupling technologies (mainly based on PtX), and; vi) electricity transmission technologies. More details about the specific technologies by category can be found in Bogdanov et al. [1].

Energy demand is modelled for electricity, heat and fuels. Heat is modelled for three temperature levels, and different types of fuels considered are: hydrogen (gaseous and liquid), methane (gaseous and liquid), and liquid hydrocarbons (comprised of gasoline, diesel, marine and kerosene jet fuels). Those liquid fuels can be produced as e-fuels via the Fischer-Tropsch process, i.e., the chemical process for the production of liquid hydrocarbons from the transformation of syngas, which can be based on green e-hydrogen and CO<sub>2</sub> captured from the air.

In short, the LUT-ESTM has the capability to simulate transition scenarios for an energy system that matches the supply with the demand from all energy consumption activities. The high temporal resolution of the model allows the identification of crucial elements related to flexibility options based both on energy storage and energy sector coupling technologies, under different multi-node configurations. The multi-node approach enables any desired configuration of regions (or zones), power transmission interconnections, and sectoral integration.

### 3.2. Scenarios description and simulated configurations

In this study, it was defined a set of scenarios varying the spatial resolution and a set of scenarios varying the sector coupling, and the associated scenarios resulting from a combination of both sets. Concretely, three scenarios were defined with varying spatial resolutions: 1-node, 6-nodes electrically isolated (6-nodes-isolated) and 6-nodes electrically interconnected (6-nodes-interconnected). The following four scenarios were defined with sector coupling variations: power (P); power and heat (PH); power, heat and transport (PHT); and power, heat, transport and desalination (PHTD). The modelling tool was run for these 12 transition scenarios from 2015 to 2050, applied to Chile.

Table 1 shows the configuration for each simulated scenario. In the case of 1-node, the final energy demand of Chile was considered as one compact geographical consumption node. This means that the energy demand from any sector involved was allocated to the capital of the country. Here, the energy supply based on RE sources is taken from any

**Table 1**

Simulated scenarios configuration. Abbreviations: power, P, heat, H, transport, T, desalination, D.

Spatial resolution	Sectoral configuration	Scenario
1-node	P	1
	PH	2
	PHT	3
	PHTD	4
6-nodes-isolated	P	5
	PH	6
	PHT	7
	PHTD	8
6-nodes-interconnected	P	9
	PH	10
	PHT	11
	PHTD	12

part of the Chilean territory, assuming the existence of sufficient power transmission lines. In the case of 6-nodes scenarios, the country was subdivided into six zones with one geographical consumption point per node. The locations of the specific geographical points per node are the same than those used in a previous study [21], which can be found in the dataset [96]. For the 6-nodes-isolated scenarios, the final energy demand of each node is self-supplied by the RE potential within the specific zone. In the case of 6-nodes-interconnected scenarios, the nodes can exchange electricity through interzonal grid transmission, meaning that the energy demand of a node can be supplied from RE technologies allocated in another zone.

### 3.3. Input data and technical and financial assumptions

All input data are based on a previous work applied to Chile [21]. Historical power generation capacities, projection of the final energy demand by sector, and RE potential can be found in the dataset [96].

Technical and financial assumptions for the energy-related technologies used in the modelling tool, obtained from different sources, is presented in the Supplementary Materials (see section S1). These assumptions are based on updated learning curves of all the key technologies. To calculate the capital recovery factor for each technology, the weighted average cost of capital was set at 7%. The currency value is set for the year 2020.

## 4. Results

This section explains the results of the 12 investigated scenarios to reach 100% RE systems in Chile. Recall that these scenarios result from combining the three scenarios of spatial resolutions (1-node, 6-nodes-isolated and 6-nodes-interconnected) and the four scenarios of sector coupling configurations (P, PH, PHT, and PHTD). The results are presented at the national level to analyse the effect and benefits of the electrical and sectoral integration, under different geographical multi-nodes scenarios for the whole energy system of the country. This is also a further step of our previous study applied to Chile in which it was found that a transition towards a fully defossilised energy system across all sectors by 2050 is a more cost-optimal solution than the government's official scenario [21]. Moreover, in this 100% RE pathway, carbon neutrality can be reached by 2030 [21], and, it is an option that would have more socio-economic benefits than the government's official scenario [97].

Fig. 1 depicts the primary energy demand for the 12 scenarios during the transition period by energy form: fossil fuels (extracted from oil, coal or natural gas), heat (captured from solar thermal collector or geothermal reservoirs), bioenergy, and electricity (mainly solar PV, wind power, and hydropower). As can be seen in Fig. 1, the major trend in all scenarios is that fossil fuels, used across all sectors, are mainly and gradually replaced by primary electricity. While primary heat, used for electricity and heat generation purposes, only appears in a significant

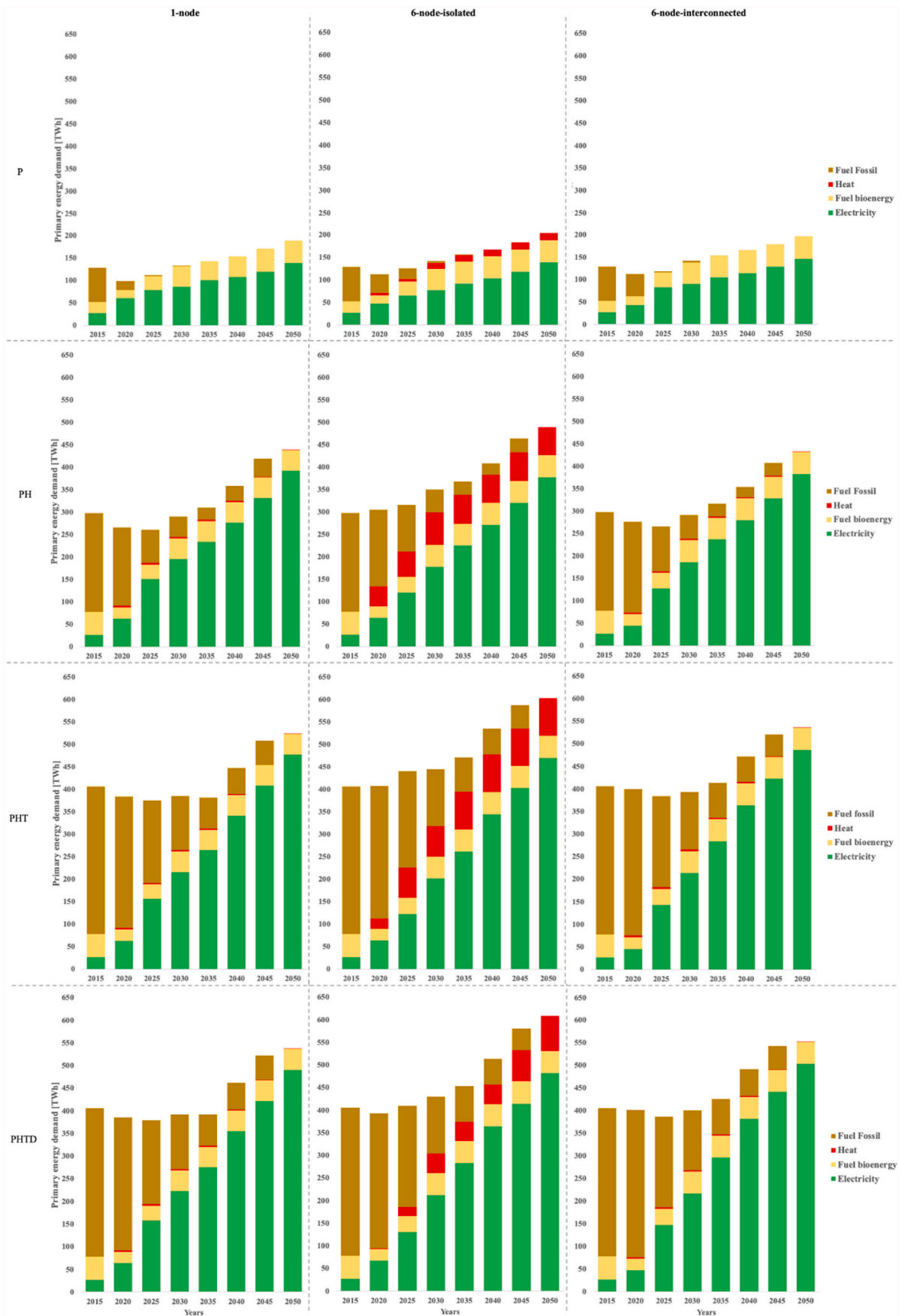


Fig. 1. Primary energy demand by energy form for each scenario from 2015 to 2050.

manner in the 6-nodes-isolated scenarios. This suggests that primary heat becomes a cost-optimal alternative when transmission lines are not present for electricity exchanges between nodes. On the other hand, the bioenergy share, also used for electricity and heat generation, does not vary significantly from 2015 to 2050 in all scenarios.

