Smart Energy Approaches for Carbon Abatement

Scenario Designs for Chile's Energy Transition

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Smart energy approaches for carbon abatement: Scenario designs for Chile's energy transition

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ABSTRACT

This study develops scenarios aiming to transition the Chilean energy system in 2050 to 100% renewable energy; taking into account local resource potentials, demands, cross-sectoral integration of the electricity, heating, transport, and industrial sectors, and synergies in their related infrastructures. The energy system model EnergyPLAN is used to simulate the hourly operation of the energy system. The relationship between potential CO_2 emissions reductions and relative costs is estimated using marginal abatement cost curves with the EPLANoptMAC tool to assess the optimal sequence of capacity expansion and carbon abatement alternatives. The analysis demonstrates that it is possible to carry out this transition from a technical perspective more efficiently than what is proposed with current national scenarios while still aligning with climate neutrality targets; and that, in different phases of the Chilean energy transition, specific options could be prioritized based on an improved balance between carbon abatement and costs.

1. Introduction

Countries worldwide are shifting towards clean and sustainable energy sources as part of a green energy transition. In Chile, this shift is of particular importance due to the country's issues with air pollution resulting from the inefficient combustion of fuels in the heating sector [1,2], and historical dependence on fossil fuel consumption which has led to issues in the past securing natural gas and is more exarbated by the current energy crisis affecting worldwide fuel supply. Chile's energy system is currently supplied with large shares of fossil fuels, making up around 67% of the primary energy supply (PES) in 2019 [3]. In response, Chile's government continues to develop long-term plans to tackle both air pollution decontamination [4] and the decarbonization of the energy system with secure energy supply sources [5,6], as well as specific climate actions which consider diversified technology alternatives like district heating (DH), cogeneration through combined heat and power (CHP), and further integration of renewable energy [7–9].

The country's legally established process of long-term energy planning (*Planificación Energética de Largo Plazo* - PELP) outlines potential scenarios corresponding to different expected energy demands and technology developments across end-use sectors. The current PELP scenarios include the adoption of different technologies, policy measures, technology costs, and fuel price developments to illustrate potential carbon neutrality pathways [10]. Yet, key enabling technologies and infrastructures are not fully represented in such national scenarios. Technologies such as district heating and Power-to-X (PtX) pathways for electrofuel production could prove essential in the transition towards a decarbonized energy system [11–13], as well as enabling sector coupling and integrating variable renewable energy sources (VRES) as secure and locally available energy sources [14,15]. Thus, it is imperative to consider these options for the future of Chile's energy system.

In the context of Chile, past studies have assessed the potential of increasing the share of VRES in the energy system and accomplishing emission reductions through disaggregated optimization [16–18] or with integrated assessment models [19], but focused exclusively on the electricity sector. Similarly [20–22], have focused on assessing specific renewable potentials and developments rather than taking a broader system perspective. More recent studies have actively considered system

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and cross-sectoral integration. Paardekooper et al. [23] developed national scenarios using a cross-sectoral modelling approach that considers the impacts of coupling the electricity and heating sectors, excess industrial heat, and utilizing CHP and DH as potential solutions to the issues mentioned above with a particular focus on the impacts of heating scenarios to reduce particulate matter emissions. Osorio-Aravena et al. [24,25] go beyond, analyzing 100% renewable energy scenarios for the power, heat, transport, and desalination sectors. However, the scenarios reviewed are not necessarily aligned with standard practices and tools used in Chile's nationally determined contributions (NDCs) plans [26] and most current energy planning process [10], including the use of marginal abatement cost (MAC) curves as means to show decarbonization priorities with explicit technological detail and system effects.

MAC curves in climate and energy policy are widespread, serving as tools to easily visualize the costs per unit of emission reductions for varying amounts of emission abatement and measures [27,28]. However, the application of MAC curves can have shortcomings in representing individual measures' costs and abatement potentials without a holistic system view, as is the case in Chile [26,29]. Likewise, when applied with energy system models, MAC curves will be limited and contextualized to the modeling tool's specific configuration and system resolution [30]. Studies have used MAC curve approaches to assess CO_2 abatement in the power and heating sectors [31–34], transport [35–37], industry [38], and all sectors representing the energy system as time-slices [39–41]. However, bottom-up representations of the energy system with an hourly resolution including all sectors can provide a more systematic and representative view of abatement potentials in the transition towards highly renewable energy systems [42]. While model-based MAC curves have been used in sector coupling scenarios [43], no prior application of these has been found outside of a European context or to identify CO_2 reduction measures while incorporating a Smart Energy Systems approach with cross-sectoral synergies going beyond electrification by including the integration of key infrastructure across the different sectors.

In this paper, we put forth alternative decarbonization scenarios for Chile's energy transition based on the Smart Energy Systems concept, which focuses on the integration of the whole energy system by including all sectors – with their synergies and related infrastructures –to find suitable energy efficient and cost-effective solutions to reach a low carbon energy system [15]. Here, this is formulated via a set of design principles and steps modelled as scenarios by simulating the energy system. Subsequently, this approach is complemented by designing optimized abatement scenarios yielding a MAC curve, which – in turn – can graphically showcase the priority of the different measures relative to their cost-effectiveness and potential for CO_2 abatement, considering a system perspective.

In this way, the scenarios can be better assessed in line with Chile's current national determined contribution (NDC) targets and long-term energy planning process, presenting the different measures under a transparent and easy-to-visualize framework that can support policymakers in designing energy transition strategies and supportive policies towards an alternative decarbonized future energy system. In addition, the application of the methodology presented in this paper illustrates how coupling modelling approaches can provide both different yet complementary perspectives to addressing a national energy transition more comprehensively than with a single-model approach, while at the same time offering a comparison of the results of both modelling approaches. Although practical comparisons of optimization and simulation approaches for local decarbonization scenarios have been assessed previously in the literature [44], an additional novelty of this study is providing a comparison of results obtained with model-based MAC curve optimization approaches on a national level with expert-based scenario simulations to assess decarbonization alternatives.

