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Why reducing socio-environmental externalities of electricity system expansions can boost the development of solar power generation: The case of Chile

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ABSTRACT

In recent years, the transition towards low-carbon electricity systems has increased the development of renewable generation and, in turn, of transmission infrastructure. Importantly, developing low-carbon technologies (that are generally located far from load centers) and their associated network infrastructure, may conflict with land uses that are valuable by society (e.g. the presence of national parks, indigenous development, touristic zones, etc.). Appropriately addressing this conflict is key for policy makers and regulators to foster an effective, sustainable, and socially acceptable system expansion. In this context, this work analyzes the effects of accounting for these land-use, socio-environmental externalities on the expansion of the entire power system. For a more effective mitigation of system expansion impacts on land uses, we propose to coordinate the needed investments among the various market participants such as generation developers and network planners. To assess this proposal, we develop a two-stage stochastic program that determines the future generation and network expansions considering both (i) a balance between monetary/investment costs and their corresponding socio-environmental externality costs (derived from the land-use impacts of new electricity investments), and (ii) different levels of coordination among market participants. Hence, we can assess the benefits of various coordination strategies against the actual approach to system expansions with no coordination among developers. By running various case studies based on the Chilean electricity system by 2030, we show that recognition of socio-environmental externalities at the moment of deciding system expansions can have a significant impact on the location of future infrastructure and, remarkably, on the entire mix of new generation projects. Particularly, we found an increase in bulk, transmission-connected solar power generation capacity by circa 25% when land-use externalities are considered in the system expansion problem. This is so because bulk solar power generation projects tend to present less socio-environmental impacts (since the solar power potential is generally higher in deserts and arid regions, away from populated areas) and, up to a certain extent, have the ability to displace the need for other generation technologies, particularly hydropower, located in areas with significantly conflicting land uses. We also demonstrated the benefits of investment coordination in supporting both an increased penetration of solar power generation, and an economically effective and sustainable development of a low-carbon power system in Chile.

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1. Introduction

1.1. Motivation

The transition towards a low-carbon electricity system requires the development of significant electricity infrastructure, including both renewable generation and networks.

In the case of Chile, the Atacama Desert has been pointed out as one of the places on earth with the highest levels of irradiance. This area is characterized by its high altitude, prevalent cloudless conditions and relatively low columns of ozone and water vapor (Cordero et al., 2016). The total solar power potential of the country would allow the addition of more than 2 TW capacity in solar power plants, including photovoltaic (1.6 TW) and Concentrated Solar Power (0.5 TW) (Chilean Energy Ministry and GIZ, 2014), which would be capable of producing more than 40 times the total energy demand of the country in 2050 (Chilean Energy Ministry, 2015). Importantly, the land in the Atacama Desert presents almost none alternative uses, allowing a more effective development of solar power generation from the perspective of its externality costs. Similarly, the associated network infrastructure presents smaller externality costs. Notice that this feature may not be particular to Chile since high solar power potentials are frequently located in deserts and arid regions. Hence, the development of bulk solar power generation may present, in general, lower externality costs compared with other technologies as the alternative uses of the associated land may not be as valuable as that in other areas.

New infrastructure generally features substantial negative externalities on society and the local environment, which ultimately might drive social opposition and, in turn, construction delays and cost increases. In the extreme, investors can even be prevented from developing their projects. There are several examples in the world that point out conflicts between electricity infrastructure, society and the environment (Komendantova and Battaglini, 2016). For example, in the power generation sector, large infrastructure projects have faced significant social oppositions [e.g., the anti-nuclear movement in Japan after the Fukushima disaster (Fackler, 2012), and the opposition to hydropower reservoirs projects in the Chilean Patagonia such as HidroAysen (Romero et al., 2009)]. The transmission sector has faced similar conflicts such as the construction of the Beauly-Denny line in the UK (Tobiasson and Jamasb, 2016), the Grain Belt Express in the US (Cardwell, 2016), and the HidroAysen transmission line in Chile (Astorga and Urquiza, 2013). In this context, finding the right set of system investments that complies with investors' expectations and, at the same time, with the increasingly higher expectations and constraints imposed by policy makers and society, is not trivial.

1.2. Literature review and contribution

There are several methodologies and models used by market participants and regulators for sitting electricity infrastructure and thus mitigating their environmental impacts. For transmission networks, these methods are mainly based on multi-criteria decision analysis (MCDA) and geographical information systems (GIS) such as ERPA, OPTIPOL, and EPRI (Araneo et al., 2015; Bevanger et al., 2014; EPRI, 2006). Apart from these methodologies, policy makers have also implemented early participatory processes with inhabitants and different stakeholders to define, together, the value of the land-use (Bailey and Devine-Wright, 2014; Komendantova, 2018). One of the problems with the above-mentioned methodologies and policy practices is that most of these analyze the socio-environmental problems using an *ex post facto* approach, when assets have already been decided to be built, without considering their externalities in an early stage of the planning process (Dedemen, 2013; Husain et al., 2012; Schmidt, 2009; Uzoukwu, 2010; Williams, 2003). In the case of Chile, for instance, the environmental studies and permits are carried out after the planning authority, in this case the National Energy Commission (CNE), has mandated the network investments (Chilean Energy Ministry, 2016a). Hence, environmental studies can change the sitting of the line but not the primary decision (i.e., building it or not). Note this corresponds to a suboptimal outcome from regulation since, clearly, the construction of a power line can be avoided if a substitute network (or even generation) investment (one that features a lower externality cost, for example) is carried out. Note that the construction of generation projects can also be eliminated if others are built.

In this vein, (Matamala et al., 2019) proposes consideration of, in an early stage and before network investments have been decided, land-use externalities associated with candidate network investments. Hence, under this approach, the resulting network investments are being selected attempting to mitigate socio-environmental problems, preventing the construction of assets with potentially significant impacts. One of the key contributions of this work is the explicit modeling of coordination among several project developers. Hence, similarly to (Konstantelos et al., 2017; Strbac et al., 2015) where coordination among project developers is also modeled, (Matamala et al., 2019) proposes the coordination of future investments as a means to reduce land-use externalities from new assets. Clearly, building shared transmission corridors by coordinating and aggregating the need for transmission capacity from various generation projects (rather than building individual lines, one for each developer/generation project), will allow developers and planners to alleviate costs and also the impacts of such investments on the environment.

Although the abovementioned progresses (including methods, models and practices) have been significant and have facilitated the expansion of power systems in complex and conflicting situations, these feature two main limitations. First, as mentioned earlier, the abovementioned methodologies analyze the socio-environmental problems using an *ex post facto* approach, when assets have already been decided to be built. Second, generation investment decisions are considered already made when analyzing the impacts of network expansion. In other words, negative externalities associated with network infrastructure are not considered in generation investment decisions.

