Net energy analysis and life cycle energy assessment of electricity supply in Chile: present status and future scenarios

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Abstract

Chile is one of the fastest-growing economies in Latin America, with a mainly fossil fuelled electricity demand and a population projected to surpass 20 million by 2035. Chile is undergoing a transition to renewable energies due to ambitious national targets, namely to generate 60% of its electricity from local renewable energy by 2035, and to achieve a 45%renewable energy share for all new electric installed capacity. In this work, we present a comprehensive energy analysis of the electricity generation technologies currently deployed in Chile. Then, we analyse potential future scenarios, considering a large deployment of RE, mainly PV and wind, to replace coal-fired electricity. The life cycle assessment (LCA) and net energy analysis (NEA) methods are applied in parallel to provide complementary indicators, respectively nr-CED and EROI, and identify weak spots and future opportunities. Special focus is given to the effect on EROI of transporting fossil fuels to Chile. Results show that a large deployment of PV and wind can significantly improve the overall net energy performance of electricity generation in Chile, while leading to an electricity supply mix that is >60% less reliant on non-renewable energy.

1. Introduction

Today, one of the most crucial challenges in the energy sector is how to reduce environmental impacts while addressing the upward trend in the energy demand. A transition towards low-carbon energy technologies represents a key factor in mitigating climate change and reducing environmental impacts (IEA, 2017a). Also, in the face of rising scarcity of energy resources caused by a global increase in energy consumption, energy security is a crucial concern, especially in fast-growing countries.

Chile is a country that boasts a diverse natural resource endowment, and, besides being the world's largest copper producer (USGS, 2017), it has traditionally been a major exporter of agricultural, forestry and fishery products. However, over the past decade, it has also become one of the fastest-growing economies in Latin America, and its population is projected to grow at an average annual rate of 0.6%, reaching over 20 million by 2035 (Ministerio de Desarrollo Social, 2013). Concomitantly, the country's natural resource-based model has started to show its limits, in part due to increasing environmental concerns, and the country now faces a range of challenges as population density increases and economic structures change. Overall, Chile is a net importer of energy, and its largely fossil-fuelled electricity demand is expected to increase from approximately 70 TWh/yr to over 100 TWh/yr by 2020 (Ministerio de Energía, 2015; IEA, 2017a).

The Government of Chile's concerns about security of energy supply, sustainable development and environmental problems, led to the ratification of the Paris Agreement, and to commitments to develop policies on climate change and to achieve sustainable development objectives (Gobierno de Chile, 2015). In particular, to address the energy security issue, as well as reduce its carbon intensity, Chile is embarking on a radical energy transition with ambitious targets: to generate 60% of its electricity from locally-available renewable energies by 2035, and 70% by 2050 (Ministerio de Energía, 2014a, 2015). Its 2014-2018 Energy Programme also aims to achieve a 45% renewable energy share for all new electric installed capacity between 2014 and 2025 (IRENA, 2015; Ministerio de Energía, 2015).

Any such major energy transition will inevitably entail a large number of decisions to be made, and economic considerations can of course be expected to play a large role in determining them. A number of economic modelling tools are available and have been used to investigate similar scenarios in the literature, among which MARKAL [Fishbone and Abilock, 1981; Fishbone et al., 1983; Beger et al., 1992; Nakata, 2004; Kannan, 2011], TIMES [Loulou et al., 2005; Krakowski et al., 2016], LEAP [Nakata, 2004], and others. All these approaches share a common principal goal in the minimization of the overall cost of supplying energy services; however, in doing so, when evaluating the potential implications of alternative energy technologies, they are inevitably susceptible to a range of market-induced distortions, such as: sector-specific economic incentives, feed-in tariffs, subsidies, discount rates, etc. Instead, we argue that there is an important role to play for a framework of analysis, such as the one that we adopt in this paper, which eschews conventional economic numeraires and describes the performance of the energy systems at play exclusively in terms of physical units such as kg, MJ, etc. and their derivatives. Such an approach positions itself squarely within the discipline of 'biophysical' economics, which is represented by a growing body of literature (Cleveland, 1987; Cleveland, 1999; Dale et al., 2012; Carbajales-Dale et al., 2014; Bobulescu, 2015; King and van der Bergh, 2018; Day et al., 2018).

Thus, the purpose of this work is two-fold: firstly, to evaluate the energy performance of all the electricity generation technologies as currently deployed in Chile, including a detailed weak spot analysis. Secondly, to investigate potential scenarios of electricity generation with a larger deployment of renewable energies, evaluating the resulting net energy availability and long-term dependence from non-renewable primary resources, by means of Net Energy Analysis and Life Cycle Assessment.

2. System description

2.1 The current grid mixes

Until the end of 2017, electricity generation in Chile took place in four independent electric grid systems (CNE, 2017a): the Northern Interconnected System (Sistema Interconectado del Norte Grande - SING), the Central Interconnected System (Sistema Interconectado Central - SIC), the Aysen System (Sistema Eléctrico de Aysen - SEA) and the Magallanes System (Sistema Eléctrico de Magallanes - SEM). Of these, the first two collectively accounted for over 95% of the total electricity generation (respectively, SIC: 70% and SING: 25%). The SIC grid covered the central and southern regions of the country, including the main consumption centres around the capital Santiago, and served 93% of the Chilean population. The SING grid mainly supplied electricity to the mining and mineral industries in the north of the country (Ministerio de Energía, 2015), and until 2017 over 90% of such electricity was thermoelectric.

The SIC and SING grids were connected at the beginning of 2018, with a 600 km high voltage line, aimed at drastically reducing transmission bottlenecks and facilitating the transmission of new renewable energy generation capacity, as well as enabling the northern grid to benefit from the load-smoothing effect of the pumped hydro storage capacity that is present in the SIC grid (Araneda et al., 2015; Electricidad, 2016). The project was named Transmisora eléctrica del norte (TEN), and comprises 500 kV AC lines and electric substations (Diario Oficial de la Republica de Chile, 2016). The resulting combined grid now covers almost all of the demand for electricity in Chile, and is aptly named National Electricity System (Sistema Eléctrico Nacional – SEN) (CNE, 2018).

The first part of our analysis focuses on the generation technologies deployed in the two former main Chilean electricity grids (SIC and SING), with 2017 as the chosen baseline year (the latest year for which complete statistical information on electricity generation was available at the time of writing).

On the whole, Chile has two major domestic primary energy resources that can be used for electricity: wood for biomass generation and water for hydroelectricity generation. The country has only limited domestic fossil energy resources and this exposes its economy to energy security risks.

In 2016 (the latest year for which statistical information on fuel imports was available at the time of writing) all of Chile's coal demand was satisfied by imports (CNE, 2016), coming from Colombia (~43%), the USA (~33%), Australia (~21%) and Canada (~3%). For many years Chile's main source of imported natural gas was Argentina, but since 2004 it has faced import restrictions, which have led to pursuing other sources of imports (CNE, 2016), in the form of liquefied natural gas (LNG) from Trinidad and Tobago (79%) and Norway (21%) being delivered for use in the SIC grid. Also, crude oil is imported from Brazil (62%) and the USA (38%), and diesel is imported from the USA (CNE, 2016).

According to the latest available data for a full year (CNE, 2017b), shown in Figure 1, the SIC electricity mix in 2017 was composed mainly of thermoelectric electricity (~46%) and hydroelectric power plants (~39%), while the contribution of wind, PV (Grágeda et al., 2016) and biomass electricity cumulatively accounted for less than 15% of the total electricity generated. As illustrated in Figure 2, the SING grid was even more heavily reliant on fossil fuels (~90% of the total electricity demand), with notably no hydro capacity because of the geomorphological characteristics of the territory (high-altitude dry plains).