2. Methods and research design

This section describes the methods and assumptions used in the analysis. First, the energy system analysis and models' descriptions are presented. Then, the principles behind the initial scenario development are outlined. An overview of the data used across the modelled scenarios is also included, with additional details included as supplementary material in the Appendix.

2.1. Energy system modelling with EnergyPLAN

The scenarios presented in this study are formulated with the energy system modelling tool EnergyPLAN [45], which is a widely validated and used tool to simulate and analyze the operation of national energy systems, including the electricity, heating, transport, and industry sectors [46]. It simulates the operation of the entire energy system for a given target year, balancing hourly the supply and demands, including the system's imports and exports of electricity. Scenario inputs include annual energy demands, aggregated capacities of conversion units and plants, and hourly time series for variable renewable energy production and electricity and heating demands. In addition, EnergyPLAN also includes investment and operation costs, fuel prices, CO_2 prices, and different emission factors [45,47]. Moreover, the tool can serve as a core calculation engine for simulation-based optimization models and has been coupled with several other optimization algorithms and energy system models [48].

In the present study, the Chilean energy system is modelled in EnergyPLAN, considering different scenarios for carbon abatement. These scenarios include the scenarios from Chile's long-term energy planning process and newly formulated scenarios applying a Smart Energy Systems approach to reach a 100% renewable energy system [15]. Furthermore, EnergyPLAN is used to develop the MAC curves in conjunction with an optimization algorithm, in order to identify alternative abatement priorities, as explained in the following section.

2.2. Model-based marginal abatement cost curves with EPLANoptMAC

The MAC curve optimization model presented by Prina et al. [49], EPLANoptMAC, is applied to the case of Chile. This model couples the energy system simulation tool EnergyPLAN – as the core calculation engine – with a single-objective hill-climbing optimization algorithm to sequentially simulate energy system scenarios with incremental values of different decision variables, and minimize abatement costs at each incremental step. These decision variables represent various abatement measures, such as the capacity expansion of renewable supply technologies, fuel replacements, and changes in energy demands.

The EPLANoptMAC model is configured with inputs for a reference energy system scenario, the set of measures as decision variables to be assessed with their respective incremental values, and the number of steps to evaluate these measures. The incremental changes to the decision variables are then fed as inputs to EnergyPLAN to generate scenarios. Subsequently, the outputs produced are evaluated across the competing scenarios, finding the scenario with the decision variable yielding the minimum cost of carbon abatement (CCA). This is defined in Equation (1) as the ratio between the difference in total system costs of the new resulting scenario and a reference case and the potential emission reductions.

$$CCA_i[MUSD\ /\ ton\ CO_2] = \frac{Cost_i - Cost_{ref}}{Emissions_{ref} - Emissions_i} \tag{1}$$

The measure with the lowest CCA is selected as the new reference in the next step of the iteration. After this, the procedure repeats, modifying the new reference scenario with incremental changes to the decision variables. Finally, the algorithm stops when CO_2 abatement is no longer possible for the given decision variables in case these have reached their maximum end-value or fail to converge or when the predefined number of steps is reached [49].

In addition to the steps outlined originally in Ref. [49], a new constraint has been included to the algorithm to limit at each step the amount of biomass to a maximum of 130 TWh. This is done to ensure that each incremental scenario considers some technical and sustainability limitations of the system. The algorithm has been updated to consider additional effects of sector coupling in decision variables with dependent parameters such as the associated infrastructure costs and supply options when considering incremental shares of district heating to replace individual boilers, and fuel replacements when implementing biofuel and electrofuel productions. Moreover, the original algorithm presented in Ref. [49] and developed in Python has been ported to run with the Julia programming language [50], and to perform the EnergyPLAN runs in batches (i.e., Spool mode) at each step rather than running each individual change in decision variable one-by-one with new instances of EnergyPLAN. These updates significantly increase the algorithm's performance, bringing down computational time.

2.3. Overview of modelling inputs and assumptions

The data inputs for modelling the energy system scenarios are obtained from Chile's national energy databases and previous studies, as outlined in Table 1. These inputs include the reference demand projections and installed capacities for power generation and renewable electricity generation potentials [10]. In addition, estimates related to district heating were obtained from the Heat Roadmap Chile project [23,51] including estimates for demand profiles, district heating potentials, losses and costs, and excess heat potentials. These estimates complement the heat demand estimated by carrier from the PELP's demand projections [10]. Furthermore, hourly profiles for electricity demand and VRES production were obtained from the national energy coordination agency [52], as were the estimated energy accounts for hydropower and storage [53]. Finally, cost assumptions and fuel prices were obtained from the national energy coordination agency when available [54] and supplemented with data from the Danish Energy Agency's (DEA) technology catalogues, which present comprehensive descriptions of investment costs and data for energy conversion technologies [55–59].

2.4. Scenario framework

2.4.1. Replication of Chile's long-term energy planning PELP scenarios

In the current PELP, three different scenarios are presented: (i) a scenario following "*current trends*" considering a conservative post-pandemic economic recovery and slow uptake of renewable energy capacities and energy efficient technologies; (ii) a "*carbon neutrality*" scenario with middle-of-the-road trends; and (iii) an "*accelerated transition*" scenario which also depicts a carbon neutral case but, happening earlier in time due to rapid economic growth and fast development of new technologies and ambitious implementation of energy efficiency measures [10].

These scenarios illustrate potential pathways for Chile's energy system towards 2050. While the scenarios above depict potential low-carbon futures of Chile's energy system, they do not fully showcase a fossil-free, 100% renewable energy system, but rather allow for some remaining shares of fossil fuels and their respective emissions. These scenarios consider offsetting the remaining emissions with forests acting as carbon sinks. Moreover, the modelling behind these scenario results does not explicitly consider key enabling technologies for sector coupling, fuel replacements with different PtX other than hydrogen, nor an hourly resolution over a full year, which is beneficial to adequately capture the fluctuations across the different end-use demands across all sectors and the different energy supply sources [61].