Hence, we expand on the state of the art by analyzing the impacts of land-use externalities on expanding simultaneously both generation and network infrastructure. To mitigate such externalities, we consider the effects of coordination among project developers in generation and transmission investment decisions. By running several case studies on the Chilean power system by 2030, we analyze the role of different generation technologies, particularly solar power generation, in a system expansion that attempts to mitigate land-use externalities. For comparison purposes, we also study the consequences of ignoring negative externalities and of different levels of coordination of future investments among market participants and planners.

1.3. Paper structure

This paper is organized as follows. Section 2 presents the methodology and the optimization problem (which is presented in detail in the Appendix). Section 3 introduces the case studies, including the input data of the Chilean power system by 2030. Section 4 presents our system expansion results with and without consideration of land-use externalities and with various degrees of coordination among project developers. Finally, Section 5 concludes.

2. Proposed methodology

2.1. General description of the model

We determine the future expansion of the power system, including both generation and transmission assets in a co-optimized fashion, considering investments in renewable and conventional generation. The model minimizes total costs taking account of generation and network investments along with operational costs associated with generation dispatches in multiple operating conditions. In this vein, the model considers various time slices to resemble a year of operation in an accurate manner, capturing a combination of different levels of demand and outputs of renewable generation. We also consider an array of hydrological/inflow scenarios to capture the possibility to face various hydro conditions, particularly droughts as these conditions can threaten system reliability.

We use this model to study the expansion of the electricity systems under different coordination strategies in an attempt to minimize externalities associated with alternative land-uses and valuable objects. The modeled coordination strategies attempt to avoid piecemeal developments of system expansions that are observed when various project developers undertake generation and network investments. Hence, to minimize externalities, the model can bundle together various transmission projects (minimizing the strip of land associated with the right-of-way) and/or select those projects, in generation and transmission, that feature the minimum impacts on alternative land-uses that are valuable to society (e.g., national parks, communities settlements including indigenous communities, etc.).

In this vein, the model considers four different strategies for coordinating investment decisions among market participants:

(i) Radial, fully decentralized strategy (i.e., no coordination): In this case, each owner of a candidate generation project builds a direct, “radial” line to the main power system to connect his project. This is undertaken without coordinating with further project developers and thus the line capacity is fitted to the necessities of the single project only. Additionally, we consider access restrictions for connecting the new line to the main power system, avoiding landing on substations that are owned by other generators and non-regulated large consumers.[1] For each new project, there are various candidate landing points. This strategy corresponds to that with the lowest level of coordination (no coordination at all).

(ii) Radial, partially decentralized strategy: This strategy is equal to the previous one except for the restrictions on landing points associated with new lines. Under this approach, new lines connecting new projects to the main system can consider substations owned by other generators and non-regulated large consumers as potential points of landing/access to the electricity system. Therefore, there are more options (available nodes) for connection to the main power system. For each new project, there are various candidate landing points.

(iii) Pseudo coordinated strategy (coordination at a local level): Under this approach, a group or cluster of candidate generators located nearby can coordinate themselves to build shared transmission infrastructure. This share network is composed of a “collector” substation (located in the centroid of the cluster) to which each project connects and from where the cluster is connected to the main system through a single transmission line. For each cluster of new projects, there are various candidate landing points. The clusters, though, are not optimized within the system expansion planning problem and are, instead, given as input parameters.

(iv) Fully coordinated strategy (coordination at a global level): This strategy is equal to the previous one except for the possibility to interconnect clusters of generators among themselves. Thus, after interconnecting clusters among themselves, this group of clusters can be connected to the main system in several ways using one or various lines. This strategy corresponds to that with the highest level of coordination.

A graphical representation of the four coordination strategies is shown in Fig. 1, which demonstrates the potential benefits of coordinating systems investments in terms of minimizing socio-environmental impacts and externalities. Explicitly, Fig. 1 illustrated how coordination may help to avoid a valuable object.

2.2. Model structure and features

The system expansion planning problem is formulated as a two-stage stochastic program that identifies, in the first stage, the optimal generation and network assets to be installed and, in the second stage, power system operation for various operating conditions (representing combined wind, solar and demand levels) and hydrological scenarios. The model, which is also a stochastic mixed integer linear program (SMILP), minimizes total cost, including generation investment costs, network investment costs, system operating costs, and socio-environmental cost due to generation and transmission investment externalities. Each of these cost components are explained next in detail.

The model considers monetary costs, with 3 cost components: (i) Generation investment cost, associated with the investment cost of the new power plants, (ii) Transmission investment cost, associated to the investment cost of new network infrastructure, and (iii) Operational cost, which is determined in a stochastic basis considering various hydrological scenarios and operating conditions that represent combinations of demand, wind, and solar power levels in different areas of the system, considering their spatial and temporal correlations across a year.

The model also considers socio-environmental cost. This corresponds to the extra cost considered in the objective function (on top of the monetary cost described above) because candidate generators and lines may be located in conflicting places. The specific extra cost of each candidate project depends on the associated valuable object that is affected by the development of the project. This extra cost is modelled through a penalty factor that multiplies the monetary investment cost of the corresponding asset. This factor depends on the importance of the valuable object in question.

By appropriately recognizing socio-environmental cost, a candidate generator or transmission line that imposes significantly high socio-environmental costs might not be selected as the model can choose to build another generator/line that avoids crossing valuable land-uses. This is one of the unique and most important advantage of our model, because we consider the main externalities of sitting power plants and transmission lines in an early stage of the expansion planning process. Some regulators, instead, study the environmental impacts of a proposed transmission line after the planning authority has already approve the construction of the project like in Chile (Chilean Energy Ministry, 2017) which may significantly limit the efficacy of the mitigating actions to minimize environmental externalities.

The mathematical structure of our model is summarized in Table 1, while the detailed mathematical formulation is presented in the Appendix. At the end of Table 1, the coordination-type constraints refer to the set of constraints used in each coordination strategy to appropriately represents the network topologies illustrated in Fig. 1. Thus, for the radial, fully decentralized and partially decentralized cases, the constraints allow only radial connections; for the pseudo coordinated case, the constraints allow internal connections within a cluster and the connections of the “collector” substations to the main system; and for the fully coordinated case, the constraints allow investment decisions in all candidate lines.

Note that although this is a single optimization problem that models a central planning investment and operational setting, it resembles the

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[1] According to the Chilean regulatory framework (Chilean Energy Ministry, 2016a), the transmission network is divided into 3 categories: national, zonal and dedicated. While the former two categories refer to regulated assets subject to full open access obligations, the latter are non-regulated assets and thus with more limited access. These dedicated network assets are owned by generators or non-regulated large consumers who use them to connect their equipment to the main grid. From a total of 305 substations in the main system, there are 42 dedicated substations owned by generators and non-regulated large consumers.