Focusing on the scenarios with sectoral integration (PH, PHT and PHTD), the increment of primary electricity throughout the transition would be a consequence of low-cost renewable electricity generation for a direct and indirect electrification across all sectors. Direct electrification of coupled sectors would start to appear in a significant manner from 2030 onwards, which mainly implies electricity for electric heating and electric vehicles on roads. Indirect electrification would start to appear in a significant manner from 2030 onwards, firstly for heat pumps and thermal energy storage (TES) that will be mainly used in space heating, and then, from 2035 onwards, for the e-fuels production via PtX processes based on e-hydrogen and CO<sub>2</sub> from direct air capture

units. The e-fuels will be used in the segments of the heat sector (such as for industrial process heat) and modes of the transport sector (such as marine and aviation) that are hard to directly electrify. This would avoid a massive technological change while fossil fuels are replaced.

In order to understand the effects and benefits of sector coupling configurations under different spatial resolution, deployed technologies, energy costs, and CO<sub>2</sub> emissions are compared for the scenarios in section 4.1, 4.2. and 4.3, respectively, and, in section 4.4, synergies of electrical and sectoral integration are described.

#### 4.1. Technological results

All technological results obtained for each scenario from 2015 to 2050 are available in five-years steps in the Supplementary Materials (SM), see section S2. Now, electricity, energy storage, and e-fuel results are presented. The discussion of these results will be focused on the end

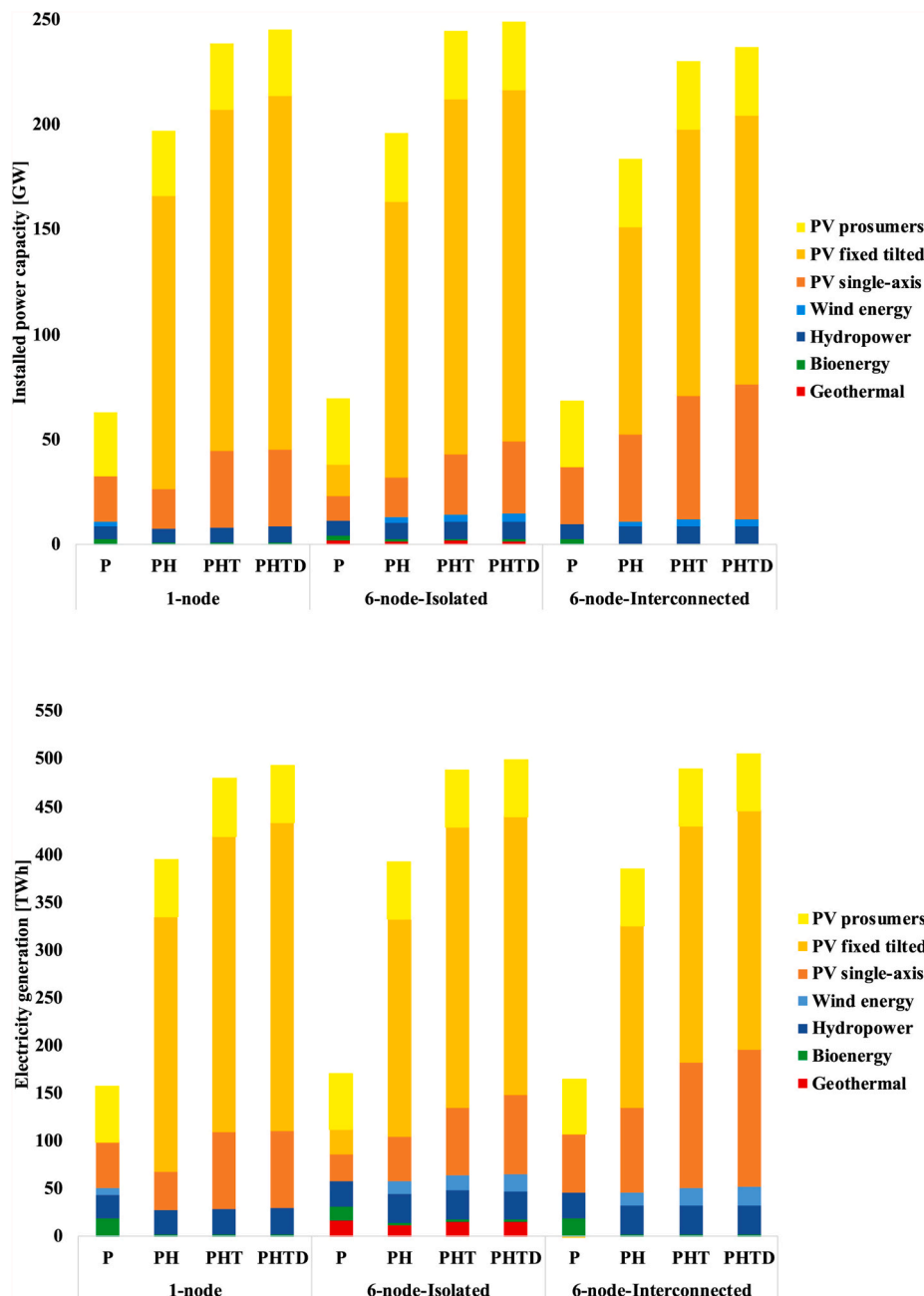


Fig. 2. Installed power capacity by renewable technology (top) and electricity generation by technology (bottom) for each scenario in 2050.

of the transition period because: 1) it simplifies the analysis across the many scenarios, in which the major trends are in line with a previous 100% RE study applied to Chile [21], in particular for the fully-coupled sectors scenarios; 2) renewable electricity will become the main primary energy source from 2030 onwards, and; 3) electrification (direct and indirect), energy storage technologies and e-fuels will be the enablers during the transition to provide flexibility and allow sectoral integration in the energy systems. All of this is in order to analyse the effects of the electrical and sectoral integration under single-node and multi-nodes scenarios in a transition towards a fully renewables-based energy system.

4.1.1. Electricity

Fig. 2 shows the installed power capacity (top) and electricity generation (bottom) by RE technologies at the end of the transition period for the 12 scenarios. Solar PV is found to be the dominant technology in all scenarios by 2050; where, its installed capacity and electricity generation is within a range (depending on the scenario) of 83–97% and 65–94% of the total capacity and generation. The PV installed capacity varies within a similar range across spatial resolution in relation to the sector coupling configuration: 52–59 GW between P-1-node, P-6-nodes-isolated and P-nodes-interconnected; 173–189 GW between PH-1-node, PH-6-nodes-isolated and PH-nodes-interconnected; 218–231 GW

between PHT-1-node, PHT-6-nodes-isolated and PHT-6-nodes-interconnected, and; 225–236 GW between PHTD-1-node, PHTD-6-nodes-isolated and PHTD-6-nodes-interconnected. However, the energy diversity (a mix of solar PV, wind power, hydropower, geothermal, and bioenergy) is higher in the coupled 6-nodes scenarios (PH, PHT and PHTD), especially in terms of wind power contribution, which is almost zero in the coupled 1-node scenarios. This aspect is more noticeable, in terms of more diversity, when regions are restricted to supply their own demand (6-nodes-isolated).

