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CONSTRUCTION OF A CHILEAN ENERGY MATRIX PORTRAYING ENERGY SOURCE SUBSTITUTION: A SYSTEM DYNAMICS APPROACH

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Abstract

The energy matrix is a useful tool for understanding the trends of production and consumption in a country and for evaluating long-term energy policies. In this paper, we model the evolution of Chile's energy matrix using a behavioral simulation model. The model is developed and calibrated by considering a dynamic substitution of energy sources. Chile's stated policy is to become less dependent on imported fossil fuels, to increase security of supply and improve the environment. Our simulation experiments show that the energy matrix is very robust with regards to external fuel prices and changes in investment cost. Thus, in order to be able to observe changes in the composition of the energy matrix, there is a need for strong intervention by the regulator, or the government, to provide incentives for renewables.

Keywords

Energy planning, System Dynamics, energy matrix, Chilean energy sector

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1. Introduction

From the 1970s, and initially caused by the oil crisis, there has been a focus on energy models dealing with (integrated) energy resource planning (Georgopoulou et al., 1998; Jebaraj & Inian, 2006; Loken, 2007). The aim of these models has been to facilitate efficient planning, forecasting and optimal use of the various types of energy source, and similarly for the corresponding consumption sector, at the national level (Jebaraj & Inian, 2006). Most of the recent models use a simple representation of the demand side, usually a single-variable, linear, inverse demand function, which does not capture any dynamic adjustment to past prices or energy substitution (Abada et al., 2013).

Among these different models, the energy matrix is a useful instrument for policy assessment, since it provides insight into the production and consumption trends by energy source and sector, under different scenarios. It can either be considered as an indicator of the structural trends in the energy sector and be used by policy makers and regulators (Fontaine, 2011), or as a tool for potential investors to evaluate investment opportunities based on changing demands and requirements of the energy sector and associated infrastructure.

The dynamic energy-matrix analysis we perform is based on the approach developed by Moxnes (1987), who constructed a simulation model of the European OECD countries' industrial energy demand that explained the historical fuel substitution during the period 1960-1983. In a subsequent study, Moxnes (1990), shows that this framework provide a good fit to historical time series of fuel choices in European OECD countries' electricity generation. In order to construct a uni-equational function that represents the demand component of the model we follow Abada et al. (2013), and use a system dynamics model

to construct an adaptable demand function to be incorporated within an imperfect-competition model.

In this paper, we construct a dynamic energy-planning model that represents the energy matrix behavior. The model shows the dynamic substitution between energy sources, considering the differing effects of strategic decisions that impact the structure of the matrix, and it allows us to analyze system behaviors over time. We analyze the evolution of the Chilean energy matrix as Chile needs to diversify its energy sources because it is heavily dependent on foreign energy supplies (Bezerra et al., 2012). Electricity is included within the energy matrix, and the model is not exclusively for electricity. More than 70% of its basic energy sources are imported (Bezerra et al., 2012), and this situation will not change significantly in the coming years (García et al., 2011). Chile has no significant oil, gas, or coal resources, so the only domestic alternative is hydropower and other renewable energy sources (Bezerra et al., 2012). This is an uncomfortable situation resulting from a rapid increase in energy demand driven by economic growth in the region (Aravena et al. 2012), by oil price fluctuations (García et al., 2011), and by the restriction in natural gas supply from Argentina (Ponzo et al., 2011). Furthermore, Chile has a private and competitive market driven by reforms introduced in the early 1980s. These reforms included the deregulation of the electricity sector, with separation of generation, transmission, and the distribution of electricity (Bezerra et al., 2012). More recently, Chile has been trying to promote diversification of the power matrix to increase the share of non-conventional renewable energy (NCRE). The question is whether it will help reduce the dependence on imported fuel and reduce environmental impacts in the medium to long-term (García et al., 2011).

This paper is organized as follows: Section 2 presents a review of the Chilean energy sector. Section 3 provides a brief overview of the methodology while Section 4 discusses the validation of the methodology and presents the calibrated model for the energy sector in Chile during the period 1980 to 2012. We conclude with a discussion of different options for the Chilean energy sector that can contribute to the diversification of the energy matrix, thereby reducing dependence on imported energy sources.