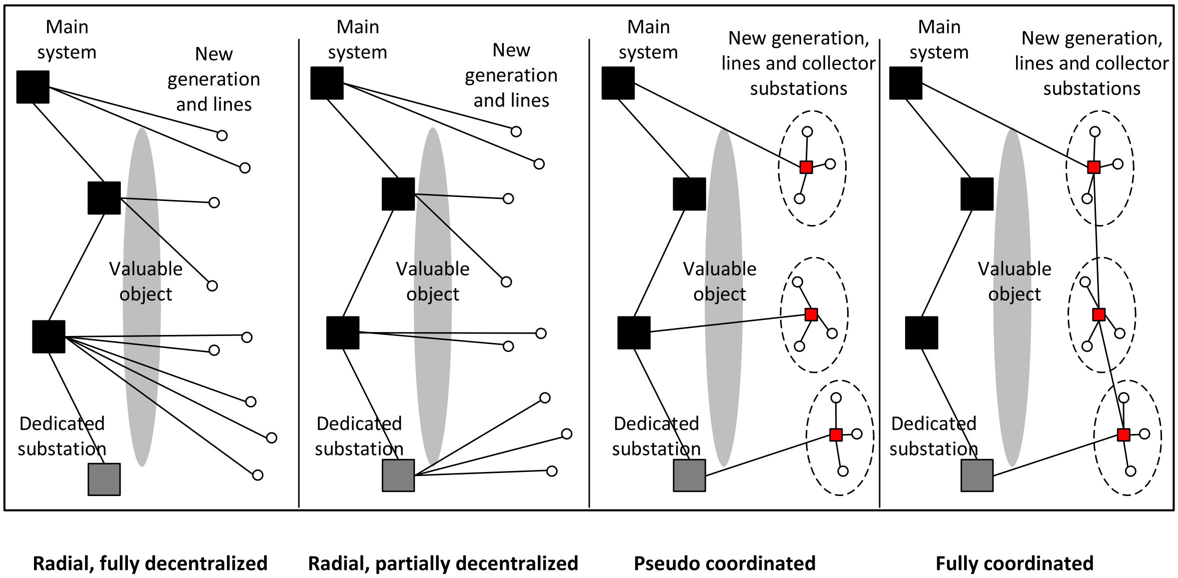

Fig. 1. The four coordination strategies to expand power system infrastructure.

Table 1
Structure of our proposed two-stage stochastic program for generation and transmission investments.

Minimize{ Generation and transmission investment cost + System operation cost + Socio-environmental cost due to generation and transmission investment externalities }
Relevant decisions variables: • New renewable generation installations through binary variables • New thermal generation capacity through continuous variables • Network reinforcements through continuous variables that increase capacity of existing assets • New lines through both binary variables and continuous variables (to recognize both fixed and variable cost in new lines) • Generation dispatches and power transfers Subject to: • Energy balance constraint per node, per time period, per inflow scenario • Maximum power generation capacity constraint per generator, per time period, per inflow scenario • Maximum hydro production (in energy terms) per season, per hydropower generator, per inflow scenario • Power transfer constraint per line, per time period, per inflow scenario • Coordination-type constraints

expansion of the electricity market with decentralized investment decisions in generation, made by different and competitive market participants. The demonstration of how this central planning problem maps into the market equilibrium problem can be found in reference (Muñoz et al., 2017).

Although ignoring hourly system behavior and using time-block modelling (through various time slices) instead may lead to lose some arbitrage opportunities and short-term generation distortions, solar power generation is very stable in the case of northern Chile (with a low forecast error), which is likely to imply that the impacts of our approximations would be minimal.

3. Case studies

The proposed optimization model is applied on the Chilean power system by 2030. We aim to fundamentally analyze (i) how recognition of valuable objects and land-uses affects system expansions, including the mix of renewable generation technologies, and (ii) how coordination of system expansions (undertaken by several market participants) may minimize externalities and optimize the portfolio of system expansion projects. We particularly focus on the impacts on solar power technologies.

To do so, we compare system expansions (particularly solar power generation) under the four coordination strategies presented earlier, with and without recognition of socio-environmental costs/externalities. The reader should bear in mind that the current approach in Chile features a timid investments coordination among project developers and a timid recognition of socio-environmental costs when planning network infrastructure, usually undertook *ex post facto*, after lines constructions have been approved/decided.

3.1. Main input data

3.1.1. Generation

3.1.1.1. Existing generation capacity. The existing installed capacity of generation is obtained from public information published by the Chilean Independent System Operator, Chilean ISO (CEN, 2017). In particular, we consider all plants already installed and those under construction as shown in Table 2 (in total there are 400 power plants, which represent 23.8 GW).

3.1.1.2. Candidate renewable and thermal generation to expand system capacity. We consider a total of 419 candidate generators, where 182 are solar power plants, 73 wind power plants, 161 run-of-the-river power plants, and 3 natural gas / LNG power plants. Their locations are shown in Fig. 2. The capacity and the location of each project can be obtained from public information [(SEA, 2017), (PUC-TECO-UCH, 2016) and (CNE, 2015a)].

Table 2
Installed capacity by 2030.

Technology	Total capacity [MW]	Variable cost [US$/MWh]
Hydro reservoir	3,286	–
Hydro run-of-the-river	4,297	–
Solar	2,516	–
Wind	1,608	–
Biomass	423	42
Cogeneration	117	93
Coal	4,646	38
Natural gas/LNG	2,929	76
Diesel	3,923	143
Total	**23,745**	

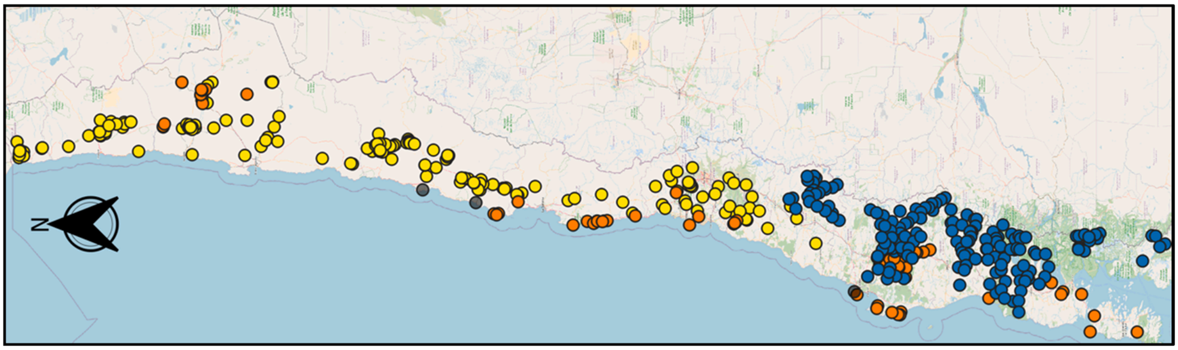

Fig. 2. Chilean map of candidate generation projects. Circles refer to the new generation (yellow for solar, orange for wind, blue for hydro and grey for natural gas). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Likewise, we consider investment costs per technology published by the Ministry of Energy in (Chilean Energy Ministry, 2015). These data are shown in Table 3, which also shows the total capacity in candidate projects per technology.