Therefore, to initialize a comparison benchmark, these scenarios have been replicated and adjusted in EnergyPLAN. The input assumptions mentioned in Section 2.3 are applied, with adjustments made to power plant capacities in cases where the originally assumed capacities from PELP become insufficient to cover the system's hourly energy demands. The comparison of these scenarios with the ones generated for this study are presented in Section 3.3. The underlying data assumptions for these scenarios is available in the supplementary materials.

Table 1
Data sources for modelling scenarios.

Data	Source
Installed power capacity	PELP [10]
Renewable electricity potentials	PELP [10,60]
District heat potentials, excess heat supply & DH infrastructure costs and losses	PELP [10] & Paardekooper et al. [23,51]
Hourly distributions and productions from VRES, and energy demands	PELP [10], CNE [52,53], Paardekooper et al. [23,51]
Technology costs and fuel prices	CNE [54], DEA [55–59]

2.4.2. Design principles to develop a Smart Energy System scenario for Chile

This study aims to explore alternative decarbonization scenarios to those present in Chile's national energy planning process. Namely, including a system redesign that allows for a 100% renewable energy and clean supply through energy efficiency, flexibility, and coupling of the different sectors and their infrastructures. This process is conceptualized via a series of steps and guiding principles following a Smart Energy Systems approach [15], similar to those outlined in past studies under different contexts [62–67] but adapted to fit the case of the Chile energy system, where at each step not only new technology and fuel replacements occur, but also more VRES capacity is introduced. These steps also consider that new energy technologies are commercially available by 2050. The steps and principles considered can be formulated as follows.

1) **Identifying a "Reference" scenario**: This scenario is designed as a benchmark for comparison, which replicates capacities and projected energy demands for 2050 from Chile's PELP scenarios. Namely, it includes the estimated power generation capacities, space heating, and industrial demands from the PELP's "*current trends*" scenario while also including the developments from the "*carbon neutrality*" scenarios in both electricity demands and in the implementation of energy efficiency measures in transport [6], and hydrogen fuel replacements expected from Chile's hydrogen strategy [68]. The latter already includes measures such as the partial electrification of road transport and industry, heat savings, and fuel replacements with direct hydrogen use. Moreover, it includes the phase-out of coal in the electricity generation sector and a high carbon tax (70 USD pr. Mton) as defined in the PELP. Therefore, these measures will be embedded in the subsequent scenarios.
2) **Implementing diverse heating supply options including individual heating and district heating**: Building up from the previous steps, a redesign of the heating system is undertaken. This step entails expanding the share of the heating supply covered by district heating and upgrading to efficient individual heating solutions by electrifying the individual heat supply with heat pumps. The addition of district heating comes in hand with implementing a diversified supply, including combined heat and power (CHP) plants, large-scale heat pumps (LSHPs), heat recovery from industrial processes, and renewable heat sources such as solar thermal and geothermal. The excess heat supply also enables an additional level of cross-sectoral integration when considering the prospect of new fuel production technologies such as hydrogen and electrofuels. The Heat Roadmap Chile study results are consider to design adequate levels of district heating [23,51].
3) **Fossil fuel replacements in transport with biofuels and ammonia**: From the reference scenario, a significant share of the transport demands is not electrified or replaced with hydrogen. Therefore, this step examines some initial fuel replacements with

biofuels and e-fuels from biomass hydrogenation across all transport demands and the use of ammonia for maritime fuel demands as abatement measures, as suggested in past studies [67,69]. In turn, this transformation requires the expansion of electrolyzer capacity, air separation units, hydrogenation plants, and electrofuel synthesis. Applying these technologies increases the expected electricity demand; thus, additional renewable capacity will be installed at this step. Moreover, these conversion processes and plants will yield reusable amounts of excess heat, contributing to the district heating supply and adding an extra degree of flexibility to the overall system.

4) **Fossil fuel replacements in industry with biogas**: This step in the transition consists in converting industry and mining demands from natural gas demands to biogas and synthetic gas. In turn, this transformation requires the increase of biomass gasification capacity, with its respective electricity demand. In addition, coal consumption in this sector is replaced with biomass.
5) **Replacement of remaining fossil fuels with CO_2-based electrofuels**: The final step considers replacing the last remaining fossil fuel consumption in the transport fleet with electrofuels derived from CO_2. Converting the remaining liquid fuel demand requires new carbon capture and utilization (CCU) and expanding the technologies introduced in Step 3.
6) **Smart Energy Chile (SECL) scenario**: The last step considers the cumulative decarbonization developments in the energy system, and includes an additional biogas consumption as a final fuel replacement in the gas grid to the remaining fossil fuel demands corresponding to natural gas. This final adjustment in the modelled scenario starts yields a 100% renewable energy system. Although this scenario presents an overall increase in biomass consumption relative to the reference, it stays below the current consumption levels today, thereby ensuring a sustainable consumption level.

At each step, more VRES capacity can be incorporated into the system (while staying within their available technical potentials), namely additional capacities of solar photovoltaics (PV), onshore wind, and concentrated solar power (CSP). These steps, summarized in Fig. 1, do not necessarily represent a sequential transition in terms of the priorities to implement change. However, for ease in the modelling, these are applied in bulk sequence, thereby facilitating the analysis of the different technologies' roles in the country's decarbonization goals and the comparison with current national scenario development.