In all sectoral configurations, the 6-nodes-isolated shows the highest installed capacity compared to the other two spatial resolutions. And, the 6-nodes-interconnected scenarios show lower installed power capacities for the PH, PHT and PHTD sector coupling configurations, compared to 1-node and 6-nodes-isolated spatial resolutions. This (6-nodes-interconnected) reflects the capability for transmitting electricity from one node to another, mainly when the final energy demand increases; implying that less installed capacity is needed at national level. This happens due to more deployment of solar PV single-axis tracking capacity (that has higher full-load hours than fixed-tilted power plants), which is an outcome of the optimisation process within an interconnected energy system with high flexibility. In the same line, the 6-nodes-interconnected spatial resolution reveals less curtailment than the 6-nodes-isolated in all sector coupling configuration: 7.7% less in P,

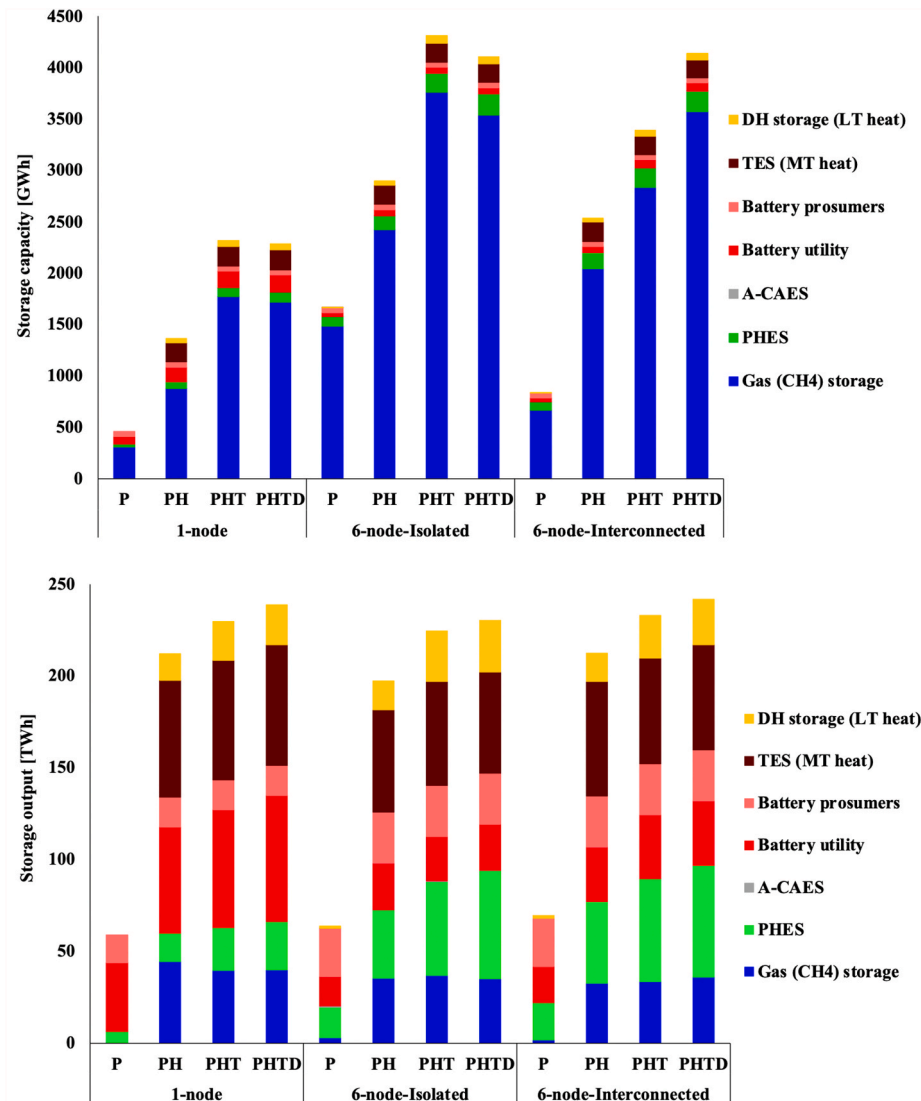


Fig. 3. Storage capacity (top) and storage output (bottom) by technology for each scenario in 2050.

3.1% less in PH, 0.9% less in PHT, and 1.1% in PHTD (more details in the SM, Table S2.25). Also note that the electricity generation in this spatial resolution is higher, e.g. 7–13 TWh higher for the PHTD, which can be attributed to the transmission losses. All of that is a synergetic effect based on flexibility provided by electrification, interconnection and sectoral integration, but also provided by energy storage and e-fuels.

4.1.2. Energy storage

Fig. 3 shows the total storage capacity (top) and storage output (bottom) for both electrical and thermal storage technologies at the end of the transition period for the 12 scenarios. The storage capacity ranges related to the sector coupling configuration are: 457–1662 GWh between P-1-node, P-6-nodes-isolated and P-nodes-interconnected; 1364–2900 GWh between PH-1-node, PH-6-nodes-isolated and PH-nodes-interconnected; 2321–4311 between PHT-1-node, PHT-6-nodes-isolated and PHT-nodes-interconnected, and; 2288–4138 GWh between PHTD-1-node, PHTD-6-nodes-isolated and PHTD-6-nodes-interconnected. Here, the 1-node shows around 50% lower storage

capacity requirements than the other two spatial resolutions. This is because most of the primary energy, which is based on RE sources taken from any part of the country, is directly used on a single node allocated in the centre of the country. However, the other two spatial resolutions, in which each node has a different level of RE sources, need to store energy for supplying the demand in different geographical points of the country because of transmission limitations. In any case, gas storage will become the most installed capacity in all scenarios; accounting for a share range of 64–89% of the total storage capacity between the 12 scenarios. This is mainly due to the power-to-gas process for the production of e-fuel (refer to the following section), which increases with the final energy demand provoked by the sectoral integration.

As can be seen in Fig. 3 (bottom), the range of storage output by spatial resolution is similar for each sector coupling configuration. The shares of gas storage output for the PH, PHT and PHTD configurations in all spatial resolutions is within a range of 14–21% of the total storage output. The electricity storage output is within a share range of 42–51%. This indicates that all storage technologies are needed to provide