2. The Chilean energy sector

Chile is a country heavily dependent on imported fossil energy, as more than 70% of its primary energy sources are imported. It has no significant oil, gas, or coal resources, leaving the further development of hydropower and other renewable energy sources as the only long-term alternative to imports (Bezerra et al., 2012). The current situation is illustrated in Table 1, which shows the breakdown between the primary energy sources in Chile in 2011. Fossil fuel has the largest share, of which oil comprises 44%, natural gas 26%, and coal 21%. The domestic sources are hydro, 9%, with other renewable sources contributing 0.18% of total consumption (CNE, 2012).

Energy Source	Market Share (% of total)
Oil	44
Natural Gas	26
Coal	21
Hydro	9
Other Renewables	0.18

Table 1. Energy mix – 2011 **Source:** (CNE, 2012)

In the last two decades, Chile has faced a number of situations that have impacted the delivery of energy, such as a severe drought that drove the country to power rationing in the late 1990s, unforeseen restrictions on natural gas supplies from Argentina since 2004,

and in recent years reduced inflows of water for hydropower (CNE, 2012). These cases show the vulnerability of the Chilean electricity system to external events. Chile has replaced existing power plants with plants that operate primarily with coal and diesel, which has led to an increase in the share of coal, from 12% in 2006 to 21% in 2011 (CNE, 2012; García et al., 2011).

The dependence on fossil fuels has increased the interest in alternative energy sources that can lower this dependence while at the same time reducing environmental impacts (García et al., 2011). This interest has led to public policies involving diversification of the power matrix, with an increasing share of NCRE in the medium and long-term (García et al., 2011). The discussion of renewable energy has also created the foundation for the 2008 Chilean NCRE law, which implemented a requirement of all electricity sub-sectors, i.e. power traders, distribution companies, and generators, to certify that at least 10% of the energy comes from NCRE, self-produced or purchased from other generators (Congreso Nacional de Chile, 2008). This law required an initial five percent obligation from January 2010 until 2014, followed by an annual increase of half a percent per year, reaching ten percent in 2024 (Bezerra et al., 2012). This is the first move attempting to reduce energy dependence in order to ensure stability and economic development (García et al., 2011).

However, there are barriers to the development of NCRE: for example, the high cost of investment combined with the limited possibilities of financing, and connection to transmission lines, and secure long-term contracts (CNE, 2012). Additionally, NCRE in Chile are currently at an early stage; however, even when they are a good alternative, representing a complete solution for electricity demand growth, they are expected to increase at a rate of only 6% per year (Rudnick & Mocarquer, 2008). To complicate the

issue, Chile does not have enough arable land to establish crops with bioenergy potential, as competition with land used for food production would leave little land available for NCRE technologies (García et al., 2011).

Chile has potential for further hydropower developments (Bezerra et al., 2012), estimated at around 9000 MW (CNE, 2012). However, their consideration needs to take into account that these resources are located either in indigenously populated areas, **or** in regions with high tourism potential (Bezerra et al., 2012). It is expected that the growth rate will be between six and seven percent per year. This projected growth will require a significant increase in new investments, creating an additional 8GW to meet demand – almost a doubling of the 2011 level (CNE, 2012). This raises further concerns given the dependency of Chile on external supplies of fossil fuels (Bezerra et al., 2012; CNE, 2012). A more detailed description of the potential evolution of the Chilean energy matrix can be found at Comisión Nacional de Energía (CNE) and (IEA, 2012).

3. Literature and method

Over the last forty years, different methods for energy planning have been developed, e.g. multi-criteria analysis (Georgopoulou et al., 1998, and Loken, 2007), econometrics (Zhidong, 2010), and combined methodologies as proposed by Terrados et al. (2009). Another type of econometric model is an integrated assessment model which takes a broader (inter-disciplinary) approach to the modeling of particular environmental issues including energy, e.g. Stanton et al. (2009). However, most energy planning models are static in nature and do not capture the dynamics of the industry well. Our objective is to focus on the changes in energy sources over the medium to long-term. We propose to use a simulation method based on system dynamics. This approach applies a variation of control theory to managerial and decision problems that has been used in a range of different contexts (Forrester, 1961; Sterman, 2000, Morecroft, 2007). System dynamics