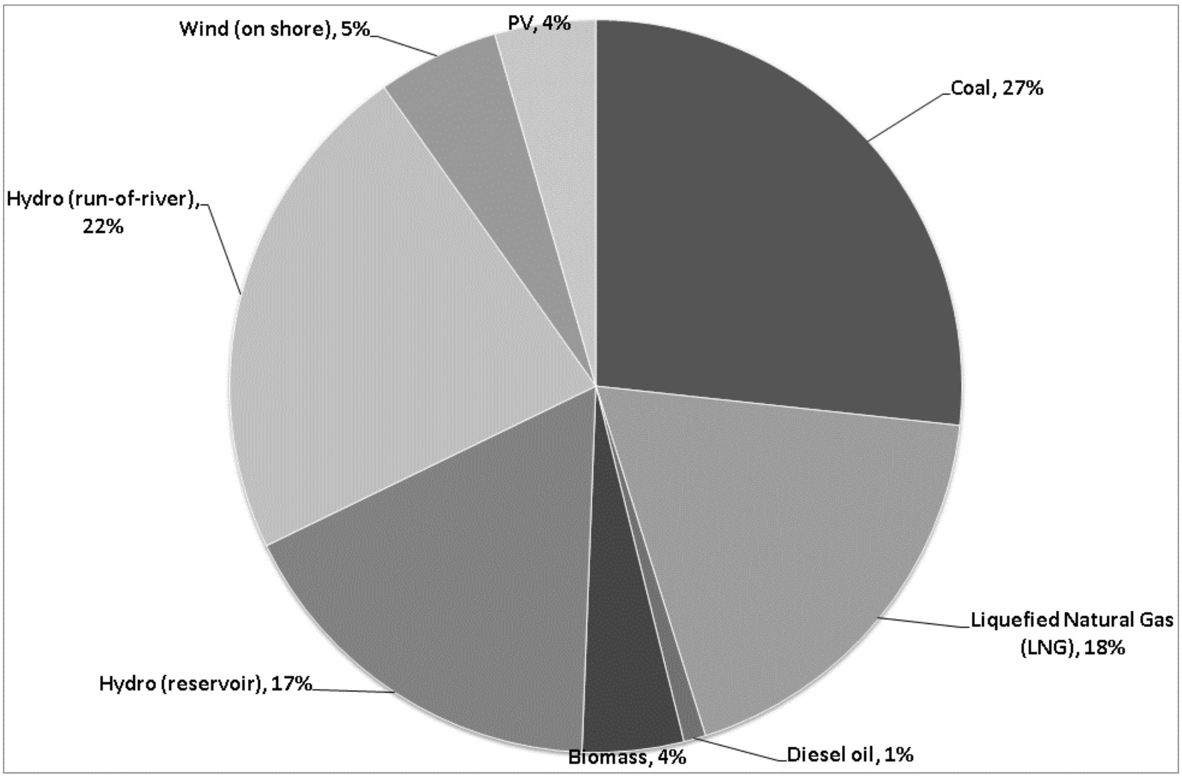

Figure 1 – SIC grid mix in terms of electricity delivered in 2017.

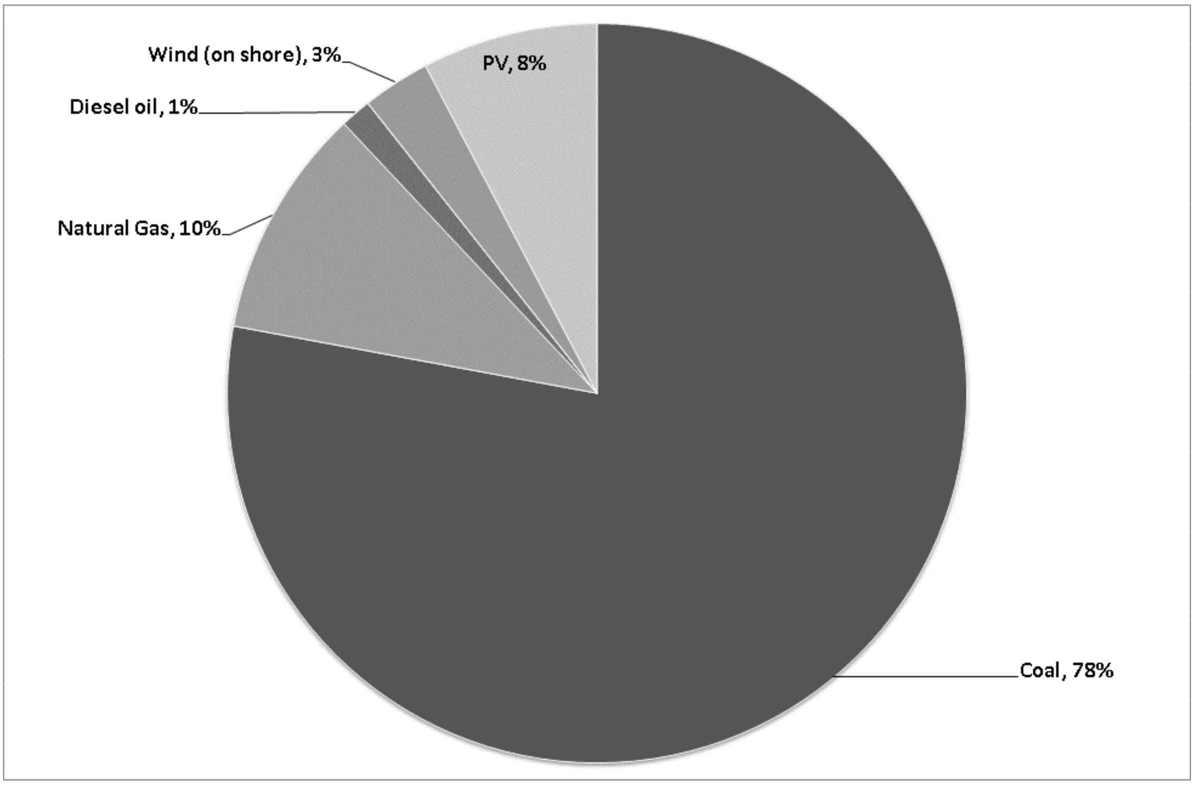

Figure 2 – SING grid mix in terms of electricity delivered in 2017.

2.2 Future scenarios

As illustrated in Figure 3, based on the reported steady trends over the past two decades in the SIC and SING grids (CNE, 2017b), our own extrapolations indicate that the electricity demand in both the northern and southern regions of Chile is expected to increase by approximately 50% by 2035. We therefore assumed for the year 2035 an overall electricity demand in the new SEN grid equal to 150% of the sum of the 2017 electricity demands in the SIC and SING grids.

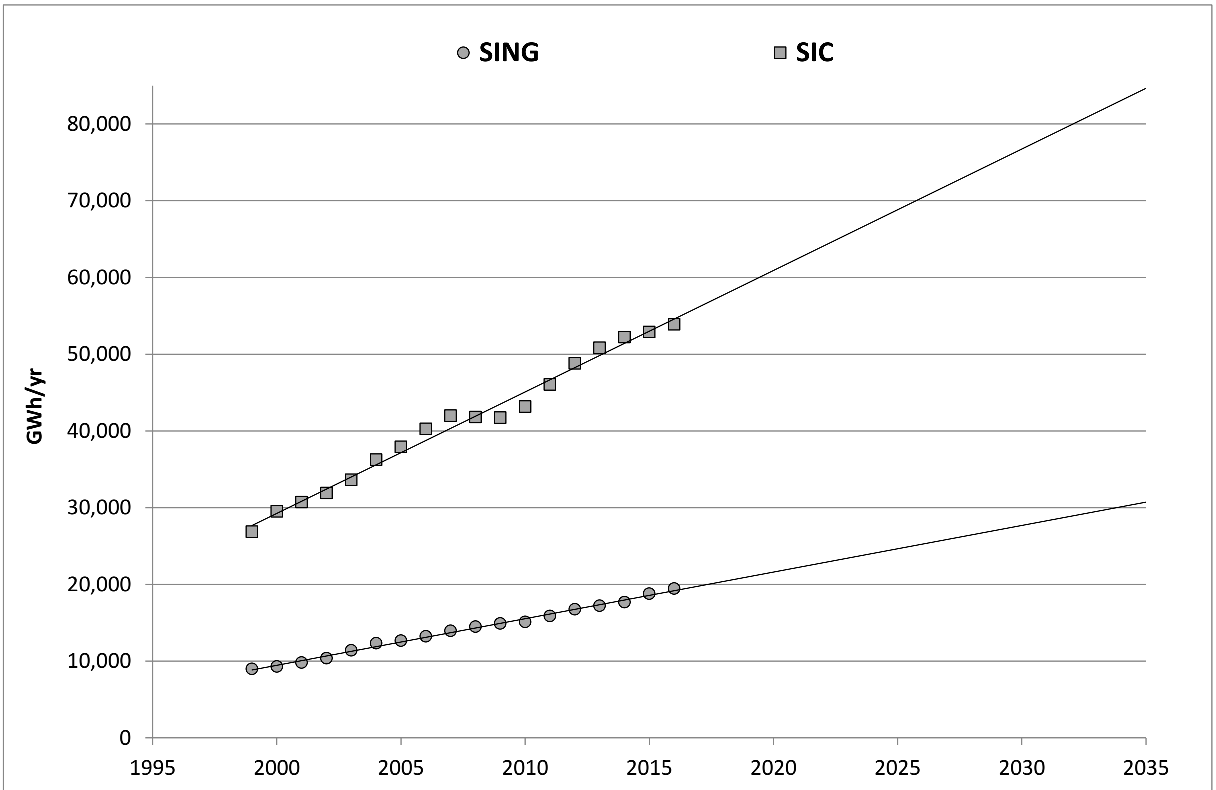

Figure 3 – Historical trends of cumulative electricity generation in SIC and SING grids (CNE, 2017b), and linear extrapolations to 2035.