3.1.2. *Transmission system*

The expansion of the transmission network considers both investments in the main system to upgrade its capacity (also called reinforcements) and investments in new lines required to connect new generation to the main system.

3.1.2.1. Existing main network. We consider a 305-node representation of the Chilean electricity system, following practices by the Chilean ISO (CEN, 2017). Within this network, there are 42 nodes or substations that are owned by generators or non-regulated large consumers (part of the so-called dedicated system), which are not available for connecting new lines coming from new generation projects under the radial, fully decentralized coordination strategy. Also, we consider 426 links (lines and transformers) in 5 voltage levels (500, 220, 154, 110 and 66 kV). The existing network infrastructure features an initial or present capacity that can be enhanced towards 2030. The topology of the main transmission system modeled is shown in Fig. 3.

3.1.2.2. New substations. We model 486 candidate nodes/substations for new power generation as follows: 182 nodes associated with new solar power plants; 73 nodes associated with new wind power plants; 161 nodes associated with new run-of-the-river power plants; 3 nodes associated with new natural gas/LNG; and 67 nodes associated with "collector" substations (centroids of the clusters of renewable generation).

3.1.2.3. New power lines. For the radial cases, there are 835 candidate lines in 2 voltage levels (220 and 110 kV). We consider 2 candidate lines per each renewable generation project and 1 line per each natural gas-fired power plant. In summary, we model 364 candidate lines for solar power plants; 146 candidate lines for wind power plants; 322 candidate lines for run-of-the-river power plants; and 3 candidate lines for natural gas plants.

For the pseudo and fully coordinated cases, there are 553 and 647 candidate lines, respectively, in 2 voltage levels (220 and 110 kV): 134 candidate lines to connect a candidate "collector" substation to the main system (2 candidate lines per each collector substation); 416 candidate lines to interconnect the renewable generation project within a cluster to its candidate "collector" substation; 3 candidate lines to connect candidate natural gas power plants; and 94 candidate lines to interconnect 2 candidate "collector" substations (only for the fully coordinated case).

Table 3
Solar, wind, hydro, and thermal candidate capacity and their costs.

	Total capacity [MW]	Investment cost [US$/MW.yr]
Solar	16,289	198,510
Wind	7,549	164,213
Hydro	10,890	360,018
Natural gas / LNG	5,473	109,202
Total	**40,201**	

3.1.2.4. Transmission investment (monetary) cost. The transmission costs are divided into fixed and variable costs. The fixed investment cost represents the annualized value of the investment plus maintenance and administration costs associated with substation equipment at the ends of a line or transformer. The variable cost, on the other hand, represents the annualized value of increasing the capacity of a transmission line or transformer in one power unit (i.e., 1 MW). All values consider N-1 security criterion, i.e. double circuit. For lines, costs also consider the payments associated with right-of-way strips of 50 m wide. The costs considered in Table 4 are obtained from (CNE, 2015b). These costs are summarized in Table 4.

3.1.3. *Socio-environmental cost or externality cost of transmission*

As mentioned earlier, we consider several valuable objects such as national parks, indigenous communities, tourist interest zones, etc. As explained in (Chilean Energy Ministry, 2016b), the concept of valuable objects is inspired by international methodologies for the identification of conservation elements, or high conservation values (Brown et al., 2017). Accordingly, valuable objects have been defined as "variables of different nature that are considered particularly important and special by the society and which may or may not have a level of protection or guardianship by the State". The list of all VOs considered in this study is shown in Table 5.

All of them feature a precise location and cover a specific area in the Chilean map as shown in Fig. 4. Once areas representing VOs are identified on the map, we define a specific score for that area, proportional to the importance of each VO. If various VOs use a common area, the score of that area is equal to the summation of each VO's score.

Hence, a transmission project can intersect various VOs as shown in Fig. 5, which also illustrates how to calculate the total score for a given project. Likewise, generation projects can also be affected by various VOs if they are located in an area that is common to two or more VOs. This is also illustrated in Fig. 5. As the total score allocated to a single project can be very high, scores are normalized. These normalized scores are the ultimately penalty factors that are multiplied times the investment costs of the projects to obtain their corresponding externality costs.

4. Results

Fig. 6 shows the optimal mix of generation technologies expanded towards 2030 for the following coordination strategies (i) radial, fully

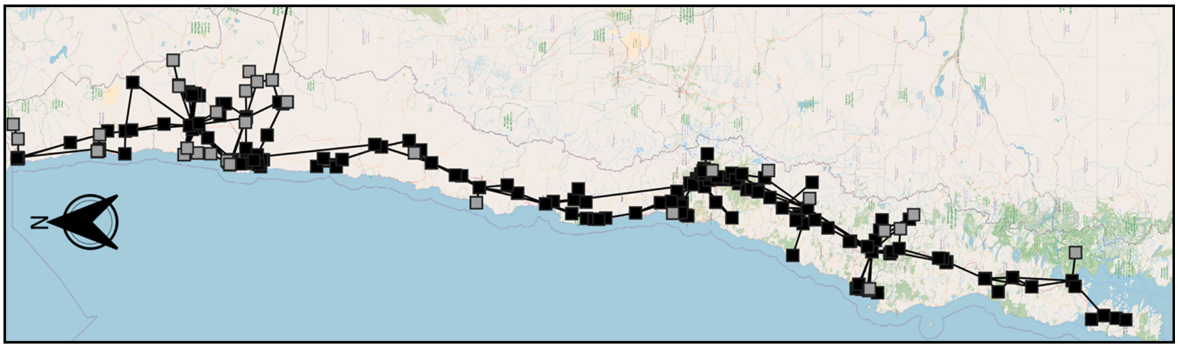

Fig. 3. Chilean map of the main transmission system (including the Chile-Argentina interconnector). Squares refer to existing substations (black for open access and grey for dedicated). Existing power lines are drawn in black.

Table 4
Transmission investment (monetary) cost.

	Fixed investment cost [Million US $/yr]	Variable investment cost in [US$/MW.km.yr] for lines and [US$/MW.yr] for transformers	Right-of-way cost [US$/km. yr]
Lines 500 [kV]	2.68	66	7,249
Lines 220 [kV]	0.86	124	7,249
Lines less than 220 [kV]	0.14	146	7,249
Transformers	1.78	2168	

Table 5
List of considered valuable objects.

	Geographical information
Conservation	National Parks National Reserves Natural Monuments Private Protected Areas Protected National Lands Priority Sites for Biodiversity Conservation Ramsar Sites Nature Sanctuaries
Tourism	Typical or Picturesque Areas Historical Monuments Touristic Destinations Areas of Tourist Interest Tourist Circuits and Tourist Attractions
Planning	Urban Areas
Property	Areas of Indigenous Development Indigenous Communities

decentralized strategy; (ii) radial, partially decentralized strategy; (iii) pseudo coordinated strategy; and (iv) fully coordinated strategy. Each of these strategies are obtained for two cases: with (CE) and without (IE) the consideration of land-use externalities.