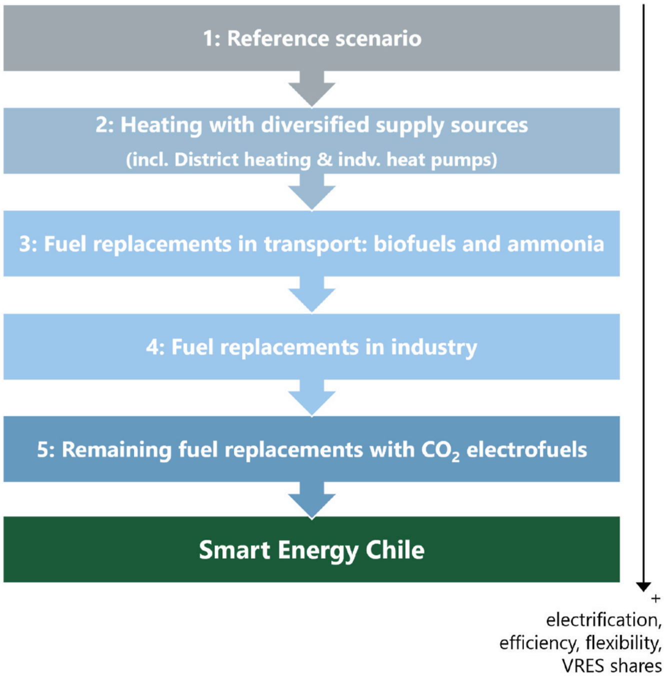

Fig. 1. Depiction of steps leading toward a Smart Energy Chile scenario.

2.4.3. Identification of abatement priorities and capacity expansion

To provide a complementary perspective of the different abatement priorities, the steps described in the previous section are contrasted with sequential scenarios generated via the MAC curve optimization from EPLANoptMAC. In this way, the individual measures embedded in the bulk of each Smart Energy step can be discretized to show an optimal decarbonization pathway based on the minimum cost of carbon abatement.

These measures translate to new decision variables in the EPLANoptMAC model. Meanwhile, the starting point considers the "*Reference scenario*" described in Step 1 in the previous section, and the end-values take the capacities and fuel substitutions from the "*Smart Energy Chile*" scenario.

3. Results and discussion

Here, the results of the different analyses are presented. First, key operational indicators are showcased for the Smart Energy Chile scenario steps, and the MAC-curve generated results. These include primary energy mix, CO_2 emissions, electricity supply, demands, and curtailment. Then, these results are compared to the PELP scenarios, including their total system costs.

3.1. Towards a smart energy Chile scenarios

Based on the scenario design principles and assumptions mentioned in Section 2.4., a series of scenario steps were developed, leading toward a Smart Energy Chile scenario. These steps – shown in Fig. 2– lead toward a 100% renewable and decarbonized energy system.

In the reference scenario, some consensus non-controversial actions are already in place; for example, coal phase-out for power production, electrification of private and public road transport, and energy efficiency measures in buildings.

In the second step, the implementation of district heating solutions and electrification of the heating sector similar to those proposed in Refs. [23,50] are introduced and curb biomass and fossil fuel consumption. This is largely facilitated by integrating VRES – already present in the system – into the heat supply through both individual and large-scale heat pumps and moving away from individual fossil-based fuel boilers. Furthermore, coupling this electrified heat supply with district heating infrastructure enables the possibility of using thermal storages; thereby providing additional system flexibility. At the same time, the district heating infrastructure introduced in this step allows for the diversification of heat supply options, with the integration of otherwise wasted excess heat from both power production (combined heat and power – CHP –plants) and industry.

In step three, the production of alternative fuels for transport adds a modest increase in biomass consumption as well as new electricity demands. This is mostly driven by one-to-one substitutions of oil fuels with biomass-derived fuels and ammonia, which is also introduced to cover maritime demands, along with related electrolyzer and air separation capacities. Correspondingly, new VRES capacities have to be introduced. Due to the additional capacities and fluctuating supply, the amount of curtailment will also increase. Meanwhile, the introduction of these new fuel production processes also acts as new heat supply options since these produce large amounts of recoverable heat as a by-product, which can be integrated into the district heating supply. Overall, the changes introduced in this step lead to a considerable reduction in carbon emissions: more than half relative to the reference.

Following this, step four sees a larger increase in biomass consumption compared to previous steps, mostly due to the replacement of natural gas with gasified biomass, as well as a modest increase in