In terms of potential for the future evolution of the grid mix, Northern Chile is characterized by optimal solar resources as the climate is dry, cold, and at high altitude with a large amount of solar irradiation, which leads to great potential for the deployment of solar energy (Del Sol and Sauma, 2013; Fthenakis et al., 2014; Escobar et al., 2014; Escobar et al., 2015). Indeed, already at the end of 2016, Chile became the top PV installer in Latin America, ranking 10th globally for newly added capacity during 2016 [Hasan et al., 2017]. Additionally, geographical characteristics such as long coastlines, valleys and mountains, create significant wind potential which is estimated at approximately 40,000 MW (Watts et al., 2016). Also, importantly, a recent governmental study on long-term energy policy has shown that solar and wind are highly accepted renewable energy sources in Chile (Ministerio de Energía, 2015), and several governmental scenarios already include large deployments of PV and wind (Ministerio de Energía, 2017).

Instead, new large-scale hydroelectric power projects in Chile have been negatively affected by widespread environmental concerns and social opposition. In recent years, the Chilean government was forced to cancel plans for a new large hydroelectric dam (the “HidroAysen” project (BBC, 2014)), and since then opposition by environmental and indigenous groups has increased even further (IEA, 2018). Partly as a result of this state of affairs, any mention of hydroelectricity in government reports and studies is always accompanied by sustainability concerns due to social, as well as environmental, aspects (Ministerio de Energía, 2014b, 2017), and the law of renewable energy 20.257 in Chile even classifies large hydroelectric dams of over 20 MW capacity as “non renewable” (Ministerio de Economía, 2013).

As illustrated in Figure 4, in drafting the main scenario for the composition of the SEN grid mix in 2035, we therefore assumed that the Chilean government’s 60% renewable energy target for that year would be met by a combination of PV (40%) and wind (20%) generation, thereby fully replacing coal. This emphasis on PV and wind as the two key renewable technologies for the future evolution of the Chilean grid mix is fundamentally in line with what has been reported by the International Renewable Energy Agency (IRENA, 2015), and with several of the long-term energy scenarios developed by the Chilean Ministry of Energy (Ministerio de Energía, 2017).

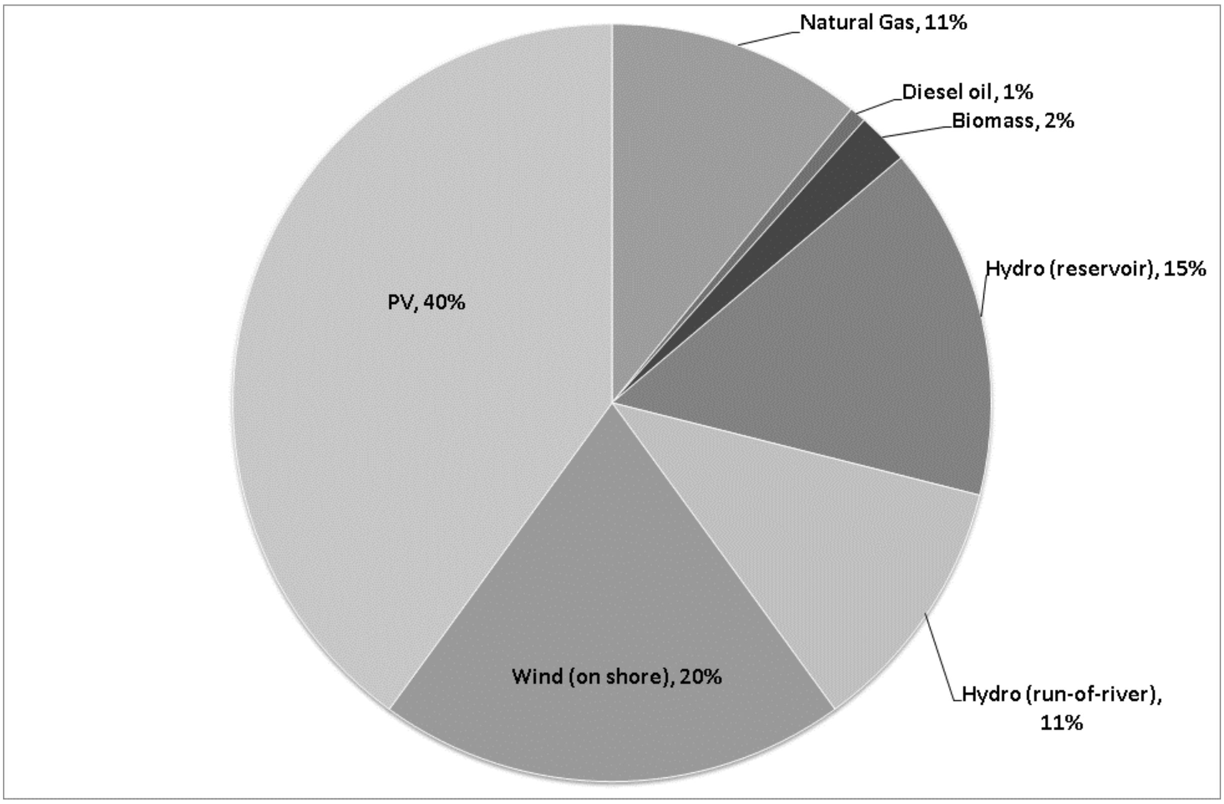

Figure 4 – Projected SEN grid mix in terms of electricity delivered in 2035.

In terms of PV-specific assumptions, we modelled the technology shares of the current PV installed capacity in Chile on the basis of the latest respective figures for the whole world (Fraunhofer ISE, 2018), i.e., 70% multi-crystalline (mc-) Si, 24% single-crystalline (sc-Si) and 6% cadmium telluride (CdTe). In our future scenarios for 2035, these shares are then expected to change to 50% mc-Si, 20% sc-Si and 30% CdTe. Specifically, an increased penetration of CdTe PV is assumed, since this is currently the best-performing PV technology in terms of EROI (Leccisi et al., 2016). Based on historical trends and learning curves, significant technical improvements may be expected for all future PV systems. To take this into account, we conducted a sensitivity analysis whereby PV module efficiencies in 2035 are allowed to range from the latest reported current values, i.e.: 16.8% for mc-Si, 18.7% for sc-Si and 17.0% for CdTe (Chen et al., 2018), up to the improved figures consistent with the intermediate "realistic" estimates provided in the recent IEA literature

(Frischknecht et al., 2015a), i.e.: 21% for mc-Si, 22% for sc-Si and 20% for CdTe. Similarly, the energy required for production of PV modules in 2035 is assumed to range from the current values to -20% in the case of mc-Si and sc-Si PV and -10% in the case of CdTe (after: Frischknecht et al., 2015a). PV module lifetime and performance ratio (PR) for 2035 have been kept at the commonly estimated values of 30 years and 0.8 respectively (Frischknecht et al., 2016), as have the technology-specific degradation coefficients, i.e.: 0.6%/yr for mc-Si, 0.23% for sc-Si and 0.3%/yr for CdTe (Jordan and Kurtz, 2011).

The main technical challenges facing a large deployment of PV and wind in Chile include the variability of electricity supply as it relates to the need for firm 24/7 supply to the mining facilities in the north, and concerns about grid stability in general (Fthenakis et al., 2014). The capacity factors[1] (CF) of PV and wind (as well as hydro) are largely determined by the availability of the respective renewable energy flows, and tend to fluctuate year by year depending on weather conditions. Solar irradiation in the deserts of northern Chile is relatively constant and predictable, but wind availability is less so. Also, PV and wind technologies lack a 'built-in' energy storage system, and the only way to directly control their output and adapt it to the electricity demand profile is to resort to curtailing during times of peak production, which of course negatively affects the yearly average CF.