Comparing IE against CE cases, Fig. 6 demonstrates that solar power generation is always increased when considering externalities in the capacity expansion planning problem. This increase in solar power generation capacity is counterbalanced by a decrease in hydro generation capacity and, sometimes, a decrease in natural gas capacity. For wind generation, instead, there is no clear patterns between IE and CE cases as wind generation capacity may increase when considering externalities [as per cases (i) and (ii)] or decrease [as per cases (iii) and (iv)]. An interesting result shown in Fig. 6 is that, when generation and

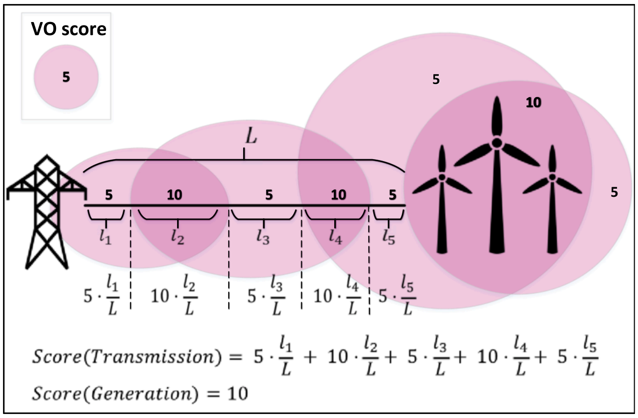

Fig. 5. Representation of the impact of VOs on system infrastructure. VOs cover a specific area as well as system infrastructure. In areas with various VOs, scores are summed.

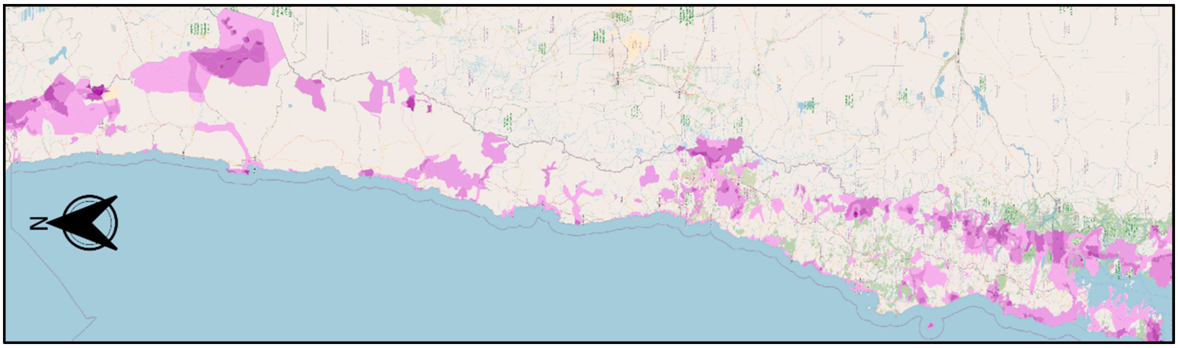

Fig. 4. Chilean map of valuable objects (VOs). Purple shadows refer to the degree of penalization associated with land-use externalities (the darker the shadow, the higher the penalization). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

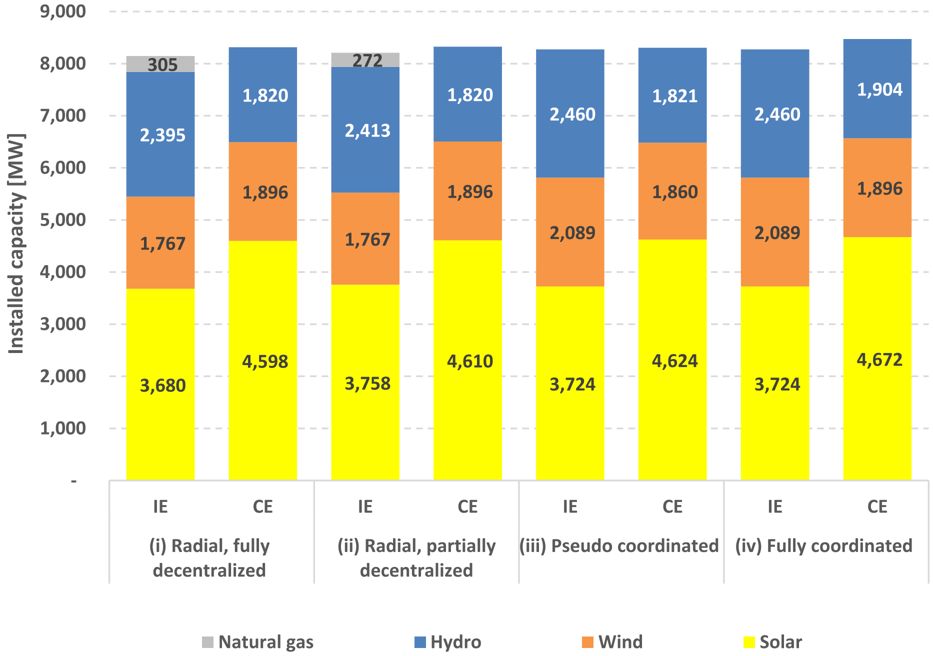

Fig. 6. New generation capacity by 2030. IE refers to ignoring externalities and CE refers to considering externalities.

transmission companies are coordinated (like in the pseudo and fully coordinated cases), there is no installation of new thermal power generation regardless of externalities being recognized. More remarkably, notice that solar power generation is maximized when externalities are considered and when investments are fully coordinated, demonstrating that coordination decreases the integration costs of renewables, particularly of solar power generation.

As mentioned, there is an important trade-off between solar and hydropower generation when considering externality costs. Interestingly, this happens because of the significantly increased number of VOs in the south of the country. As solar and hydropower generation are located in the north and south of the country, respectively (compare Figs. 2 and 4 in the previous sections), recognition of VOs will shift generation expansions from south to north as conflict with other land-uses is significantly smaller in the north. This is shown in Table 6, that demonstrates the higher socio-environmental costs of the system expansions that ignore externalities in their design. As ignoring externalities in system expansions drives higher installed capacity of hydropower plants located in conflicting areas of the country, the real socio-environmental costs of these plans end up being significantly more expensive. In a similar vein, Fig. 7 shows how recognition of externalities within the capacity expansion planning problem leads to minimize investments in conflicting areas (shadowed in purple) under all coordination strategies.

Another interesting result, which opposes the principle of economies of scale in the case of hydropower generation, refers to the benefits to expand the system based on smaller but more power units. In effect, if externalities are considered, the model prefers to realize more and smaller projects of hydropower generation. On the contrary, when externalities are ignored, the model prefer to deploy less and bigger power plants. Furthermore, increased coordination facilitates the integration of smaller projects of hydropower generation as the fixed costs of transmission are socialized among a higher number of participants. This is shown in Table 7 (note that this can also be observed in Fig. 7).