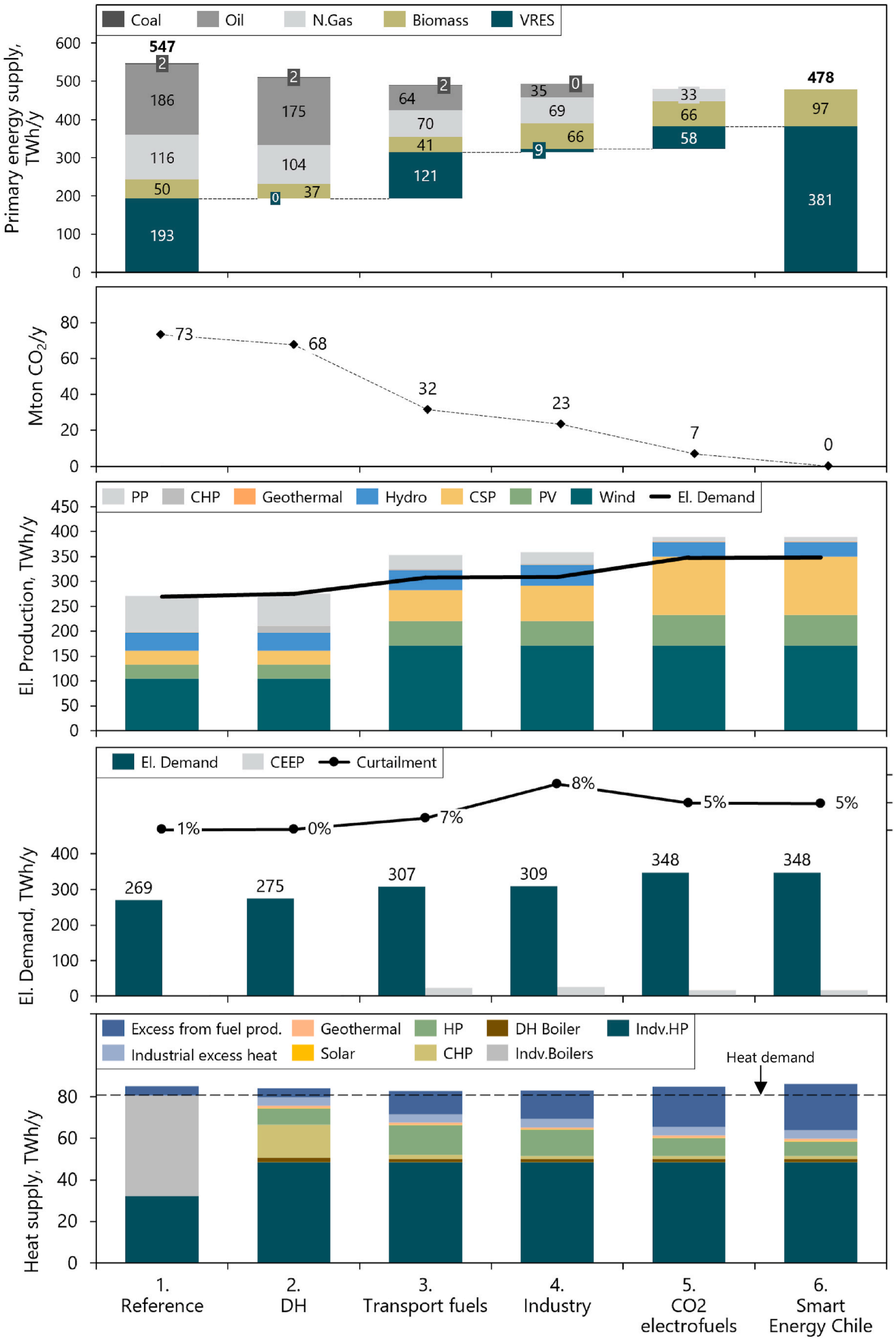

Fig. 2. Overview of steps towards a Smart Energy Chile scenario in primary energy supply, total electricity demand, and curtailment throughout the different CO$_2$ marginal abatement steps.

electricity demand. Meanwhile, step five sees a more substantial change in the primary energy supply mix, with the substitution of the remaining fossil fuels in the transport sector with e-fuels from CO_2 hydrogenation. Similar to previous steps, this requires new buildup of hydrogen production and VRES and new carbon capture capacity. Despite the increase in electricity production, the increase in demand and flexibility from the technologies introduced in this step translate to relatively lower curtailment levels than in the previous two steps. Moreover, the fuel production processes also further the supply of recoverable excess heat. In all, this step also significantly reduces CO_2 emissions, with only about 10% of emissions compared to the reference.

Finally, in the last step – constituting the Smart Energy Chile scenario – a full transition is undertaken in which all the remaining fuels for heat and power production are replaced with green fuels. More specifically, the remaining natural gas consumption is replaced by gasified biomass and biogas. This final step sees a primary energy supply shares of about 80% and 20% for VRES and biomass, respectively. This represents almost a twofold increase in the VRES supply compared to the reference scenario, while the quantity of primary biomass supply remains comparably less than today, amounting to an approximated consumption of 17 GJ per capita. As a result, this final step presents a fully decarbonized fossil-free energy system scenario.

3.2. Marginal abatement costs curves

To generate the MAC curves, the set of decarbonization measures leading to the Smart Energy Chile scenarios has to be considered in a separate manner, discretizing them into incremental deployment steps. These steps are applied in EPLANoptMAC, resulting in the optimized MAC curve presented in Figs. 3 and 4.

As illustrated in Fig. 3, the expansion of PV and onshore wind capacity takes a prominent role early on in Chile's energy system decarbonization, as it provides a cost-effective and carbon-free supply of electricity. At an intermediate stage of decarbonization, some fuel replacements can already be realized by introducing biofuels in the transport sector and considering some related and required infrastructures like hydrogen electrolyzers.

At around this intermediate stage of the transition, the sequence of abatement measures can already reach the nationally determined carbon abatement emission target for 2050, which equates to CO_2