However, intermittency can be effectively addressed by combining various renewable energy generators (Nikolakakis and Fthenakis, 2011), as well as by the planned interconnection of the SING grid with the SIC grid, and by further developing pumped hydro capacity in the SIC grid so as to also serve as load-smoothing storage for both grids. Grid stability may then be further enhanced by means of power plant controllers, dynamic voltage power management, frequency droop control and fault-ride-through capacity (Morjaria et al., 2014).

Given the inherent uncertainty on the degree to which these measures will be successful in addressing and solving the intermittency and stability issues, in our sensitivity analysis of the

[1] Capacity factors (CF) are defined as the ratio of the average effective power output to the nominal installed power.

future scenario, different proportions of the generated PV and wind electricity are assumed to be curtailed and routed into pumped hydro (PH) storage, as illustrated in Figure 5.

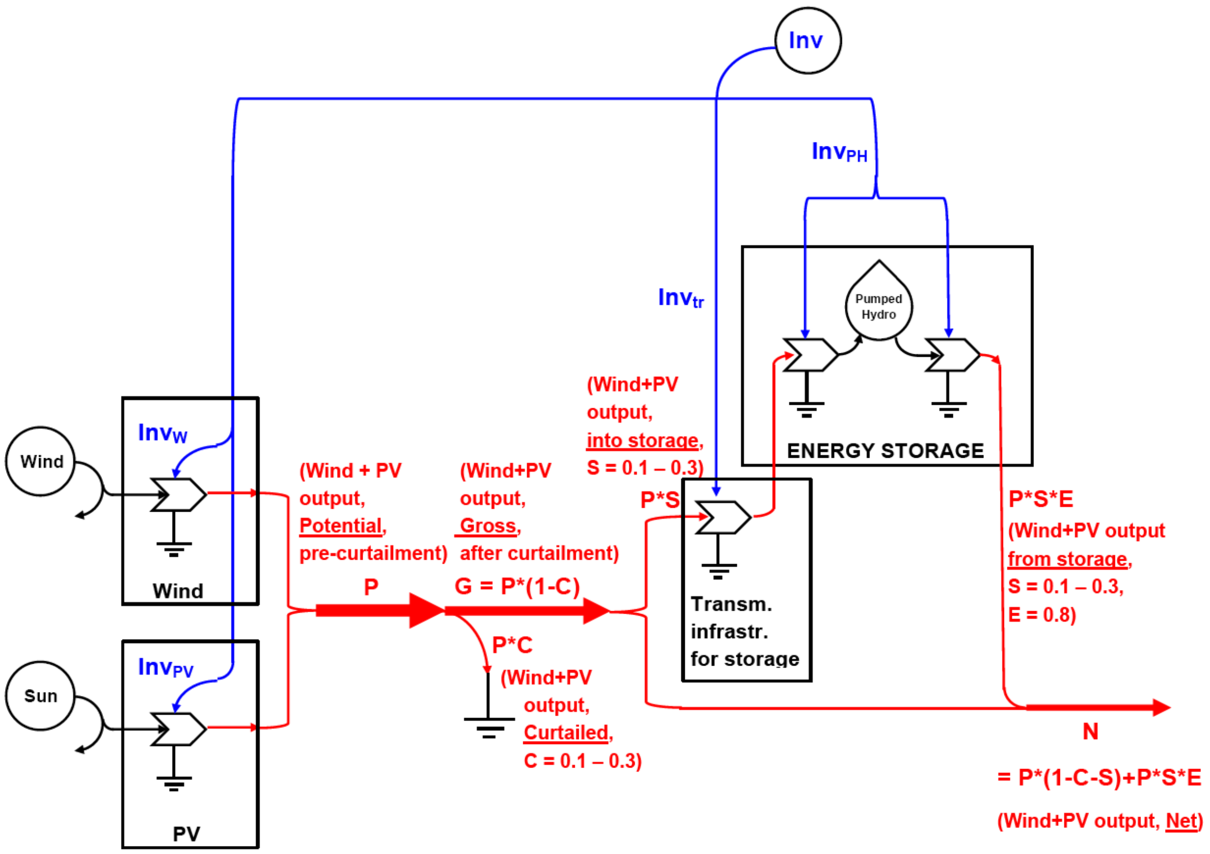

Figure 5 – Flow diagram showing P = potential electricity production by PV and Wind power plants (pre-curtailment), G = gross production (after curtailment), and N = net production, including storage and transmission losses. C = curtailment percentage (10-30%); S = storage percentage (10-30%); E = overall storage loop output/input efficiency (80%). Inv_W = energy investment for Wind power plants; Inv_{PV} = energy investment for PV power plants; Inv_{tr} = energy investment for storage-related transmission infrastructure; Inv_{PH} = energy investment for Pumped Hydro storage.

Within such sensitivity analysis, the percentage of gross electricity generation that is routed into storage (S) is allowed to vary continuously from a minimum of 10% to a maximum of 30%; similarly, the percentage of gross electricity generation that is curtailed (C) is also allowed to vary continuously from 10% to 30%.

The “Best case” scenario implies the achievement of optimal demand-side management, to the extent that both storage and curtailment requirements would be minimized (to 10%). At the opposite end of the spectrum, the “Worst case” scenario implies a severe mismatch between the generation and demand profiles, to the point that even a comparatively large percentage of storage (30%) would not be enough to balance supply and demand, and would still require a large share (30%) of PV and wind electricity to be curtailed. In the intermediate scenarios, either comparatively large pumped hydro capacity is assumed to be available and largely sufficient to compensate for an intermediate degree of generation/demand mismatch, requiring little curtailment; or conversely a more constrained availability of pumped hydro is assumed, and consequently more curtailment is required to compensate for similar levels of generation/demand mismatch.

Throughout the range of storage and curtailment percentages spanned by the sensitivity analysis, the PV and wind installed capacities are dynamically over-dimensioned so as to keep the respective amounts of net electricity delivered to the grid constant.

Additionally, in all scenarios, the extant installed capacities of natural gas and diesel-fired power plants are assumed to be maintained, as these are readily-dispatchable options that play an important role in ensuring grid stability. However, the future sourcing of natural gas imports to Chile depends on political, rather than technical, limitations. This being the case, we evaluated a spectrum of options for the future, ranging from a “Worst” case in which a complete shutdown of all natural gas imports from Argentina will lead to 100% of the gas being imported in the form of LNG, to a “Best” case in which the historically prevalent imports from Argentina will be fully restored, leading to zero demand for additional LNG imports from overseas. Also, given that, at present, the average conversion efficiencies (“heat rates”) of gas-fired power plants in the SIC and SING grids appear to be sub-optimal (CNE, 2017b; *cf.* Table 1) with respect to the current state of the art (IEA, 2017b), we allowed these heat rates to vary from the current statistically reported values up to 60% (representative of modern combined cycle gas turbines (CCGTs)), and thus contribute to the overall sensitivity analysis of the future scenarios.

Finally, the additional energy investments for grid adaptation (including the new transmission lines) and for newly-deployed pumped storage capacity and CCGTs, as well as the energy investments for all thermal plant decommissionings, have also been included in the models for all scenarios.

3. Methods

In this work, like in previously published studies (Raugei and Leccisi, 2016; Leccisi et al., 2016; Jones et al., 2017; Raugei et al., 2017), we applied two complementary methods that share common elements in structures and procedures, namely Life Cycle Assessment (LCA) and Net Energy Analysis (NEA).

LCA’s principal energy indicator is the cumulative energy demand (CED), measuring the total primary energy (PE) that must be harvested from the environment to produce a given amount of usable product or energy carrier (Frischknecht et al., 2007, 2015b). Also, LCA differentiates between renewable and non-renewable energy resources and flows, and the non-renewable primary energy that is harvested per unit of system output over the full life cycle is referred to as non-renewable cumulative energy demand (nr-CED). Given the critical environmental issues posed by the depletion of non-renewable energy resources, and the strategic importance of achieving a larger degree of independence from them, in this paper we shall focus on the discussion of the nr-CED metric.

NEA then provides a valuable *alternative* viewpoint on the performance of an energy system (Carbajales-Dale et al., 2014). Its principal metric is the Energy Return on Investment (EROI), which measures the ratio of the energy delivered to society by the analysed system to the sum of energy inputs deliberately diverted from other societal uses and invested in the supply chain and all stages of the life of the system under study. Such energy investment (Inv) is usually accounted for in terms of cumulative primary energy. Instead, as discussed elsewhere (Raugei et al, 2016; Raugei and Leccisi, 2016; Leccisi et al, 2016), when calculating the EROI, the energy delivered by the system (i.e., the EROI numerator) may be expressed either in terms of direct energy carrier (EC) output:

(1) $EROI_{EC} = Out_{EC} / Inv$

or in terms of its *equivalent* primary energy:

(2) $EROI_{PE\text{-}eq} = Out_{PE\text{-}eq} / Inv$.