Table 6
Total costs for the four coordination strategies when ignoring and when considering externalities.[1]

		Cost [Million US$/yr]			
		Ignoring externalities		Considering externalities	
		Transmission	Generation	Transmission	Generation
(i) Radial, fully decentralized	Investment (monetary)	200	1,916	146	1,879
	Socio-environmental	9	514	3	67
	Operational (monetary)	1,706		1,978	
	Total	**4,346**		**4,073**	
(ii) Radial, partially decentralized	Investment (monetary)	202	1,935	142	1,882
	Socio-environmental	8	514	1	67
	Operational (monetary)	1,684		1,975	
	Total	**4,343**		**4,068**	
(iii) Pseudo coordinated	Investment (monetary)	208	1,968	139	1,879
	Socio-environmental	9	473	5	69
	Operational (monetary)	1,640		1,971	
	Total	**4,299**		**4,063**	
(iv) Fully coordinated	Investment (monetary)	201	1,968	129	1,924
	Socio-environmental	17	473	4	23
	Operational (monetary)	1,639		1,978	
	Total	**4,298**		**4,057**	

[1] Note that although differences among the total costs of the various strategies may seem small, differences in terms of system expansion (i.e., what is expanded and where) is tremendous.

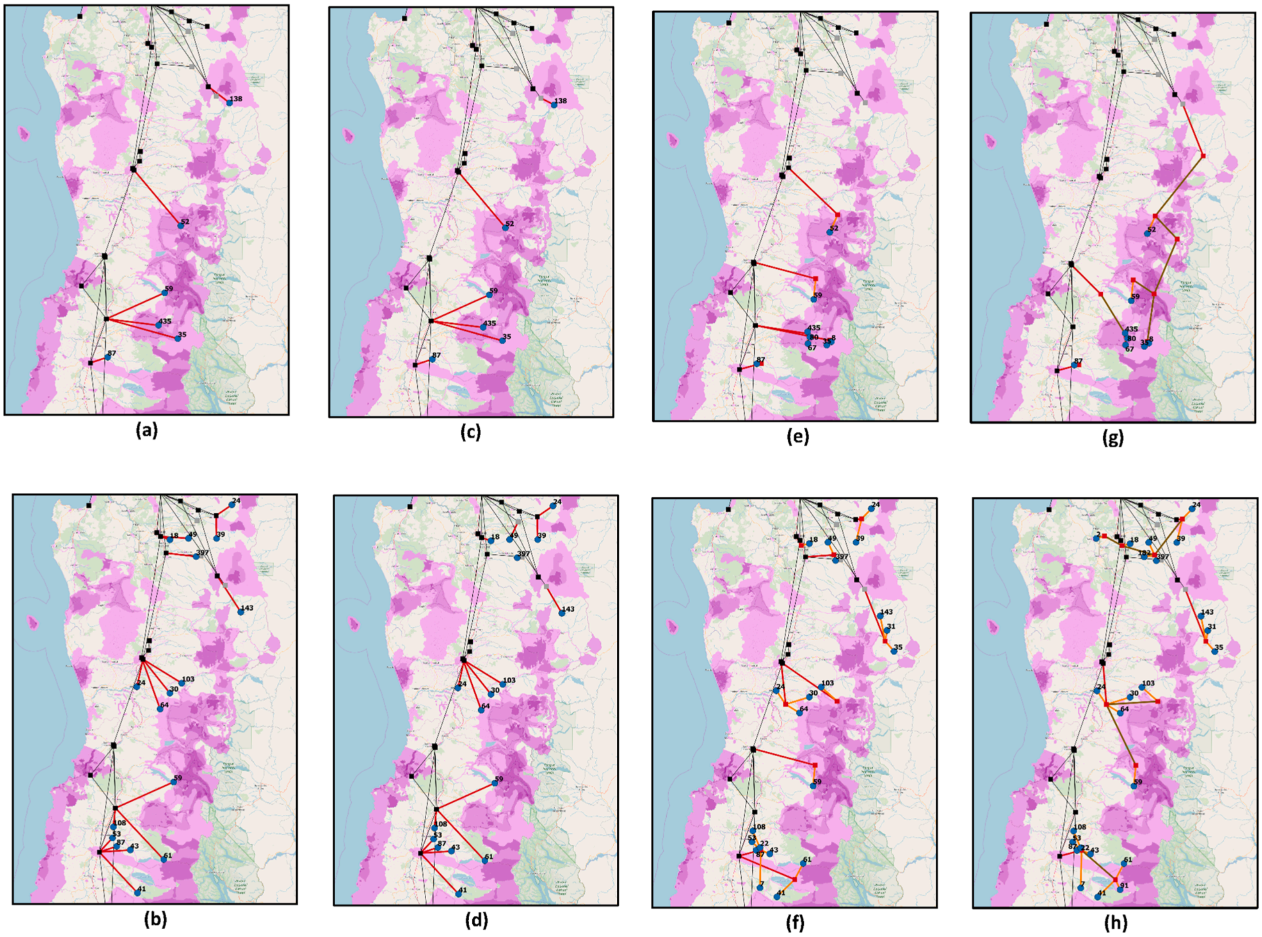

Fig. 7. New generation investment and network topologies for the four coordination strategies. Figures a, c, e, and g ignore externalities and figures b, d, f, and h consider externalities. Figures represent: radial, fully decentralized (a and b); radial, partially decentralized (c and d); pseudo coordinated (e and f); and fully coordinated strategies (g and h). Squares refer to substations (black for open access, grey for dedicated and red for collector nodes). Circles refer to new generation (yellow for solar, orange for wind, blue for hydro and grey for natural gas). Lines' colors refer to network types (black for main system's lines, red for radial lines, orange for lines from a generation project to its collector substation, and brown for collector substations' connections). Purple shadows refer to the penalization associated with land-use externality (the darker the shadow, the higher the penalization). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Conclusions

This paper analyzes, for the first time, the effects of considering coordination among project developers (in generation and transmission), who also may take account of the land-use externalities associated with their projects, on the expansion of the entire power system. For this purpose, we determine generation and network expansions under four coordination strategies, considering, on the one hand, the actual practice of developing generation and transmission infrastructure on a project by project basis, and, on the other hand, a significant coordination effort among developers and planners to increase the efficacy of system expansion. We also consider two more intermediate coordination strategies.

To compute system expansions, we use mathematical programming to optimize generation and network investments and operation, considering (i) various constraints to model the different levels of coordination, and (ii) extra components in the objective function to model socio-environmental costs associated with infrastructure sitting in conflicting places. The model is also stochastic to capture uncertainties, especially those related to hydro conditions which are particularly important in Chile. We also consider fluctuations of demand and wind and solar power outputs. Importantly, all parameters used in the model

Table 7
Number and mean size in [MW] of generation projects realized. IE means ignoring externalities and CE means considering externalities.