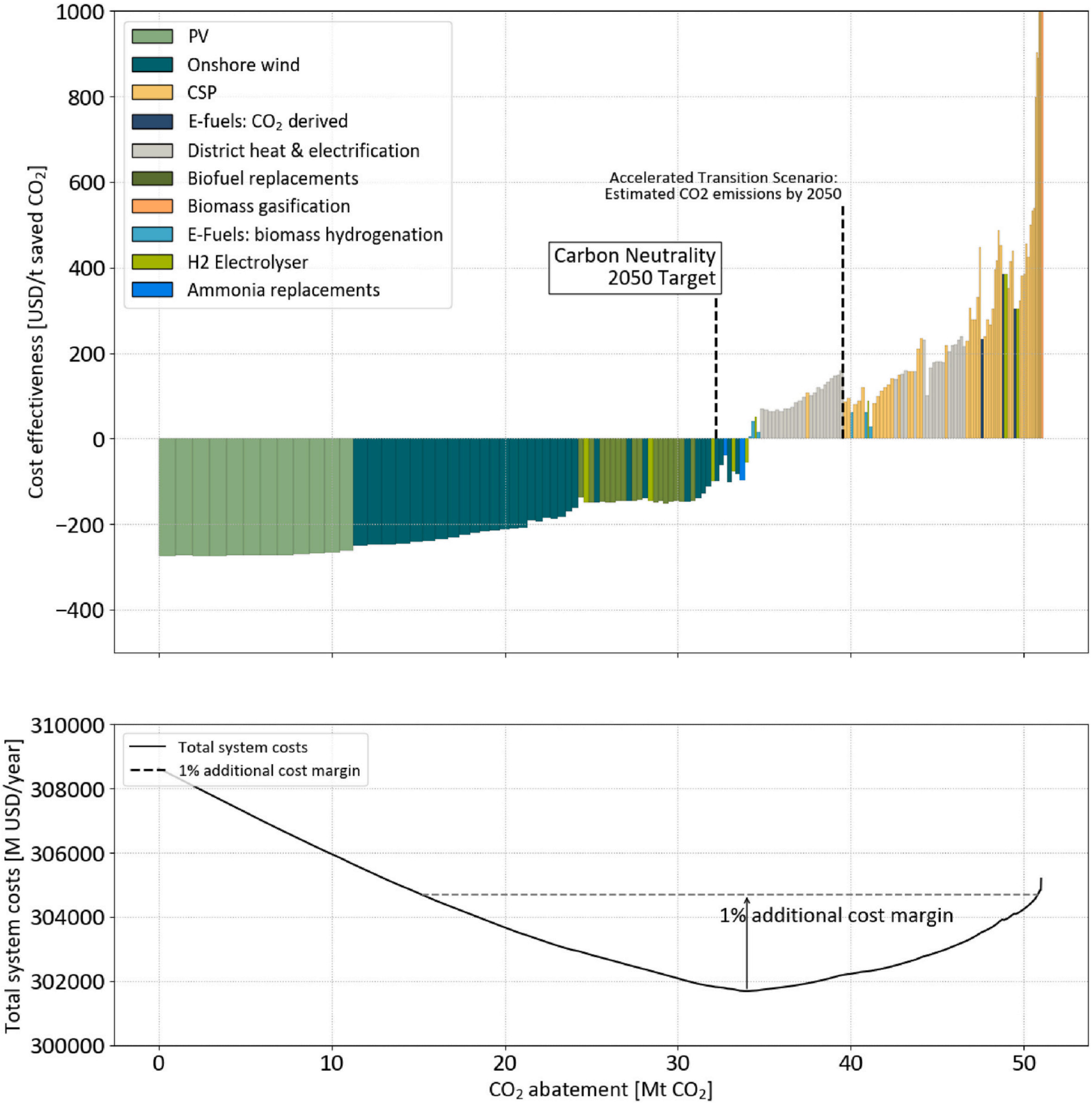

Fig. 3. MAC curve with different Smart Energy technologies and CO_2 reductions in a 2050 Chile scenario, and total system cost trends.

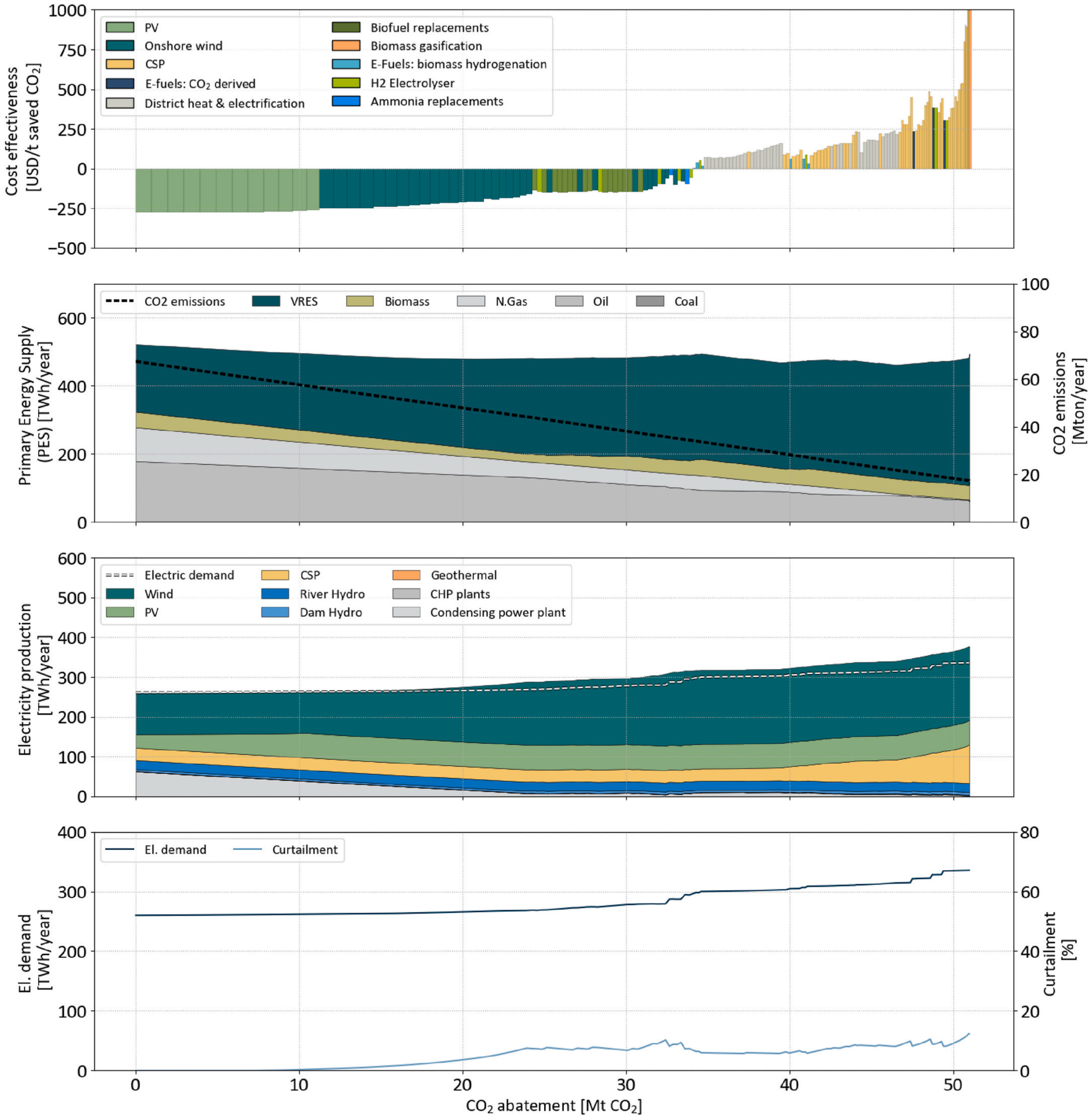

Fig. 4. Trends in primary energy supply, total electricity demand, and curtailment throughout the different CO_2 marginal abatement steps.

emissions of about 38.3 Mton per year, or a reduction of about 56% relative to 2018. Moreover, implementing the respective abatement measures up to this point yields a system design with the lowest total system costs along the transition (henceforth, also references as "*MAC - min. cost*" scenario).