$Out_{PE\text{-}eq}$ itself may be calculated according to an LCA replacement logic, as the amount of primary energy that would be required on average to produce one unit of energy carrier using the average mix of technologies used in its supply chain. For the specific case of electricity (EC = el), this would be the mix of technologies that comprise the grid:

(3) $Out_{PE\text{-}eq} = Out_{el} / \eta_G$,

where η_G is the life-cycle energy efficiency of the grid mix.

From a methodological perspective, it is interesting to note that the simple 'rule' that the EROI of an energy supply chain must always by higher than 1 for it to act as an energy 'source' only strictly holds in the case of $EROI_{PE\text{-}eq}$, for which both the numerator and denominator are expressed in the same units of primary energy (Arvesen and Hertwich, 2015). In this work, however, in order to side-step the added complexity deriving from $EROI_{PE\text{-}eq}$ being a metric of performance that also depends on the efficiency of the grid mix as a whole, we shall mainly focus on discussing the 'straight' $EROI_{el}$ indicator results.

Also, for all the conventional thermal energy technologies, it is of paramount importance to differentiate between the EROI of the crude resource at point of extraction, that of the feedstock fuel refined and delivered, and finally the $EROI_{el}$ of the generated electricity. Unfortunately, examples of inconsistent 'apples and oranges' comparisons are found in the literature wherein, e.g., the EROIs of 'raw' fossil fuels at the well/mine mouth have been presented alongside with and compared to those of renewable technologies that directly deliver electricity (Hall and Day, 2009; Murphy and Hall, 2010). However, more recently, this important distinction has been the object of wider and wider acknowledgement and discussion (Hall et al., 2014; Murphy et al., 2016; Day et al., 2018).

In all cases, the functional unit (FU) of our analysis is 1 MJ of electricity delivered. From a practical standpoint, the analysis was carried out in a series of inter-linked spreadsheets, populated with statistical data for electricity generation in Chile (CNE, 2016, 2017b) and a wide range of background data on the energy investments taking place along the supply chains of all individual electricity generation technologies that comprise the SIC and SING grids. The main source for these background data was the reputable Ecoinvent database (Ecoinvent, 2016). Given the rapid pace at which the PV sector has evolved in recent years, and the centrality of this technology in the future energy scenarios for Chile, the aforementioned main data source was complemented and integrated by additional up-to-date inventory information on PV supply chains, the details of which are discussed elsewhere (Leccisi et al., 2016). Specific information on the commercial freight routes used for the transport of the imported fuels and of the imported wind turbines and PV modules was also sought and employed (Searates, 2017). No material or energy inputs were estimated indirectly by means of economic input-output tables (Leontief, 1985; Bullard et al., 1978) or otherwise converted from monetary units to physical units by means of ‘energy-to-money’ ratios.

Finally, when calculating the nr-CED and $EROI_{el}$ for the entire grid mix, the following equations apply:

(4) $$\text{nr-CED}_G = \Sigma_i (\omega_i \cdot \text{nr-CED}_i) + \text{nr-Inv}_{grid}$$

where nr-CED_i is the nr-CED of electricity generated by technology i, ω_i is the share of technology i in the grid mix, and nr-Inv_{grid} is the additional non-renewable primary energy investment for grid adaptation and energy storage.

(5) $$EROI_{el,G} = 1 / [\ \Sigma_i (\omega_i / EROI_{el,i}) + Inv_{grid}]$$

where $EROI_{el,i}$ is the $EROI_{el}$ of electricity generated by technology i, ω_i is the share of technology i in the grid mix, and Inv_{grid} is the additional (renewable + non-renewable) primary energy investment for grid adaptation and energy storage.

A schematic illustration of the overall methodological approach, identifying all the key energy flows taken into account, as well as a range of tables detailing all the model parameters and assumptions, are provided in the Supplementary Information, which is available at www.sciencedirect.com.

4. Results

4.1 Energy performance of the generation technologies comprising the SIC and SING grid mixes in 2017

EROI calculations for the coal, oil, natural gas and biomass supply chains as they apply to the electricity generation sector in the two main electric grids of Chile in 2017 are reported in Table 1. It is noteworthy that the average power plant conversion efficiency values (R) in Table 1 have been duly calculated as the technology-specific weighted averages based on the officially reported data on feedstock fuel consumption per unit of electricity generated for all the individual thermal power plants operating in the SIC and SING grids (CNE, 2017b). Therefore, while some of these values (specifically those for natural gas turbines) might be somewhat lower than expected, they are in fact truly representative of the current situation in Chile.

	Coal (supply mix)	**Oil (supply mix)**	**Natural gas (supply mix)**	**LNG**	**Biomass**
EROI (at source) **= Out_E / Inv_E**	**65**	**24**	**120**	**6.8**	**54**
EROI (delivered) **= Out_D / (Inv_E**	**20**	**17**	**65**	**6.1**	**32**

+ Inv_D)					
EROI (refined) **= Out_R / (Inv_E + Inv_D + Inv_R)**	**20**	**6.2**	**65**	**6.1**	**32**
R	0.34 (SIC) 0.29 (SING)	0.33 (SIC) 0.28 (SING)	N.A. (SIC) 0.45 (SING)	0.38 (SIC) N.A. (SING)	0.15 (SIC) N.A. (SING)
$EROI_{el}$ (electricity) **= (Out_R · R) / (Inv_E + Inv_D + Inv_R + Inv_{PP})**	**6.2 (SIC)** **5.4 (SING)**	**2.0 (SIC)** **1.7 (SING)**	**N.A. (SIC)** **28 (SING)**	**2.3 (SIC)** **N.A. (SING)**	**4.3 (SIC)** **N.A. (SIC)**

Table 1 – Energy investments per unit of energy carrier delivered, along the fuel supply chains that are used for electricity generation in the SIC and SING grids, and resulting EROI calculations.

Out_E = Energy output ('return') of the extraction process; Inv_E = Energy Investment for resource extraction (in the particular case of LNG, this includes liquefaction); Out_D = Energy of the delivered crude resource; Inv_D = Energy Investment for resource delivery; Out_R = Energy output ('return') of the refining process (i.e., the power plant feedstock); Inv_R = Energy Investment for resource refining/processing (i.e., conversion into power plant feedstock); R = power plant conversion efficiency ("heat rate"); Inv_{PP} = Energy Investment for power plant construction and maintenance. N.A. = not applicable.

We found the EROI of coal at source (i.e., at mining sites in the supplying countries) to be on average still quite high (~50-75), but that the subsequent energy investment for the transport of imported coal (which represents 70% of Chilean supply) takes a considerable toll, reducing the average EROI of coal feedstock to Chilean power plants to ~20. Interestingly, a similar drop in EROI values for coal along its supply chain (from 42 at mine mouth to 27 at local storage) has been reported in the recent literature for the case of Indonesia, in spite of comparatively shorter transport distances (Aguirre-Villegas et al., 2017). The low thermal efficiency of coal combustion (34% for SIC power plants and 29% for SING power plants) then further reduces the $EROI_{el}$ of coal-fired electricity to ~6.

Compared to coal, the EROI of crude oil at the well head (sourced from Brazil and the USA) was found to be lower to begin with (~24), and – most importantly – to be further significantly reduced to EROI ≈ 6 due to the energy investment required to operate the refinery and produce diesel oil, which is the feedstock used for electricity generation in Chile. It is important to note that in this case too, our findings are corroborated by the literature. A historical review of oil production and refining in California (Brandt, 2011) indicated that while the EROI of oil at point of extraction shrank from over 100 in 1955 to less than 10 in the mid-2000s, the EROI of oil refinery products was never higher than ~6, due to the comparatively large energy investments required at the refining stage (also, because the EROI-limiting step is actually oil refining, and not oil extraction, the historical trend of the EROI of refined Californian oil is also much flatter, having gone from ~6 in 1955 to ~4 in 2005). Once again, the thermal conversion efficiency at the power plant (33% for SIC power plants and 28% for SING power plants) then further reduces the $EROI_{el}$ of diesel-fired electricity in Chile to ~2. Clearly, from a Net Energy Analysis (NEA) perspective, *relying on petroleum-based fuels is not an effective option to supply electricity to Chile*.