	Number of new projects								Mean size of new projects [MW]							
	Radial, fully decent.		Radial, partially decent.		Pseudo coord.		Fully coord.		Radial, fully decent.		Radial, partially decent.		Pseudo coord.		Fully coord.	
	IE	CE	IE	CE	IE	CE	IE	CE	IE	CE	IE	CE	IE	CE	IE	CE
Solar	11	19	12	21	22	23	22	22	335	242	313	220	169	201	169	212
Wind	9	19	9	19	14	18	14	19	196	100	196	100	149	103	149	100
Hydro	9	20	10	20	13	24	13	28	266	91	241	91	189	76	189	68
Natural gas	1		1						305		272					
Total	**30**	**58**	**32**	**60**	**49**	**65**	**49**	**69**	**272**	**143**	**257**	**139**	**169**	**128**	**169**	**123**

refer to a specific location in the Chilean map, with a remarkably high spatial resolution (using a raster of 500 × 500 meters^2), making this study the first system expansion analysis of this kind.

An important result for regulators and policy makers is that recognition of conflicting objectives like minimizing monetary expenditure and socio-environmental externality costs, at the moment of deciding system expansions, can have a significant impact on the location of future infrastructure, which ends up affecting the entire generation mix. Although it is expected to observe a difference in the location of generation and power lines due to valuable objects, the ultimate impact on the technology mix is counterintuitive. In our case studies, for example, we observe an increase in solar power generation capacity by circa 25% if externalities are appropriately recognized. Notably, we also observe a decrease in hydropower generation located in conflicting areas in the south of Chile. Our studies also demonstrate that these trends are exacerbated if projects are coordinated (even eliminating the need for further investments in carbon-intensive generation), emphasizing the importance of a central authority that undertake coordination among market participants; send the appropriate long-term signals to investors regarding VOs; and recognize, in an early stage, externalities in the network planning problem, rather than undertaking the current *ex post facto* approach to consider externalities, after network investments has been decided.

We also demonstrate that recognizing all of the above may drive the construction of more and smaller projects in hydropower generation, which may be of interest to regulators as this might enhance the competitiveness of the Chilean electricity market. The results of our work demonstrate the relevance and economic advantages of solar generation in the north of Chile, so we encourage policy makers to establish stronger incentives to boost the development of this technology.

Hence, failing to treat appropriately land-use externalities and coordination of future deployments in Chile will drive inefficient expansion and location of future electricity assets, more carbon-intensive capacity, and lower amounts of solar power generation, significantly limiting its value and future opportunities.

Declaration of Competing Interest

None.

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Appendix A. Mathematical formulation

A.1. Notation

In this section we detail the variables, parameters, and sets associated with the mathematical formulation of the proposed model. This formulation is implemented in the optimization suite FICO Xpress (Xpress-MP developer, 2018).

A.1.1. Sets

G_n	Set of generators connected to node n
$Gres$	Set of hydro reservoir generators
Lcl_c	Set of candidate lines to connect cluster c to the main transmission system
Ncl	Set of clusters
Ne	Set of seasons
Ng	Set of generators
Nl	Set of transmission lines
Nn	Set of nodes
Ns	Set of hydro scenarios
Nt	Set of snapshots or operating conditions

A.1.2. Variables

$f_{l,t,e,s}$	Transfer in line l at snapshot t in season e in hydro scenario s [MW]
I_l	Capacity of line l [MW]
K_g	New added/invested capacity of generator g [MW]
$LL_{n,t,e,s}$	Loss of load in node n at snapshot t in season e in hydro scenario s [MW]
$P_{g,t,e,s}$	Production of generator g at snapshot t in season e in hydro scenario s [MW]
X_l	Binary decision variable, where: • $X_l = 1$ if line l is built • $X_l = 0$ otherwise
Z_g	Binary decision variable; investment decision that is only used for candidate renewable generators (generators with $Class_g = 1$), where: • $Z_g = 1$ if candidate generator g is built • $Z_g = 0$ otherwise

A.1.3. Parameters

$Class_g$	Class of generator g, where: • $Class_g = 0$ for an existing generator • $Class_g = 1$ for a candidate, renewable generator • $Class_g = 2$ for a candidate, conventional (thermal) generator
$CF_{g,t,e,s}$	Availability of generator g at snapshot t in season e in hydro scenario s [p.u.]
CV_g	Variable production cost of generator g [US$/MWh]
$D_{n,t,e}$	Electricity demand in node n snapshot t in season e [MW]
$Dir_{n,l}$	Transfer direction of transmission line $l$with respect to node n: • $Dir_{n,l} = 1$ if transfer of line l is towards node n • $Dir_{n,l} = -1$ if transfer of line l is from node$n$
F_l^{ini}	Initial capacity of line l [MW]
Fix_l	Fixed investment cost of line l [US$/yr]
$GenInv_g$	Investment cost of generator g [US$/MW.yr]
$\overline{K_g}$	Energy resource (maximum) potential associated with generator g [MW]
$\overline{M}$	A large number (to apply Big-M method)
P_g^{max}	Maximum capacity of generator g [MW]
$Type_l$	Type of transmission line l, where: • $Type_l = 0$ for existing lines • $Type_l = 1$ for candidate lines from a renewable project (for Radial cases) or a collector substation (for Pseudo and Fully cases) to a node of the main system • $Type_l = 2$ for candidate lines within a cluster of renewable projects (from a renewable project to the collector substation belonging to the same cluster) • $Type_l = 3$ for candidate lines connecting 2 collector substation (from a collector substation to another one belonging to two different clusters)
Via_l	Variable investment cost of line l [US$/MW.yr]
$VoLL$	Value of lost load [US$/MWh]
ΔT_e	Duration of season e [hrs]
$\Delta T_{t,e}$	Duration of snapshot t in season e [hrs]
ρ_s^{Hydro}	Probability of hydro scenario s [p.u.]

A.2. Formulation

This section details the formulation of the two-stage stochastic mixed integer linear program (SMILP) proposed and implemented in FICO Xpress. Next, x|z refers to x given z and xy refers to x minus y, where x and y are sets and z is a condition.

A.2.1. Common formulation

In this section, we show the formulation of the mathematical problem that is common for all coordination approaches.