After this point, a few additional no-regret measures can still be realized, namely some transport fuel substitutions with ammonia and additional electrolyzer and onshore wind capacities. As seen in Fig. 4, the trend in curtailment levels resulting from the early and mid-stage introduction of VRES capacities also starts slowly stalling relative to the total electricity demand due to the flexibility provided by the introduction of new measures.

From there, the changes in the heating sector with higher penetration of district heating and electrification with individual heat pumps become a viable, albeit more expensive option. This early redesign of the heating sector allows the system to reach similar decarbonization levels to those projected under the PELP's "*accelerated transition*" scenario. At this level the expansion of district heating comes to about 20% of the space heating market, and individual heating is mostly electrified, displacing inefficient fuel boilers. Moreover, as presented in Fig. 4, these measures also introduce further reductions in the total primary energy supply, and provide additional flexibility to the system, allowing for curtailment to decrease.

Interestingly, the abatement potentials of certain measures starting at the mid-phase of the transition do not necessarily follow a linear increase. Rather, certain consecutive measures present discontinuities in their cost of carbon abatement potentials. This is partly due to the system effects of introducing certain technologies. For example, by implementing a given flexibility measure (e.g. storages, electrolyzers), the subsequent increase in generation capacity can become competitive again. Nevertheless, the resulting system designs for most of the measures past the mid-stages of the transition yield total system costs within a 1% margin of the minimum cost configuration.

In the final stages, the decarbonization relies on expensive or less mature technologies and measures, including sequentially increasing capacities of CSP (including storage), additional flexibility with electrolyzers, and e-fuel production with CO_2 hydrogenation for transport fuel replacements. In these stages, CSP will increase curtailment while new hydrogen and e-fuel production will act as counteractive flexibility measures. Considering a system scenario where all these measures are realized (henceforth, also referred to as "*MAC - max. abt*" scenario), would lead to system emissions of about 17.3 Mton per year. After this stage, the costs of subsequent abatement measures become prohibitively more expensive, causing the algorithm to stop converging.

3.3. Comparison across abatement scenarios

To illustrate the different abatement alternatives, the results from the Smart Energy Scenario steps and the MAC curve generation are compared to the PELP scenarios, replicated for this study. This comparison, presented in Fig. 5, provides a view of the performance of these scenarios based on primary energy supply, CO_2 emissions, and total system costs.

In terms of primary energy supply, the PELP scenarios (namely the "*Carbon Neutrality*" and "*Accelerated Transition")* present higher energy consumption than the other observed scenarios. This is driven by the high input assumptions concerning hydrogen production for exports, which activate power production for power plants when considering the hourly fluctuations of demand and production during a year, which is not captured fully in the original scenario development from the PELP. This also translates into cost differences, as the system incurs both larger variable costs for fuels and investment costs for additional capacity. Meanwhile, the "*Current trends*" scenario presents relatively similar levels for all indicators to the reference scenario in the Smart Energy steps, which is natural given the methodology used to develop the latter.

Across the different Smart Energy steps, efficiency gains can be observed as well as progressive CO_2 reductions, though at increasing costs relative to the reference in the last stages. Nonetheless, a cheaper system configuration can be observed at Step 4, and the cost increase in the Smart Energy Chile scenario represents less than a 1% increase relative to the reference.

At the same time, two scenarios generated from the MAC curve optimization are observed: one with the lowest system costs and one with the highest abatement level. Here, we see that the minimum cost option closely resembles Step 4 from the Smart Energy steps in terms of the energy mix and emissions, however at a lower system cost due to incurring in lower investment costs and low variable costs. Meanwhile, while reaching significantly low emission levels when compared to the reference, the highest abatement option does not reach the same abatement potential compared to Step 5 or to the Smart Energy Chile scenario. However, both of these MAC-generated scenarios present lower-cost systems than any of the system configurations from the Smart Energy steps. However, given future cost and price uncertainties this difference is marginal, making it hard to conclude whether one scenario is that much more cost-effective than the other.

Another key aspect observed in this comparison is that the Smart Energy steps allow for further degree of decarbonization at a marginal higher costs due to the fact these scenarios are not bounded by strict optimality criteria or endogenous decisions from an optimization algorithm, unlike the MAC curve approach. Rather, these scenarios have a degree of freedom that allow the exploration of solutions with higher abatement given the underlying expert-based simulation methodology used. Nonetheless, both the Smart Energy steps and the MAC curve optimization scenarios provide matching set of measures to reach the national carbon abatement targets, and provide complementary perspectives regarding abatement priorities and potential configurations of the energy system.

4. Summary and conclusions

In this study, different carbon abatement scenarios for the Chilean energy system have been developed and examined. These scenarios include Chile's nationally developed PELP scenarios, newly developed scenarios applying a Smart Energy System approach, and optimized abatement scenarios generated with the EPLANoptMAC tool.

Coupling the latter two methodologies adds great value as it provides different yet complementary perspectives on Chile's potential transition and decarbonization pathways toward 2050. On the one hand, the Smart Energy scenarios benefit from having a more granular view of how the broad measures assessed in each step can be incrementally implemented and which of these should be prioritized at different stages of the transition. For instance, prioritizing renewable capacity with high curtailment in the early and mid stages of the transition, and flexibility options at the latter stages. On the other, the optimized MAC curve generated scenarios are complemented with the analytical approach by getting pre-set targets and by the perspective provided via scenario exploration, which can look beyond the bounds of the given optimization problem. This allows exploring full decarbonization and 100% renewable energy system with key enabling technologies that might, for example, present only marginally higher costs or fail to converge due to particular system dynamics in a highly sector-coupled system.