As to natural gas, its EROI at source was generally found to be very high (~120). However, the gas is currently supplied to the SIC grid in liquefied form (LNG) (The Oxford Institute for Energy Studies, 2016). However, the EROI of liquefied natural gas (LNG) 'at source' is drastically lower than that of natural gas because of the large energy consumption in gas to liquid conversion and storage. The latter varies depending on the technology used (i.e., gas-fuelled reciprocating compressors, gas-fuelled centrifugal compressors, or electrical centrifugal compressors), and on the vintage/quality of the compressors used (NETL, 2016). Direct energy demand for conventional gas-fuelled reciprocating compressors is estimated by Ecoinvent (2016) at 5.77 MJ/Nm^3 (amount of "natural gas burned in gas motor, for storage" per Nm^3 of LNG). Another often quoted source quotes a gas consumption of approximately 8.8% of the liquefied gas volume, i.e.: 0.088*40.5 = 3.6 MJ/Nm^3 (Tamura et al., 2001). We used the arithmetic mean of these values for gas-fuelled compressors, assuming that it is be applicable to LNG imported to Chile from Trinidad and Tobago (79% of total imports), and we then calculated the total primary energy investment as 4.7 MJ/Nm^3 * 1.30 MJ_{PE}/MJ = 6.1 MJ_{PE}/Nm^3. For the remaining amount of LNG that is imported from Norway (a country endowed with plentiful hydroelectricity), we assumed that the most efficient electrically powered centrifugal compressors would be used; the corresponding energy burden was then estimated to be 2.9 MJ/kg = 3.7 MJ/Nm^3 (direct process energy consumption) (Franco and Casarosa, 2014) / 0.95 (efficiency of electrical compressor) * 1.07 MJ_{PE}/MJ (CED of hydroelectricity) = 4.2 MJ_{PE}/Nm^3. Thus, the resulting EROI of LNG is 40.5/[0.33+(0.79*6.1+0.21*4.2)] = 6.8 (where 40.5 MJ is the Higher Heating Value of 1 Nm^3 of natural gas, and 0.33 MJ is the initial energy investment for gas extraction). The subsequent transportation, re-gasification (NETL, 2016) and combustion in the SIC power plant (at a comparatively low heat ratio = 38%) then further reduce the $EROI_{el}$ of gas-fired electricity in this grid to 2.3. Therefore, while still useful as a readily dispatchable technology to balance supply and demand, *gas-fired electricity seems to contribute very little to the overall net energy gain of the SIC grid*, despite constituting almost 20% of the grid mix. Natural gas is instead supplied directly to the SING grid, via the “Gasoducto del Pacífico” pipeline from Argentina (CGE, 2017). This allows it to maintain an EROI ≈ 65 as a feedstock, and subsequently $EROI_{el}$ ≈ 28.

The $EROI_{el}$ of biomass electricity is heavily dependent on the specific type of biomass feedstock that is used, as well as on the associated supply chain. For instance, a previous investigation of the biomass fuel supply chain to the United Kingdom found that a supply mix heavily reliant on wood pellets, especially when the latter are imported from overseas, can result in an $EROI_{el}$ close to unity (Raugei and Leccisi, 2016). In Chile, however, it appears that a majority of the biomass used for electricity production comes from domestic forestry residues, in the form of woodchips, bark, and prunings. These are all relatively low-energy intensive to harvest and transport, and hence the EROI of the biomass feedstock supply to Chilean power plants is relatively high at 32. Due to a low average combustion efficiency of ~15% (CNE, 2017b), though, the final $EROI_{el}$ of biomass-fired electricity is about 4.

Contrary to the comparatively long supply chains that characterize thermal electricity generation technologies, hydro, wind and PV power systems directly harvest renewable energy resources and convert them to electricity in a single step (in other words, the only energy investment is that for the construction and maintenance of the power plants themselves), as discussed in Raugei and Leccisi (2016).

Our calculations have indicated that the $EROI_{el}$ of hydro electricity generation in the SIC grid is very high (~66), mainly due to the long-lived structures, which result in a very low level of energy investment per MJ of electricity generated. It should be noted that the CFs of dammed hydro have been negatively impaired by heavy droughts during the last 5 years, and that higher capacity factors and consequently even higher $EROI_{el}$ values for hydroelectricity may be realized in the future.

The $EROI_{el}$ of wind electricity (100% in land) was also found to be high (~19), which is helped by a relatively high capacity factor (28%). This is in line with previously reported values in the literature (Kubiszewski et al., 2010).

Finally, the $EROI_{el}$ of PV electricity generation was found to be approximately 10. This sits at the higher end of the range of previously reported values (Bhandari et al., 2015; Leccisi et al., 2016; Koppelaar, 2017), due to the exceptionally high irradiation levels in Chile.

Figure 6 summarizes the EROI results for all electricity generation technologies as currently deployed in Chile, with the analysis extending back along the respective feedstock fuel supply chains for the thermal technologies.

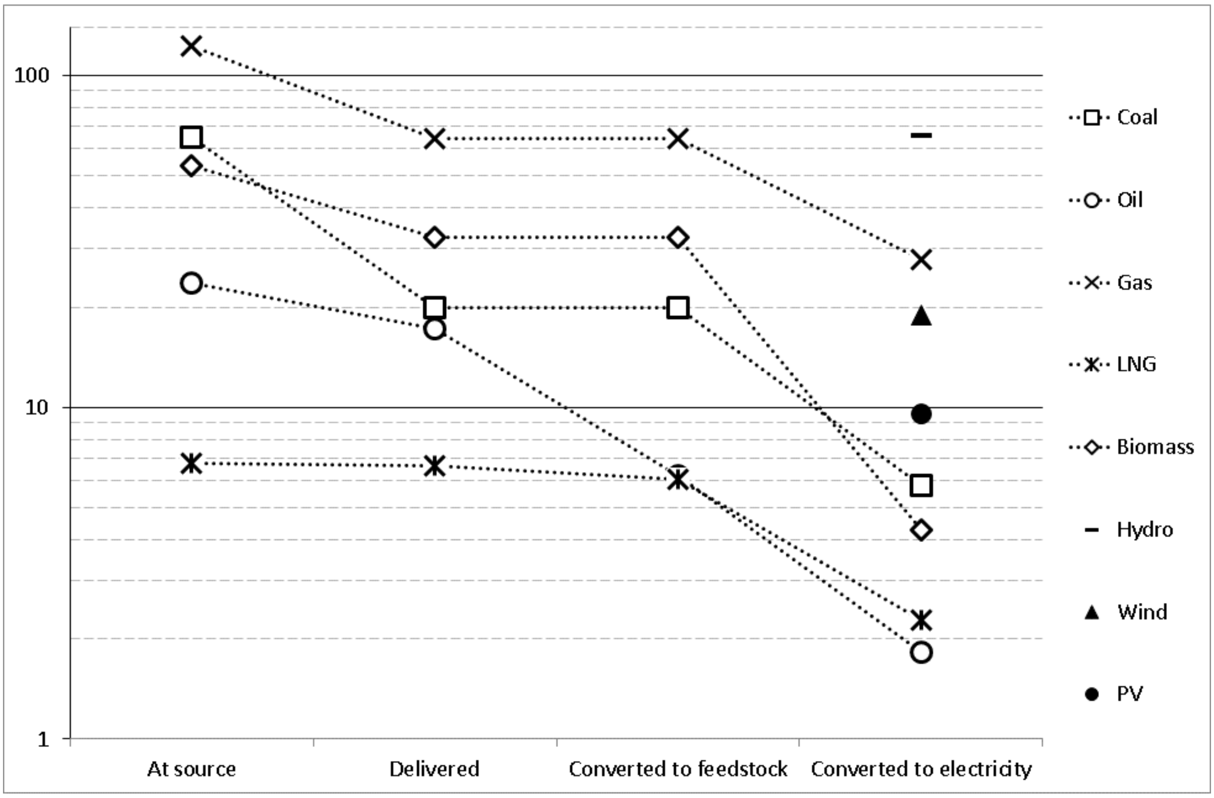

Figure 6 – EROI results for all the energy resources currently used for electricity production in Chile. For thermal technologies (coal, oil, gas, LNG and biomass), a range of EROI values are reported, corresponding to the feedstock supply chain steps indicated along the horizontal axis; for non-thermal renewable technologies (hydro, wind and PV), instead, there is no feedstock supply chain, and only the final electricity generation step applies. All EROI values are expressed as MJ of energy carrier output per MJ of primary energy investment.