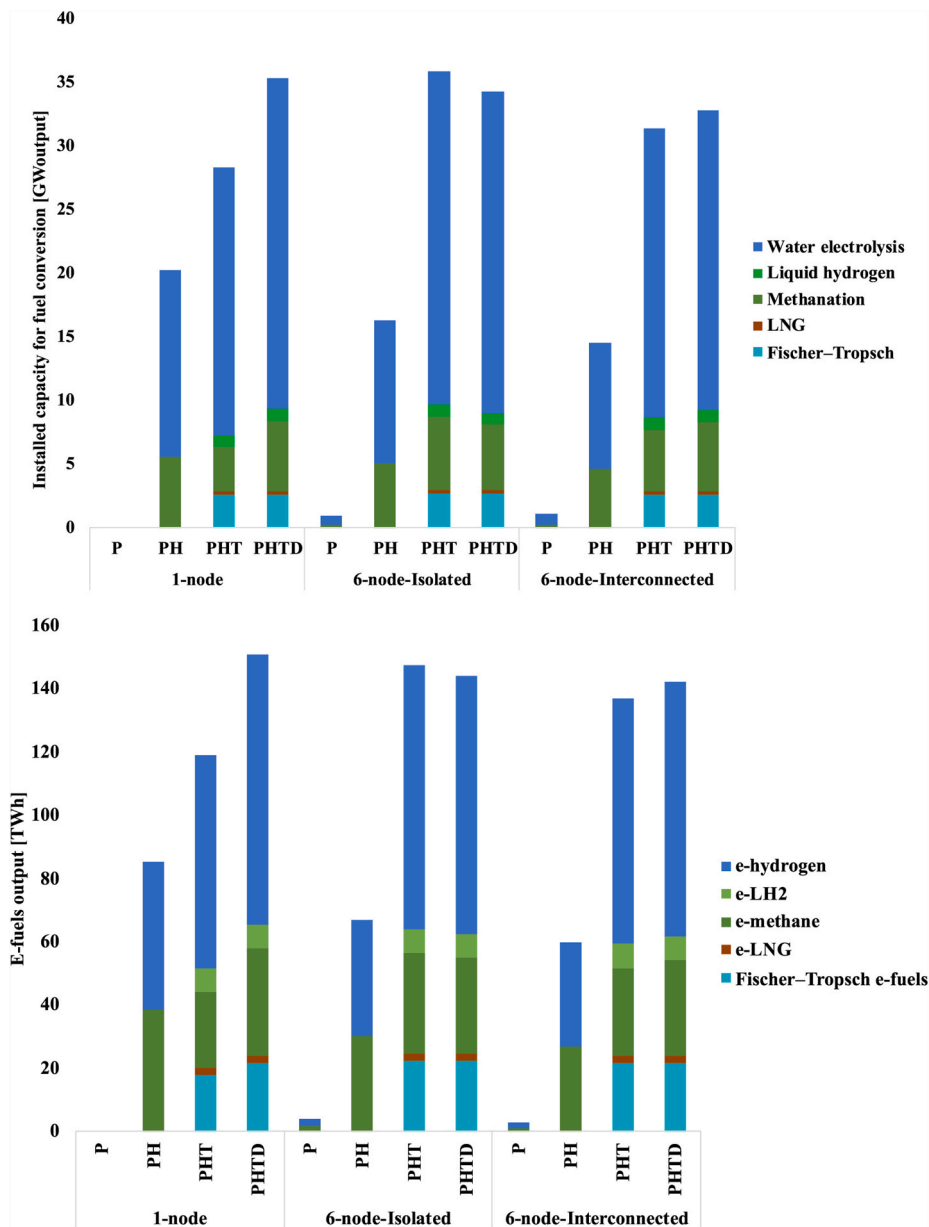


Fig. 4. Installed capacity for fuel production (top) and e-fuel output (bottom) by technology for each scenario in 2050. The x-axis labels represent the sectoral configurations and scenarios.

flexibility in the system to cover the final energy demand. This also indicates that electricity storage will play a significant role in a fully defossilised energy system under any spatial resolution and sector coupling configuration.

4.1.3. e-Fuels

Fig. 4 shows the total installed capacity for fuel production (top) and e-fuel output (bottom) by technology at the end of the transition period for the 12 scenarios. As can be seen in this figure, water electrolysis will become the main technology for e-fuel production with a share range of 68–79% of the installed capacity and 55–57% of the e-fuel output, among the scenarios. This is because green e-hydrogen is not only a fuel that can be directly used for energy purposes, but also a feedstock for the production of the other e-fuels. For the production of these other e-fuels, CO<sub>2</sub> is also needed as a feedstock. The amount of CO<sub>2</sub> direct capture from air required can be found in Tables S2.74 and S2.75, in the Supplementary Materials.

The range of the total installed capacity for fuel production and e-fuels output related to the sector coupling configuration are: 0–35 GW and 0–151 TWh for 1-node; 1–36 GW and 4–147 TWh for 6-nodes-isolated, and; 1–33 GW and 3–142 TWh for the 6-nodes-interconnected cases. In all spatial resolutions, the liquid hydrogen, electricity-based liquefied natural gas (e-LNG) and Fischer-Tropsch technologies are only present in the PHT and PHTD sector coupling configuration, since these types of e-fuels will be mainly produced for supplying the transport sector demand. Actually, in the case of the two 6-nodes spatial resolution, the e-fuels production in the PHT and the PHTD configuration is about double compared to the PH sector coupling configuration. The 6-nodes-interconnected spatial resolution shows the lowest values of e-fuels production for the PH, PHT and PHTD sector coupling configurations. This is a synergetic effect based on flexibility provided by electrification, interconnection, energy storage, e-fuels and sectoral integration, resulting from the cost optimisation for the whole energy system.

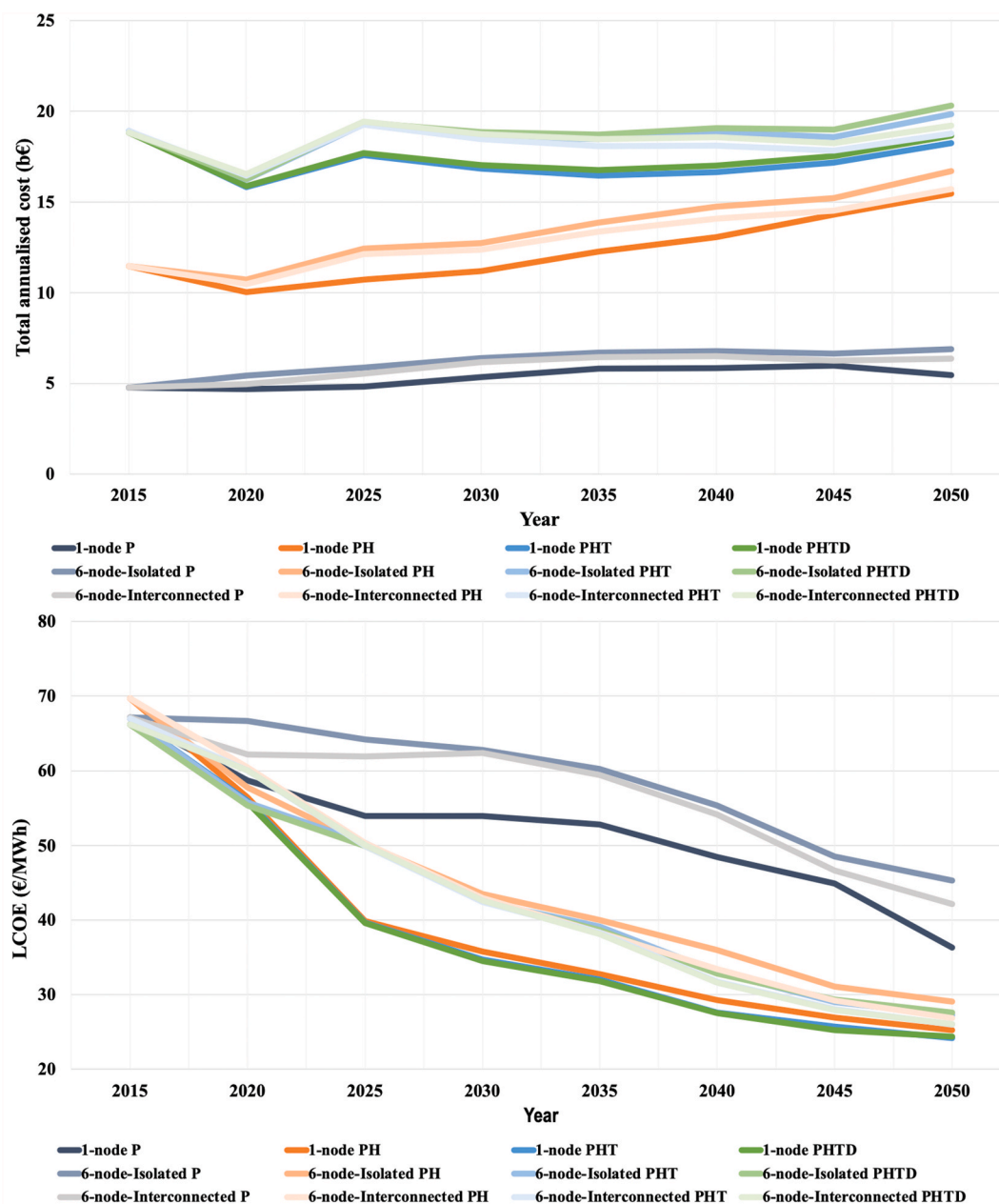


Fig. 5. Annual system costs by sector (top) and LCOE (bottom) for each scenario through the transition period.