The results from the analysis show that by following a Smart Energy System approach and the guiding principles outlined in Section 2.1, a fully fossil-free and 100% renewable energy system is technically feasible and, in fact, goes far beyond the current national Carbon Neutrality scenarios. Achieving this will require a heavy redesign of the energy system, with integration across the different sectors in terms of integrating their demands via electrification and utilizing common infrastructures and grids, which – in turn– can also provide additional system flexibility once new capacities and fuel production technologies are introduced. A large expansion in VRES capacity must occur in the initial phases of the transition, consisting of PV and Wind capacities, followed by fuel replacements and, later on, a redesign of the heat supply, including electrification with heat pumps and the expansion of district heating grids. At later stages, balancing technologies will be needed along with deploying CSP capacity to cover new electricity demands. This highlights the importance of enabling infrastructures and interconnections of the sectors to ensure that VRES can be used to their full capacity. Moreover, biomass can also take a prominent role within its available limits, in tandem with e-fuels, to reach the last stages of a transition towards a 100% renewable energy system. This could be achieved at lower costs relative to the PELP's "Carbon Neutrality" scenario, and with less than a 1% increase in systems costs relative to the reference.

Finally, the resulting MAC curve scenarios show that certain technologies with great potential for decarbonization are not yet cost-effective in terms of their costs for carbon reductions. This means that policy and other incentives should be targeted to promote and further develop these measures in the context of Chile, if these are to be implemented by 2050. Also, it shows that a less ambitious carbon neutrality could be achieved with fewer technical changes or redesigns than with the Smart Energy Scenarios. Moreover, the results also reveal the value and benefits of capturing system dynamics in generating MAC curves, as it captures the impact of enabling technologies and planning objectives with a granular and holistic approach. This is particularly important in the context of Chile, where MAC curves are used in the

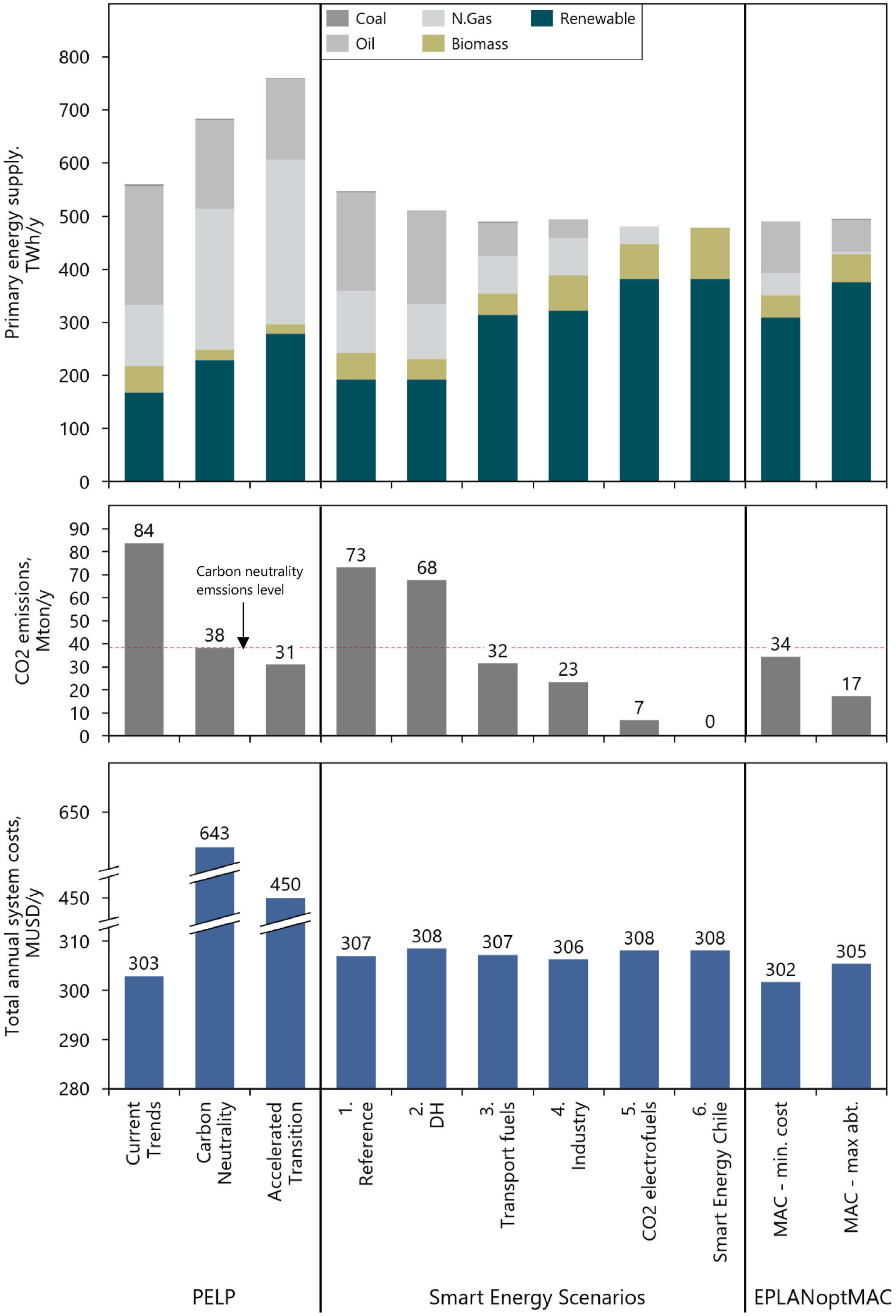

Fig. 5. Overview of key indicators across the different abatement scenarios.

assessment of NDCs and climate action plans [26,29]. Without the system perspective, valuable carbon abatement options might not otherwise show their full benefits.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2023.100098.

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