Figure 7 then illustrates the nr-CED results (MJ of total non-renewable primary energy input per MJ of electricity output) of all the analysed electricity generation technologies as currently deployed in Chile.

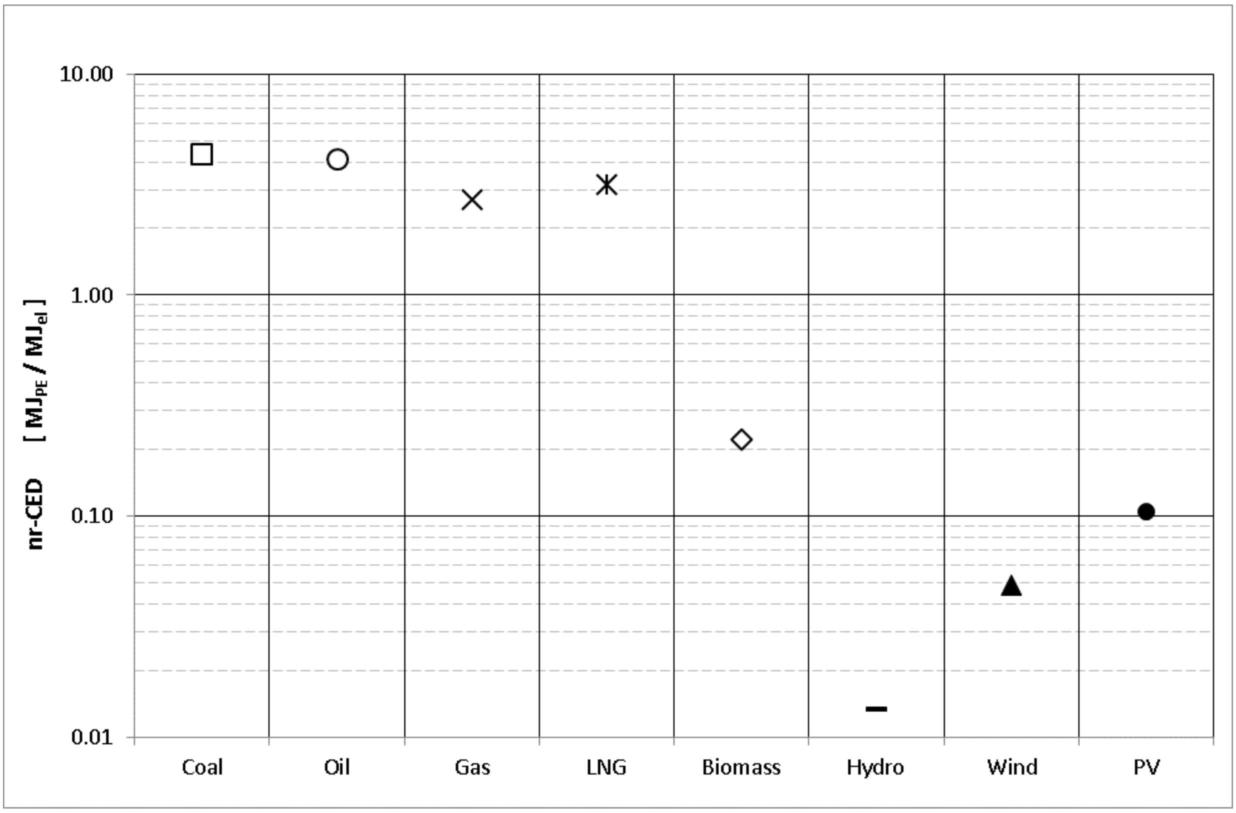

Figure 7 – nr-CED results for all the electricity generation technologies currently deployed in Chile, expressed as MJ of total non-renewable primary energy input per MJ of electricity output.

As expected, the performance of coal-, oil- and natural gas-fired electricity is broadly similar in terms of their cumulative demand for non-renewable energy, the latter being largely determined by the actual energy content of the feedstock fuels and the respective power plant thermal conversion efficiencies. As a result, roughly 2.5 – 4.5 units on non-renewable primary energy are required per unit of electricity delivered (with gas at the lower end of the scale, and coal at the higher end). It is also noteworthy that these nr-CED results for coal-, oil- and natural gas-fired power plants are broadly in line with those reported in previously published work (Raugei and Leccisi, 2016).

Biomass-fired electricity fares much better, with an order-of-magnitude reduction in the demand for non-renewable energy per unit of electricity delivered over its full life cycle. It is noteworthy, though, that biomass energy performance is still significantly worse than that of the non-thermal renewable technologies (hydro, wind, and PV), because of the comparatively larger use of fossil fuels in the biomass feedstock supply chain.

Hydro electricity generation is once again the best-performing technology, with a further order of magnitude improvement (nr-CED < 0.02 $MJ_{nr\text{-}PE}/MJ_{el}$).

Finally, both wind and PV electricity present very low non-renewable cumulative energy demand per unit of electricity in absolute terms (< 0.1 $MJ_{nr\text{-}PE}/MJ_{el}$); this performance is achieved in part thanks to the optimal environmental conditions that are present in Chile (wind and irradiation), resulting in the currently favourable CFs for these technologies. However, energy storage and curtailment may reduce these CFs in scenarios of large-scale deployment of these technologies. The extent to which this can be expected to affect the future performance of the SIC and SING grids is investigated in the following section.

4.2 Comparison of overall performance of SIC and SING grid mixes in 2017, and prospective analysis for SEN grid mix to 2035.

Figures 8 and 9 illustrate the aggregated results of our analysis of the SIC and SING grid mixes in 2017, as well as the range spanned by the sensitivity analysis performed on our future projections for the SEN grid to the year 2035, respectively in terms of $EROI_{el,G}$ and nr-CED_G.

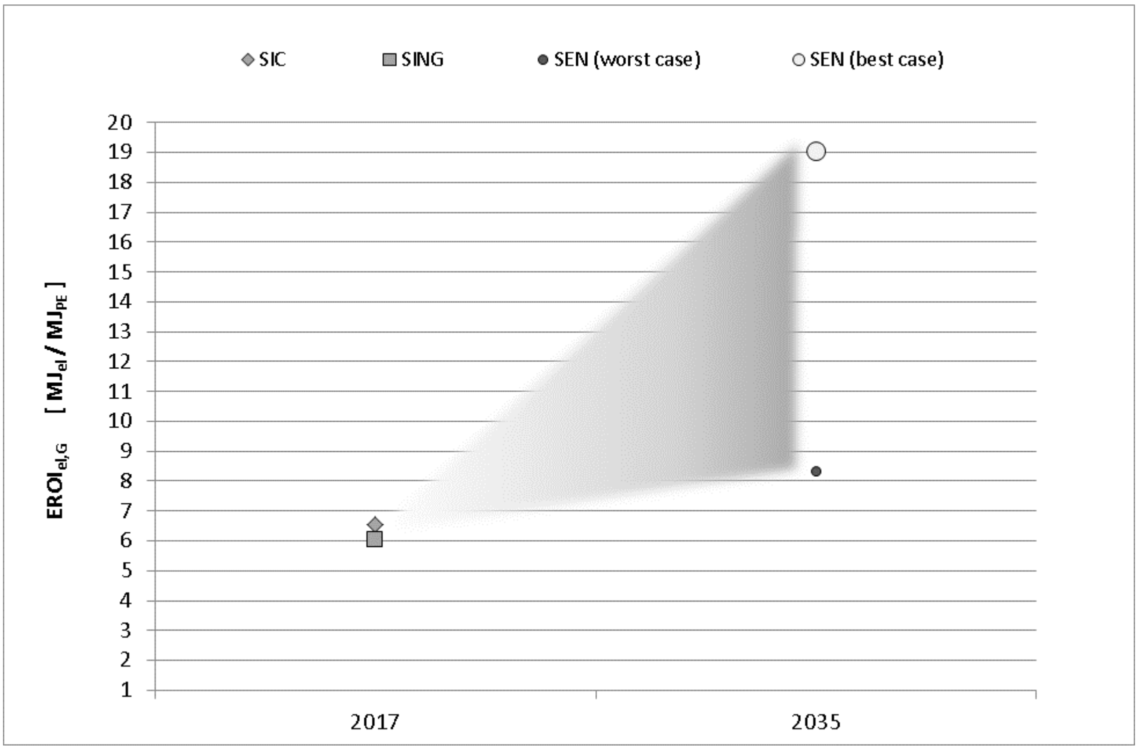

Figure 8 – $EROI_{el,G}$ of SIC and SING grid mixes in 2017, and future projections for the SEN grid to 2035 (with sensitivity analysis - best and worst case scenarios are highlighted).