### 4.2. Energy costs

Fig. 5 shows the total annualised system costs (top) and levelised cost of electricity (LCOE) (bottom) during the transition period for the 12 scenarios. The upper panel shows that the 1-node scenario has the lowest total annualised cost for all sectoral configurations, as expected because it does not capture the transmission system. In other words, transmission is unlimited and free. Also as expected, the total costs in the 6-nodes-interconnected are lower than in the 6-nodes-isolated spatial resolution in all sectoral configurations, reflecting the value of exchanging energy across zones. These cost differences can also be interpreted as the system over-cost if each region was to strive for energy autonomy.

Focusing on the sector coupling configurations, the PH reveals the highest difference in the total annualised system costs (25.8–31.4% more in 2050 than in 2015) for the three spatial resolutions compared to the other sectoral variations. In turn, the PHT and the PHTD in the 1-node and the PHT in the 6-nodes-interconnected, are the only three scenarios where the total annualised system costs by 2050 are lower than in 2015. And, in the rest of PHT and PHTD scenarios, the total annualised system costs in 2050 is just 2.1–7.3% higher than in 2015, which is quite less compared to the P scenarios that shows 12.8–30.9% higher total annualised system costs in 2050 than in 2015. All of this indicates that major sector coupling configurations (such as PHT and PHTD) have positive effects in the optimisation of the total energy system costs. This can be attributed to flexibility provoked by the sector coupling, resulting that the overall system can realise benefits.

In terms of LCOE, as can be seen in Fig. 5 (bottom), this econometric decreases from 2015 to 2050 in the 12 scenarios, within a range of 37–64%. Here, the 1-node spatial resolution shows the lowest values of LCOE for all sectoral configurations at the end of the transition period. In the 6-nodes-interconnected, LCOE is lower than in the 6-nodes-isolated in the four sectoral variations by 2050. Notwithstanding, the results by sectoral configuration demonstrate that P scenarios show the highest LCOE in the three spatial resolutions (36–45 €/MWh), followed by PH (25–29 €/MWh), PHTD (24–28 €/MWh), and PHT (24–27 €/MWh). A stronger sector coupling configuration has a positive effect on this econometric, because of the flexibility from integrating the power sector with the heat sector and in particular the transport sector. In other words, only planning the transition of the power sector overestimates the costs.

### 4.3. Greenhouse gas emissions

Fig. 6 shows the GHG emissions during the transition period for the 12 scenarios. Although each sectoral configuration shows net-zero GHG emission for the same year, independently of the spatial resolution, the 1-node shows a quicker GHG emissions reduction. In other words, in more realistic and complex energy system (such as multi-node), it is harder and takes longer to decrease the cumulative GHG emissions compared to a simplified energy system (such as single-node). Furthermore, the scenarios with more sector coupling take longer to reach net-zero GHG emissions. Recall that the PHTD scenarios represent the entire energy system, and that this entire energy system also reaches full defossilisation.

### 4.4. Synergies of electrical and sectoral integration

As highlighted in the previous subsections, the 6-nodes-interconnected scenarios lead to lower costs than the 6-nodes-isolated scenarios, because they capture the value and costs of the transmission system, as well as the sectoral integration and the local resources. In particular, this is with the best solar resources in the north, best wind resources in the south and the largest demand centre right in between. The installed power capacities by zone for a fully interconnected and fully sector-coupled energy system, fully defossilised by 2050, is presented in Fig. 7.

The model finds that the good solar resources around the demand hubs are quite competitive compared to long-distance power transmission. Cost-optimal designs of the 6-nodes-interconnected scenario rely on transmission capacity investment. Specifically, the power transmission capacity would almost double from about 5800 GW-km in 2020 to 10,600 GW-km by 2050. The maximum new installed power transmission capacity (around 1400 GW-km) would take place by 2035 (more details in the SM, Table S2.25). Whether these corridors (mainly from the central-north to the centre of the country) are built in time or not will impact the final costs but not the technical feasibility. Furthermore, the P, PH and PHT sectoral configurations do not model the reduction of the total GHG emissions of the entire energy system to zero. The 6-nodes-interconnected and PHTD sector coupling configuration would be the scenario with the reduction of net-GHG emissions to zero for the entire energy system. The 6-nodes-interconnected and PHT sector coupling configuration is the scenario with more synergies

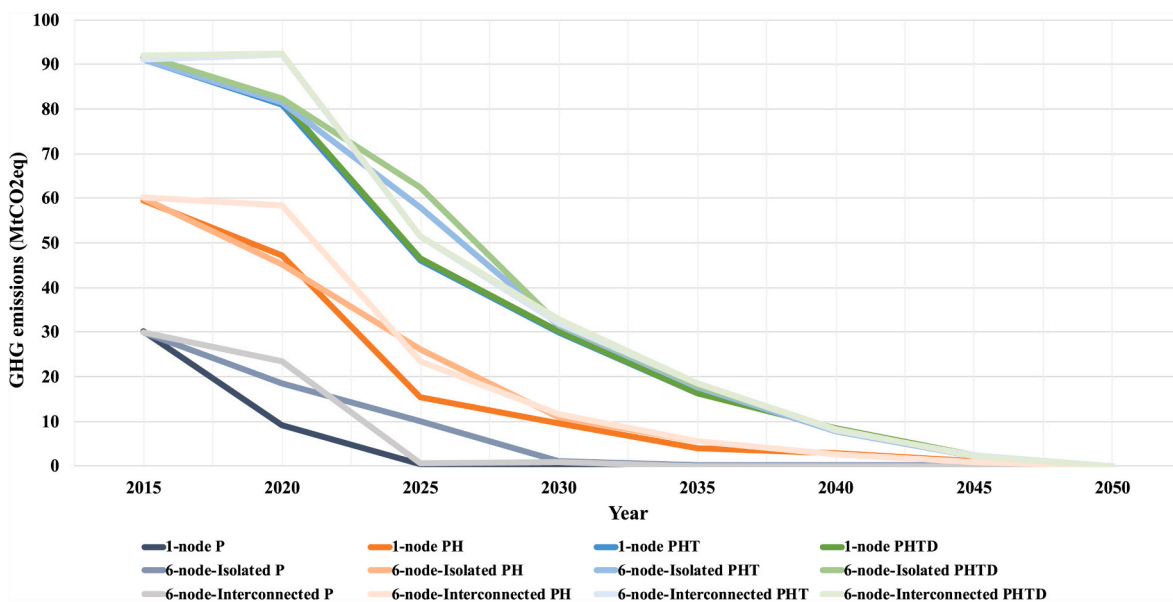


Fig. 6. GHG emissions for each scenario through the transition period.

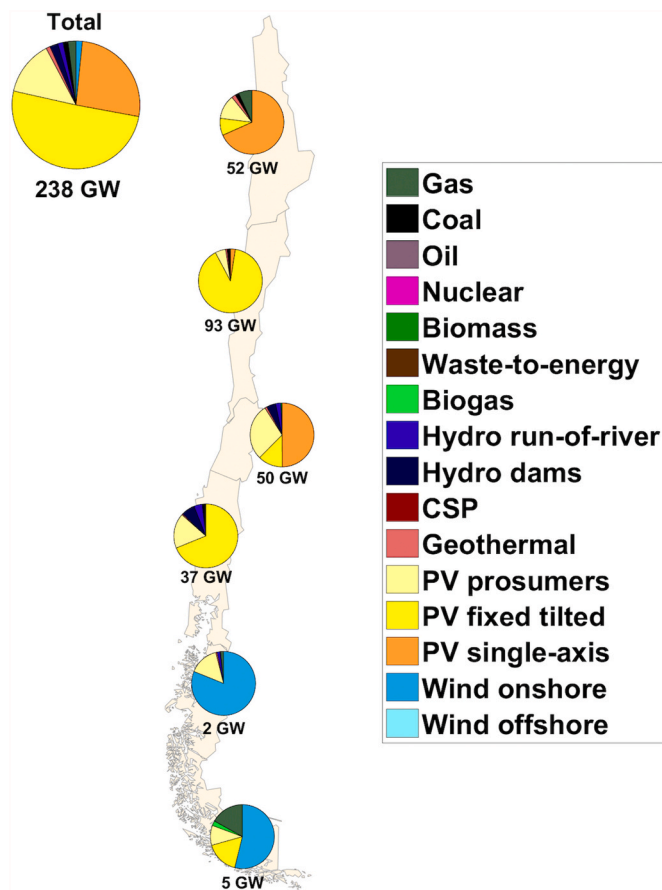


Fig. 7. Installed power capacity by technology and by zone for the 6-nodes-interconnected PHTD scenario by 2050.

between electrical and sectoral integration.