A.2.1.1. Objective function. The objective function seeks to minimize the overall cost of expanding the power system, including investments in new power plants (renewable projects and conventional technologies), investments in the transmission network, and the cost of operation of the system (generation dispatches).

$$\min\left\{\begin{array}{c} \sum_{g\in Ng|Class_g=1} GenInv_g\cdot P_g^{max}\cdot Z_g + \sum_{g\in Ng|Class_g=2} GenInv_g\cdot K_g + \\ \sum_{l\in Nl} Fix_l\cdot X_l + Via_l\cdot I_l + \\ \sum_{s\in Ns}\rho_s^{Hydro}\cdot\left(\sum_{e\in Ne}\left(\sum_{t\in Nt}\left(\sum_{g\in Ng}P_{g,t,e,s}\cdot CV_g\cdot\Delta T_{t,e}+\sum_{n\in Nn}LL_{n,t,e,s}\cdot VoLL\cdot\Delta T_{t,e}\right)\right)\right)\end{array}\right\}$$

A.2.1.2. Energy balance. In every node of the power network, energy demand needs to be supplied by either internal generation or imports. Alternatively, demand can be (partially) curtailed if local production plus imports do not suffice.

$$D_{n,t,e} = LL_{n,t,e,s} + \sum_{g\in G_n} P_{g,t,e,s} + \sum_{l\in Nl} Dir_{n,l}\cdot f_{l,t,e,s} \qquad \forall n\in Nn, t\in Nt, e\in Ne, s\in Ns$$

A.2.1.3. Production constraints. The energy produced by every installed or candidate generator is limited by its capacity or the availability of the primary resource (e.g., a solar power generator cannot produce at night). In the case of hydro reservoir, there is a constraint that limits the aggregate level of generation within a given period of time (e.g., a season). This constraint is imposed in order to correctly represent the practical limitations in the availability of stored water.

$$\sum_{t\in Nt} P_{g,t,e,s}\cdot\Delta T_{t,e} \le P_g^{max}\cdot CF_{g,t,e,s}\cdot\Delta T_e \qquad \forall g\in Ng|Class_g = 0,\ g\in Gres,\ e\in Ne,\ s\in Ns$$

$$P_{g,t,e,s} \le P_g^{max}\cdot CF_{g,t,e,s} \qquad \forall g\in Ng|Class_g = 0,\ g\in Ng\backslash\{g\in Gres\},\ t\in Nt,\ e\in Ne,\ s\in Ns$$

$$P_{g,t,e,s} \le Z_g\cdot P_g^{max}\cdot CF_{g,t,e,s} \qquad \forall g\in Ng|Class_g = 1,\ t\in Nt,\ e\in Ne,\ s\in Ns$$

$$P_{g,t,e,s} \le K_g\cdot CF_{g,t,e,s} \qquad \forall g\in Ng|Class_g = 2,\ t\in Nt,\ e\in Ne,\ s\in Ns$$

A.2.1.4. Power transfer constraints. Transfers among network nodes are limited by the capacity of the transmission system, which can be enhanced if network investments are undertaken.

$$-F_l^{ini} - I_l \leq f_{l,t,e,s} \leq F_l^{ini} + I_l \qquad \forall l \in Nl,\ t \in Nt,\ e \in Ne,\ s \in Ns$$

A.2.1.5. Generation investments constraints. Depending on the class of the generator, investment variables are constrained to be, binary or continuous. New renewable generation ($Class_g = 1$) are modeled through binary variables, while new thermal generation ($Class_g = 2$) through continuous variables.

$$Z_g \in \{0,1\} \qquad \forall g \in Ng | Class_g = 1$$

$$K_g \leq \overline{K_g} \qquad \forall g \in Ng | Class_g = 2$$

A.2.2. Additional formulation to model each coordination strategy

Unlike the previous section (that presents the common formulation to all coordination strategies), in this section we show the mathematical formulation that is added to model each coordination strategy.

A.2.2.1. Equations to model the radial, fully decentralized strategy. Within this coordination level, each candidate project can build a direct line to the main transmission system. To reduce the number of candidate topological combinations of new lines, candidate projects can be connected to the main system by either the line with the shortest path or the second shortest path and this is a decision of the SMILP optimization model (so, every candidate project present two candidate lines to the main grid connection). This is modelled through the following equations.

$$X_l \in \{0,1\} \qquad \forall l \in Nl | Type_l = 1$$

$$I_l \leq \overline{M} \cdot X_l \qquad \forall l \in Nl | Type_l = 1$$

$$\sum_{l \in Nl} X_l = Z_g \qquad \forall g \in Ng | Class_g = 1,\ \forall l \in Nl | Type_l = 1$$

A.2.2.2. Equations to model the radial, partially decentralized strategy. The mathematical formulation of this coordination strategy is the same as the Radial, fully decentralized case. The only difference of this case concerning the previous one is that in this case, the model has more interconnection options to the main system including dedicated substations that are owned by other generators and non-regulated large consumers.

A.2.2.3. Equations to model the pseudo coordinated strategy. In this coordination strategy, a group of candidate projects located nearby can coordinate to build a shared transmission infrastructure (composed of lines and a "collector" substation) and therefore connects to the main system through a single transmission line.

Hence, there are two kinds of decisions regarding new transmission lines:

(a) Topology of a candidate network among the members of the group or candidate cluster of generators
(b) Landing point in the main system to connect the candidate group of generators to the electricity system

Regarding (a), this is obtained separately and prior to run the optimization model. To do so, we determine a *minimum spanning tree* with candidate options to interconnect all members of the group/cluster of candidate projects. Regarding (b), we optimize the connection of the new line between the main system and the group/cluster of candidate generators.

In this case, each cluster of renewable projects has a unique "collector" substation. Therefore, a candidate transmission line (lines with $Type_l = 2$) can connect a candidate project (generators with $Class_g = 1$) to its candidate collector substation. So, in this specific case if the model integrates the candidate project there will be the necessity to build the candidate transmission line from the project to the collector substation. This is why we consider $X_l = Z_g$ for candidate lines and generators that belong to the same cluster.

Besides, this collector substation have two candidate lines (lines with $Type_l = 1$) in order to be connected to the main system with either the nearest or second nearest substation, as in the radial cases.

$$X_l \in \{0,1\} \qquad \forall l \in Nl | Type_l = 1,2$$

$$I_l \leq \overline{M} \cdot X_l \qquad \forall l \in Nl | Type_l = 1,2$$

$$\sum_{l \in Lcl_c} X_l \leq 1 \qquad \forall c \in Ncl$$

$$X_l = Z_g \qquad \forall g \in Ng | Class_g = 1,\ \forall l \in Nl | Type_l = 2$$

A.2.2.4. Equations to model the fully coordinated strategy. This strategy represents the maximum coordination level. Under this strategy, all candidate generators can be fully coordinated to interconnect among themselves and consider all available options as a landing substation in the main grid.

In order to reduce the number of candidate topological combinations of new lines, this formulation consider the same clusters or groups defined in the pseudo coordinated case, but rather than connecting each cluster to the main system directly, in this case, we allow the model to connect all the "collector" substations among themselves (lines with $Type_l = 3$) simultaneously with the decision of interconnection to the main system (lines with $Type_l = 1$) and interconnection inside the clusters (lines with $Type_l = 2$). We follow the approach next:

- group several candidate generation projects in various clusters, then
- interconnect these clusters among themselves,
- finally connect a few of these clusters to the main system.

$$X_l \in \{0,1\} \qquad \forall l \in Nl | Type_l = 1,2,3$$

$$I_l \leq \overline{M} \cdot X_l \qquad \forall l \in Nl | Type_l = 1,2,3$$

$$\sum_{l \in Lcl_c} X_l \leq 1 \qquad \forall c \in Ncl$$

$$X_l = Z_g \qquad \forall g \in Ng \big| Class_g = 1,\ \forall l \in Nl \big| Type_l = 2$$

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