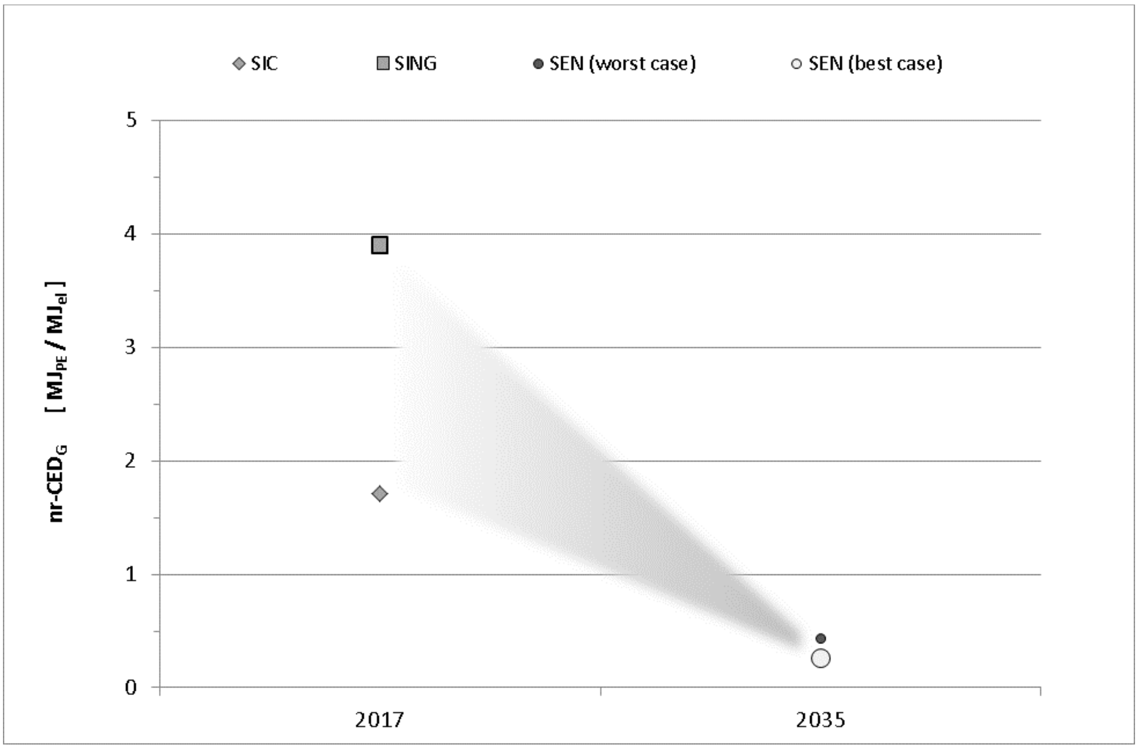

Figure 9 – nr-CED_G of SIC and SING grid mixes in 2017, and future projections for the SEN grid to 2035 (with sensitivity analysis - best and worst case scenarios are highlighted).

Firstly, looking at the results for 2017, the overall net energy performance of the SIC grid is found to be better than that of the SING grid; this is in part due to the large share of hydroelectricity ($EROI_{el}$ = 66) in the former. The nr-CED results point to an even greater disparity, with the SING grid mix being significantly less sustainable than the SIC mix, because ~90% of its electricity generation is powered by coal and gas. In contrast, the SING includes an almost 50% contribution from renewables (hydro, biomass, wind and PV).

Moving on to the results of the analysis of the 2035 scenarios , we can see a marked improvement in *both* indicators as applied to the integrated SEN grid.

Our results indicate that the overall $EROI_{el,G}$ of electricity generation in Chile may be expected to increase from approximately 6 at present to –8 - 19. The uncertainty about PV technological development and PV and wind curtailment and storage lead to this range of possible $EROI_{el,G}$ values. Additionally, part of the variability in the future estimates depends on the uncertainty about to the amounts of LNG imports and CCGT power plant efficiencies.

This essentially means that in the future, the energy investment required to sustain electricity production in Chile could be up to 66% smaller, and therefore that more of the produced electricity will be available as a 'net' contribution to the economy. At the same time, by 2035 the electricity produced in Chile may be expected to be –up to 85% less reliant on non-renewable energy sources.

In all cases, the large-scale deployment of wind and PV capacities plays a key role in bringing about these improvements, with the "Best" cases significantly aided by a potential restoration of the direct import route of natural gas by pipeline from Argentina.

It is also interesting to note that the relative robustness of these results with respect to the sensitivity analysis seem to indicate that, at least in Chile, the expected additional energy investments for grid adaptation and energy storage should not significantly hold back the overall energy performance of the grid mixes. In fact, in the specific case of the nr-CED indicator, the results are essentially dominated by the phasing out of coal, and the assumed percentages of wind and PV storage and curtailment do not appear to significantly affect the grid mix results.

Overall, this points to a potential win-win prospect for the evolution for the Chilean electricity grids, both in terms of net energy availability and of long-term independence from non-renewable primary resources.

5. Conclusions and Policy Recommendations

This work has shed light on what may be expected from the range of available electricity generation technologies in Chile, in terms of their contribution to the overall supply of net energy by the country's electricity grids, and the latter's reliance on non-renewable primary energy. Specifically, our study began with an analysis of the energy performance of the former two main electric grids in Chile, and then moved on to potential scenarios for the future of the newly integrated national grid, in which large amounts of renewable electricity is assumed to be deployed over the next two decades (up to 40% PV and 20% wind), in accordance with the Chilean government's targets.

Among the renewable options, PV and wind electricity generation are penalized by being inherently intermittent, and deploying large capacities of either technology may only be achievable if suitable power transmission and/or energy storage is made available, and/or if relatively high curtailment factors can be sustained. However, our analysis has shown that neither of these conditions is likely to significantly reduce the fundamental energy performance improvements that would ensue by relying on these two technologies to bring about the planned transition to 60% renewable electricity in Chile. In particular, when properly discounted over their long lifetimes, the additional energy investments required for new dams (for pumped hydro storage) and high-voltage transmission lines end up only marginally affecting the EROI and nr-CED of each unit of electricity supplied by the grid. Electricity curtailment is a more consequential factor, but improving EROI and nr-CED trends are maintained even in the relatively pessimistic projections in which 30% of potential wind and PV output must be prevented from contributing to the grid in order to ensure its stability. Consequently, aiming to rapidly ramp up wind and PV deployment in Chile appears to be a sound policy measure in order to meet the government's 2035 renewable electricity target. Hydro power plants are also expected to continue to play an important role, both as direct suppliers of renewable electricity and in terms of pumped hydro storage; however, the extent to which new large hydro facilities may be built remains uncertain, also due to public acceptance issues. As for biomass, while fuels sourced locally from forestry residues appear to be viable thermal resources in Chile, the subsequent $EROI_{el}$ of biomass-fired electricity is negatively affected by their low thermal conversion efficiency at the power plant.

When analysing the non-renewable options, it was realised that the potentially good net energy performance of gas-fired electricity is largely dependent on the condition that the gas be supplied by short-distance pipelines, and not imported in the form of LNG as is largely the case at present. Whether, or the extent to which, the current political barriers in the Argentina-Chile gas market may be overcome in the near future remains to be ascertained, and on this crucial political issue appears to rest the future net energy viability of gas-fired electricity in Chile as a readily dispatchable option. The coal and oil supply chains appear to be intrinsically constrained in terms of the achievable $EROI_{el}$, because of (i) the inevitable investments required to transport and refine the feedstock fuels, and (ii) the thermodynamic limits imposed on the fuel-to-electricity conversion efficiency. As such, phasing out coal (which at present is still the principal energy source for electricity production in Chile) appears to be a recommendable policy option, not only from the point of view of reducing carbon emissions, but also in order to improve the overall net energy performance of the electricity grid.

Overall, this analysis has confirmed that, when considering the impending policy decisions that will be required to guide Chile on a path to curb its greenhouse gas emissions and reduce its dependency on foreign non-renewable energy resources, replacing coal power plants with more PV and wind capacities, coupled with the provision of suitable pumped-hydro energy storage, appears to be the most promising energy policy strategy.

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