Fig. 8 depicts the energy flow of this fully interconnected and fully sector-coupled energy system, and also fully defossilised by 2050. Renewable electricity sources (mainly based on solar PV) are directly used in all sectors, stored as electric or thermal energy and converted into e-fuels. Then, e-fuels can be used in all sectors as well. Energy flows through a variety of flexibility options: batteries for short-term storage, PHES and TES for short- and medium-term storage, gas storage for seasonal variations, and a combination of Pth and PtX (power-to-gas, power-to-liquid, and power-to-vehicle). Here, green e-hydrogen is the basis for producing e-fuels [98], such as renewables-based e-hydrogen, e-methane (also SNG for synthetic natural gas), e-LNG and Fischer-Tropsch (FT) fuels. Thus, low-cost renewable electricity, multi-nodes-interconnected, e-fuels and sector coupling allow a more decentralised, integrated, flexible and demand-oriented energy system. This also allows fossil fuels to be replaced and energy-related net-GHG emissions to be reduced to zero. Such an electricity-based energy system with multiple PtX conversions and sector coupling has been suggested to be called a ‘Power-to-X economy’ as the characteristic element [99]. For the case of Chile, the even better matching term would be ‘Solar-to-X economy’. This is due to the solar PV share that in such a system by 2050 would represent 95% of the total installed capacity and 90% of the total electricity generation.

## 5. Discussion

This study demonstrates that the best way to carry out a transition towards a 100% RE system, from a techno-economic perspective, is through a multi-node interconnected and full sectoral integrated energy system. Solar PV, interconnection and full sectoral integration are key

enablers, and direct electrification of all sectors, flexibility and e-fuels are vital elements. In addition, as previously reported [21], the PHTD transition scenario to obtain a 100% RE system in Chile by 2050: i) is more cost-efficient from 2035 onwards than the current governmental scenario to achieve carbon neutrality by 2050; ii) would use about 10% of the available techno-economic RE potential for electricity generation in Chile; iii) could achieve carbon neutrality in 2030 and Chile could become a negative GHG emitter country from 2035 onwards based on the projected forest carbon sequestration.

This is the first study applied to Chile that analyses the PH and the PHT sector coupling configurations and compares single-node, multi-node isolated and multi-node interconnected scenarios. Although most of the previous findings on transitioning to 100% RE that have been considered for Chile are relatively in line with the results for some of the 12 scenarios simulated in this work, some of them differ significantly, as discussed in the following.

### 5.1. Comparison of results with studies that have included Chile

**Installed capacities and costs.** In the case of single-node studies to reach 100% RE considering the P sector only, where Chile was involved, Barbosa et al. [16] reported a total installed capacity and LCOE of 49–58 GW (37–43% solar PV, 28–40% wind power and 15–17% hydropower) and 41–51 €/MWh in an overnight scenario for the year 2030, respectively. Ram et al. [100] and Bogdanov et al. [87] reported a total installed capacity and LCOE of 39 GW (54% solar PV, 19% wind power and 25% hydropower) and 38 €/MWh by 2050. The results of research show 63 GW (83% solar PV, 3.2% wind power and 9.5% hydropower) and 36 €/MWh. In the case of a single-node study considering all sectors, Osorio-Aravena et al. [101] reported a total installed capacity and LCOE 87 GW (50% solar PV, 28% wind power and 7.4% hydropower) and 36 €/MWh, respectively. In Ref. [101], the major contribution of electricity generation across all sectors in 2050 would come from wind onshore (50%) and solar PV (39%). The results of our research show 245 GW (96% solar PV, 0% wind power and 3.3% hydropower) and 24 €/MWh, and solar PV would contribute 90% of the generated electricity. The installed capacity differences in all cases can be attributed to the projection of the final energy demand assumed for Chile (here, higher than in previous work). The LCOE and electricity generation differences reflect updates on cost assumptions for key technologies.

As shown in this work, single-node systems deliver too optimistic results for key metrics, compared to multi-nodes scenarios. This means that single-node systems provide, for instance, a cheaper energy system and lower investment costs as a result of less installed capacity needed for supplying the demand at the national level. That is mainly due to the modelling tool that chooses the lowest cost option based on the renewable sources that exist within the territory of the country, but without considering transmission lines. This finding is also in line with what was pointed out by Galván et al. [18] in the case of the power sector for South America. In fact, the seemingly lower costs from the single-node model poorly reflect reality, i.e. spatially distributed resources connected with a transmission system subject to bottlenecks. This affects the selection of technologies by the optimisation method. Instead, the multi-node systems reflect the reality much better due to the possible challenges for meeting the demand and the resulting need for grid, storage, and e-fuels production throughout the territory. Therefore, a single-node approach is not recommended as energy planning agenda for a country. This finding is also confirmed by research on the case of Bolivia [102] (based on overnight scenarios). This recommendation is easily implemented when planning the energy transition of a single country, but might prove more challenging for continental transitions, where a higher spatial resolution might face computational limits.

In the case of multi-nodes studies applied to Chile for achieving 100% RE considering the power sector only for the year 2050, Haas et al. [103,104] reported a total installed capacity and LCOE of 82–94 GW (46–70% solar PV, 23–46% wind power and 6.6–7.5% hydropower) and

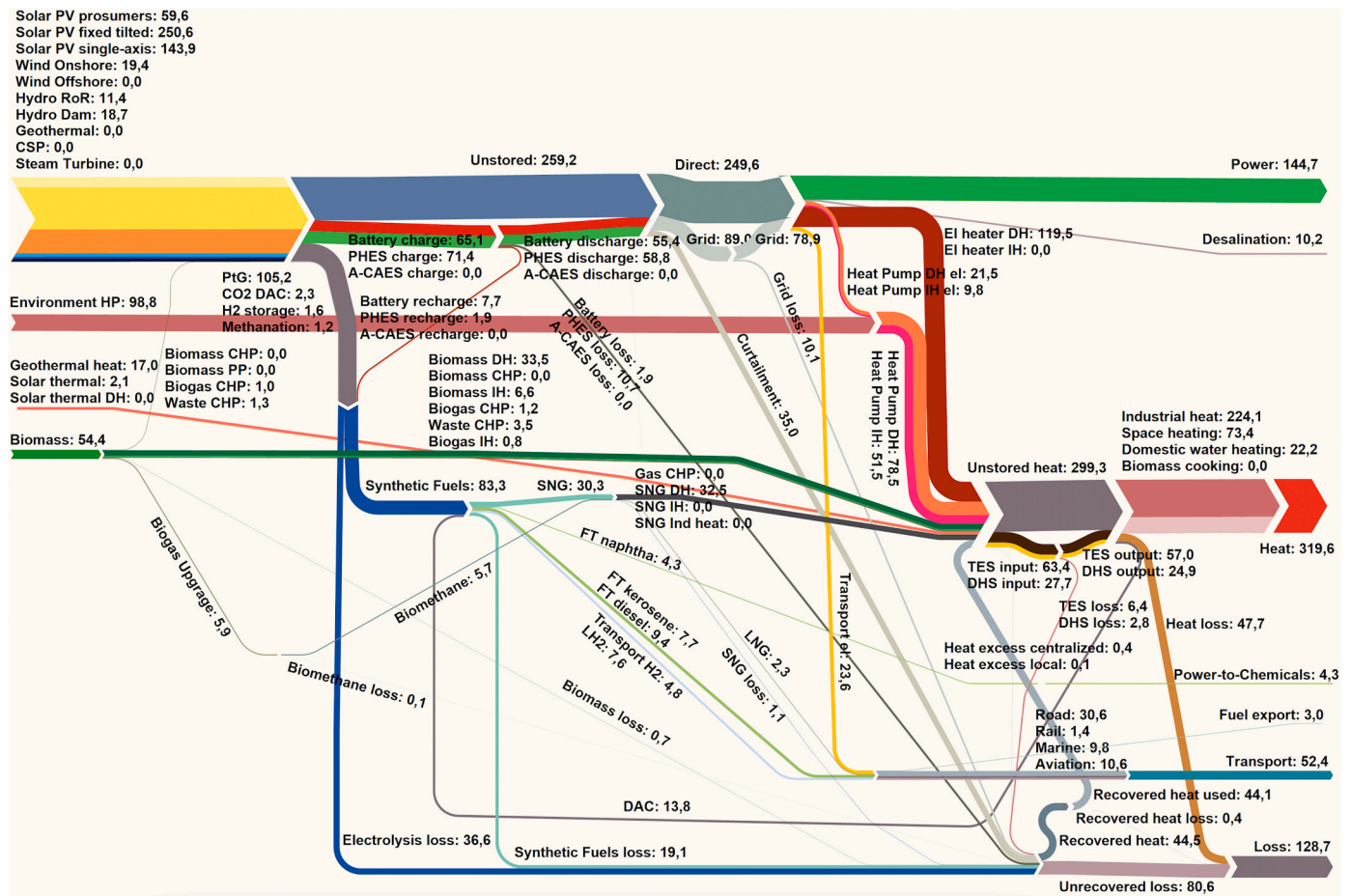


Fig. 8. Energy flow by 2050 in the 6-nodes-interconnected and PHTD scenario. Numbers provided are in TWh.

35–44 €/MWh, respectively. Gaete-Morales et al. [105] reported 53–62 GW (28–41% solar PV, 21–23% wind power and 19–23% hydropower) and 68–72 €/MWh. Babonneau et al. [106], reported 63 GW (22% solar PV, 46% wind power and 14% hydropower) and the LCOE was not given. All the studies considered electrical interconnection between the nodes. However, our results show a total installed capacity of 69 GW (86% solar PV, 0% wind power and 10% hydropower) and LCOE of 42 €/MWh by 2050. Note that the low wind capacity in the year 2050, is because we assumed a lifetime of 25 years (hence all wind capacities installed until 2025, cumulating a peak of 0.91–24.58 GW between the 12 scenarios, will have been decommissioned by 2050).

- The differences with Gaete-Morales et al. [105] and Babonneau et al. [106] are mainly related to two aspects pointed out in Ref. [107]: the use of outdated cost assumptions, which is important for cost-optimal solutions as key RE technologies have been widely underestimated in long-term energy scenarios; and some limitations of the modelling tool applied, where the low temporal resolution is the most relevant one since it has a substantial impact on an optimal energy system design.
- Differences in cost assumptions and/or temporal resolution are also present in those studies applied to Chile that include high RE penetration in the power sector, but which are not 100% RE scenarios. For instance, on the one hand, Matamala et al. [108] have obtained new generation capacities by 2030 within a range of 45–56% solar PV, 22–25% wind power and 22–30% hydropower; however, their cost assumption for solar PV (198 USD/kW or 178 €/kW) is higher than for wind power (164 USD/kW or 148 €/kW), while in our case it is

the opposite: 278 €/kW for solar PV and 1000 €/kW for wind power by that year.

- Regarding those works that contain at least one scenario with at least 95% RE for electricity supply by 2050, carried out by Amigo et al. [109] (64% solar PV, 28% wind power and 7.5% hydropower), Vargas-Ferrer et al. [110] (42% solar PV, 24% wind power and 11% hydropower), and Arriet et al. [111] (66% solar PV, 8.5% wind power and 13% hydropower), their results have to be taken carefully. Their used models, such as OSeMOSYS and GCAM, suffer from limitations in temporal resolution that has a structural impact on the optimal energy system design [112] and often cost assumptions are applied that have underestimated the role of key RE technologies in long-term energy scenarios [9,113–115]. In fact, the use of updated cost assumptions is key for energy transition analyses [116], as well as the use of models with the capability to represent key technologies and infrastructures, such as PtX for e-fuels production and sector coupling [9]. Another aspect is that most used models only include fixed-tilted PV systems, missing the lower LCOE and higher full-load hours of single-axis tracking PV [99,117]. Solar PV differentiation and cost-optimisation provide more profits for companies and governments' investments and are socially desirable, meaning that it is possible to achieve climate targets under lower overall system costs, which are transferred to customers, while more overall system diversity and near-optimal solutions may be also beneficial and socially attractive [118–120].

In the case of a multi-nodes energy system analysis considering all sectors and electrical interconnection between the nodes for achieving 100% RE scenarios, Osorio-Aravena et al. [21] reported a total installed

capacity and LCOE of 238–254 GW (91–92% solar PV, 1.3–1.4% wind power and 3.2–3.4% hydropower) and 26 €/MWh, respectively. The results of the present research show 237 GW (95% solar PV, 1.5% wind power and 3.3% hydropower) and 26 €/MWh, which are in line with [21].

A fully multi-node interconnected and fully sector-coupled energy system requires newly installed power transmission capacities during the transition period. This implies assuming that the transmission planner in Chile will be able to adequately deploy capacities. In contrast, the multi-node isolated scenarios can be interpreted as a case in which transmission fails to be deployed at a significant level. Contrasting both extremes reveals the value of, for example, timely transmission, which is one of the main bottlenecks in Chile. In any case, the very good solar resources around the demand hubs are quite competitive compared to long-distance power transmission; although cost-optimal designs of the multi-node interconnected scenario rely on transmission capacity investment. Thus, whether the transmission lines are built in time or not will impact the final costs, but not the feasibility. The multi-node isolated scenarios are techno-economically viable with a bit more investment in power generation capacities. This would be possible, for instance, with seasonal storage based on green e-hydrogen and its derivatives that become cost-competitive from 2030 onwards. Therefore, transmission is a challenge rather independently of the scenarios. In any case, this study is the first one applied to Chile that reports results with scenarios considering the nodes electrically isolated. The multi-node approach shows a more decentralised, integrated, flexible and demand-oriented energy system.

## 5.2. Comparison of findings with similar studies

In line with the findings reported by Schlachtberger et al. [15] on the comparison of multi-nodes isolated and interconnected for the European power sector, results of the present research also show that the lowest-cost solution is reached when electric transmission lines are considered. And, a multi-node interconnected system delivers the most balanced results. In any case, power sector analyses start to become increasingly limited in meaning. In particular, as low-cost electricity from solar PV and wind power enables a broad and massive electrification of the entire energy system [121], which in turn leads to a differently structured power sector, as a consequence of additional flexibility [19]. This is mainly driven by substantial flexibility provided by battery-electric vehicles, electrolyzers and heat pumps, among further flexibility options. In fact, this research indicates that power sector simulations do not present realistic electricity system costs, as sector coupling effects drastically reduce the overall electricity system costs. In other words, power sector simulations can lead to a strongly distorted resources allocation and higher LCOE than in a more balanced multi-sector energy system.

Also, in line with the findings reported by Lopez et al. [102] on the comparison of overnight single-node and multi-nodes scenarios for the case of Bolivia, the multi-node systems reflect the reality much better than a single-node system. This is due to the possible challenges for meeting the demand and the need for grid, storage, and e-fuels production throughout the territory. In addition Lopez et al. [102] underline that the full transition scenario has to be considered in any case, as overnight studies also underestimate the cost of the legacy system and other metrics, similar to the single-node case.

Furthermore, and in line with the findings reported by Brown et al. [22] for Europe and Lopez et al. [102] for Bolivia on the comparison of multi-nodes isolated and interconnected for the power, heat and transport sectors, our results also show that the multi-node isolated systems deliver results with a lack of optimisation for the entire system. There are synergies between grid interconnection and sector coupling that allow for obtaining the lowest-cost solutions. This is mainly based on additional flexibility due to sector coupling effects, and thus the overall system benefits. In addition, findings of this research suggest that a

major sector with flexibility drastically improves various metrics, while a further sector with high flexibility does not change anymore the picture drastically (decreasing marginal returns). This is the case of H and T sectors: when H is coupled to the P sector, it provokes a dramatic increment in the installed capacity of the system, while, when T sector is coupled does not significantly change the metrics. According to Bogdanov et al. [19], sector coupling enables access to low-cost flexibility. This allows substituting electricity storage options with low-cost product storage options, like power-to-heat and heat storage in case of heat sector integration; hydrogen and e-fuels storage in case of integrating the transport sector; hydrogen-based e-chemicals [122,123] and e-steel [124,125] in case of the industry sector integration, where, water electrolyzers provide the most valuable flexibility for the entire energy system. In particular, this is in combination with low-cost solar PV electricity. Furthermore, integration of sectors which do not provide flexibility, but demand baseload electricity, can also increase system efficiency for some specific cases [19]. In addition, the results also indicate that an energy system with very high excess flexibility (documented by T added to PH) can easily integrate another sector with no flexibility without negative impact on metrics (D added to PHT), as the lack of flexibility of D is well documented [19,126]. This finding is confirmed by ElSayed et al. [127] on the case of Egypt for a further expanded energy-industry-CDR system [9] (CDR, carbon dioxide removal). Operating direct air captured carbon storage [128] at near baseload but supplied almost entirely by solar PV (similar to the desalination sector in this research) shows no negative cost impact on the overall system level, finally due to a substantial remaining flexibility reserve.

In addition, also in line with a similar work [22], the results of this research show that when at least three sectors are coupled, the most important energy carrier is electricity from RE sources and the second is hydrogen mainly for its conversion into e-fuels. Here, the core characteristics are primary energy supplied dominantly by renewable electricity, high direct electrification of multiple end-use, and indirect electricity uses via power-to-hydrogen-to-X processes. All of this is based on elements such as low-cost renewable electricity, multi-nodes-interconnected, and sector coupling, where battery storage and electrolyser operation effectively balance the variable RE generation. These characteristics and elements support the emergence of a 'Power-to-X economy' instead of a 'hydrogen economy' [99], which in the case of Chile would be more appropriately called 'Solar-to-X economy'. In fact, 'Power-to-X economy' characteristics and elements allow a more decentralised, integrated, flexible, cost-efficient and demand-oriented energy system, where energy-related net-GHG emissions can be reduced to zero.

In any case, Schlachtberger et al. [15] and Brown et al. [22] have only compared the same number of nodes, isolated and interconnected. Lopez et al. [102], have only compared single-node vs multi-node scenarios, while Bogdanov et al. [19] have only compared sector coupling variation in the case of a single-node design. Therefore, this is the first study showing the effect of various sector coupling configurations under different spatial resolutions and electrical connections (single-node, multi-nodes isolated and multi-nodes interconnected). This was carried out in a full hourly resolution and within the context of a transition towards a fully renewables-based energy system.

## 5.3. Limitations of the study and future research

One of the main limitations of this work is that only three spatial resolution cases have been analysed on a limited number of nodes (1-node and 6-nodes). A study considering several numbers of nodes with various sector coupling configurations is needed. Here, on the one hand, the key question to answer is from what number of nodes onwards the effect of the cost-optimisation loses importance. And, on the other hand, it is needed to compare the impact of the number of nodes versus sector coupling configurations, while the relative area per node may also

influence the outcome. This is due to the size of nodes could lead to different solar PV and wind power installed capacities by node and affect the metrics at the national level.

Another limitation of this study is the fact that the model tool used does not include the so-called smart charging of battery-electric vehicles (BEV) and vehicle-to-grid flexibility. According to Victoria et al. [64], for the case of Europe, BEV flexibility avoids stationary batteries and reduces the usage of pumped hydro energy storage. However, this needs to be further studied to evaluate its impact at the national level and with higher spatial resolution (more than a single-node per country) [129].

Finally, a 100% RE system in Chile by 2050 across all sectors would require about 10% of the techno-economic available potential. Hence, it is suggested to evaluate a portion of the remaining 90% RE potential (mainly based on the great wind energy potential allocated in Patagonia) that would not be used for domestic supply for exporting e-fuels and e-chemicals. This is to understand Chile's opportunity to contribute to the global sustainable energy transition and to reach a global post-fossil fuels economy. Defossilising Chile's energy supply would also allow a cleaner production of the key materials that Chile exports to the world like copper and lithium.

## 6. Conclusions

This paper presents the first study showing the effect of various sector coupling configurations (power sector; integrated power and heat sectors; integrated power, heat and transport sectors; and integrated power, heat, transport and desalination sectors) under different spatial resolutions and electrical connections (1-node, 6-nodes-isolated and 6-nodes-interconnected), in a full hourly resolution and within the context of a transition towards a fully renewables-based energy system. A total of 12 scenarios were simulated using the case of Chile. These results are expected to be valuable to the energy modelling community, as well as energy policy makers.

This study also proves that a transition to reach a fully defossilised energy system in this country by 2050 is technically feasible and economically viable. Based on the findings of this work it is concluded that:

- Single-node models means to neglect the transmission system and local electricity generation profiles are strongly aggregated. This impacts the whole transition, and delivers too optimistic and simplified results for key metrics: utilisation of technologies, energy storage, system flexibility, overall costs and greenhouse gas emission reductions. These results have to be regarded very carefully.
- Only multi-node scenarios capture the possible challenges for meeting the demand by node and the need for grid transmission and storage, as well as obtaining more balanced results throughout a territory.
- By definition, multi-node isolated systems (without transmission between nodes) are more costly than multi-node interconnected systems. Understanding these over-costs for isolated systems, as in our work, is insightful for both the discussion of energy autonomy of each zone and the case if new transmission systems cannot be deployed in time.
- Only simulating the power sector can lead to a strongly distorted resource allocations, because the model is blind to 1) readily available flexibility from other sectors, for example, electrolysers and heat pumps, and 2) the energy demand of other sectors. Further sectors, like desalination, can easily be integrated without negative impacts on key metrics. The lowest cost and more balanced solution to reach a 100% renewable energy system is achieved for a fully interconnected and fully sector-coupled energy system, while no significant technical or economic barriers could be identified.

Low-cost renewable electricity, multi-nodes interconnections, sector coupling and e-fuels allow a more decentralised, integrated, flexible,

cost-efficient and demand-oriented energy system, where energy-related net greenhouse gas emissions can be reduced to zero. Such an electricity-based energy system is in line with the suggested 'Power-to-X economy' concept [99]. In the case of Chile, this would be more appropriately called 'Solar-to-X economy' given that 95% of the total installed capacity and 90% of the total electricity generation are expected to be solar PV shares.

Finally, open modelling questions are further improving the understanding of the trade-offs between the spatial resolution in term of number of nodes of an electrically interconnected system and the sectoral resolution of a fully coupled energy system. This implies that technological diversity for energy generation may be an aspect to be investigated further under near cost-optimal approaches, while cost-effective solutions are more profitable for companies and governments' investments and socially desirable for achieving climate targets under lower overall system costs.

## Credit author statement

Juan Carlos Osorio-Aravena: Conceptualisation, Investigation, Data preparation, Results analysis, Writing – original draft preparation. Arman Aghahosseini: Conceptualisation, Investigation, Methodology, Software, Results analysis, Visualization, Writing – original draft preparation. Dmitrii Bogdanov: Methodology, Software, Writing – review & editing. Upeksha Caldera: Investigation, Writing – review & editing. Narges Ghorbani: Investigation. Theophilus Nii Odai Mensah: Investigation. Jannik Haas: Investigation, Writing – review & editing. Emilio Muñoz-Cerón: Investigation. Christian Breyer: Conceptualisation, Results analysis, 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. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.energy.2023.128038>.

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