has been used in the energy area for more than forty years, as it can capture many of the characteristics of this sector, e.g. nonlinearities, feedback, delays, and dynamics interaction between factors (Sterman, 2000; Naill & Belager, 1992). Models developed using system dynamics for energy planning include the COAL and FOSSILS models developed for the U.S. government (Naill et al., 1992, Naill, 1992). Other applications include conservation (Ford & Bull, 1989), policy evaluation (Ford, 2002), and power plant construction cycles in the competitive electricity market (Bunn & Larsen, 1992). Other large energy models include the economy-energy interaction model (Sterman, 1981), and the oil life-cycle model (Davidsen et al., 1990); more recently, models of energy and climate, such as C-Roads, have been developed (Fiddaman, 2002; Sterman et al., 2015). For an overview, see Arango and Larsen (2013), Ford (1997), Bunn and Larsen (1997), and more recently Leopold (2016). For energy systems models, including system dynamics models used in the UK over the last nine years, Hall and Buckley (2016) provide an overview. System dynamics energy models have also been developed for inter-fuel substitution, as applied by Moxnes to European OECD countries (Moxnes, 1990); a similar approach was used by Abada et al. (2013) for construction of a fuel-demand function portraying the inter-fuel substitution of eight countries.

As mentioned above, there are a number of reasons why system dynamics is a good approach for the analysis conducted here, relative to a more economics-based model: (i) the need to capture the main nonlinearities in the system, (ii) the need to generate a model that represents the system in the real world (i.e. the real energy matrix), (iii) the possibilities of capturing the effect of feedback between the demand and supply side, and the long delays that influence these dynamics, and (iv) the reliance of system dynamics on numerical simulation rather than closed-form solutions, allowing for a more detailed model (Sterman, 2000; Morecroft, 2007; Ponzo et. al., 2010). System dynamics has also

a number of disadvantages. Among them, system dynamics is only appropriate if the problem is a dynamic problem, i.e. it has a time dimension, includes delays, and often includes nonlinearities. Additionally, there are frequent problems of reproducibility, and SD uses continuous simulation where discrete events are not easy to incorporate. Nevertheless, the current view is certainly to have a portfolio of different models for energy policy analysis (Hall and Buckley, 2016). Based on this, we considered system dynamics to be an appropriate framework for the representation of the energy matrix for Chile, and it could be considered as an application of the approach employed by Abada et al. (2013).

4. Model development

We review and further elaborate the model from Moxnes (1987, 1990) and Abada et al. (2013) to explore a country's energy policy options. While our purpose is to analyze the behavior of the Chilean energy matrix, we start out from a generic model that is applicable to the analysis of any country. It only becomes specific to the Chilean case when it is calibrated with historical and current prices and demand.

The model uses five energy sources, with index i : coal, oil, natural gas, hydro, and other renewable sources. We have aggregated all the renewable sources, except for hydro, for two reasons. Firstly, they represent a small share of the total energy matrix. Secondly, the policies proposed by the Chilean government are addressed to all the non-hydro NCRE, without emphasizing any one of them. It assumes that adjustments in the energy source are made beforehand, where the total cost C_i of a fuel option i is given by equation (1) as follows (Abada et al., 2013):

$$C_i = \frac{CC_i}{PBT_i} + OO_i + \frac{P_i + Q_i CO_2 + P_{CO_2}}{E_i} - PR_i . \quad (1)$$

In equation (1), CC_i represents the capital cost, OO_i is the operating cost, and PBT_i denotes the related payback time. The variable P_i is the price of fuel i (natural gas, oil and coal), P_{CO_2} is the price of CO_2 (Abada et al., 2013), Q_{i,CO_2} is the emission factor for each energy source, and the burner efficiency of a fuel is given by E_i . The last variable, PR_i , is a premium that represents a number of factors such as pollution, employment opportunities, flexibility, availability, and import dependence on the fuel (Moxnes, 1990).

The share s_i of an energy source i among new investments is a function of the relative energy-source cost. The formulation is presented in equation (2), as follows:

$$s_i = \frac{e^{-\alpha C_i}}{\sum_i e^{-\alpha C_i}}, \quad (2)$$

which is a multinomial logit model where α is a non-negative sensitivity to the cost parameter (Moxnes, 1990). According to the model, the higher the price P_i , the lower is the share s_i . The total of investments I_i in equipment for source i is estimated with the share s_i times the total investment I , as shown in equation (3):

$$I_i = s_i I. \quad (3)$$

Equations (4) and (5) represent the dynamic adjustments of installed capacity for both new (KN_i) and old equipment (KO_i). The dynamics consider the continuous process from the investments in new equipment, I_i , followed by a construction delay, through to installed equipment. New capacity is considered to become old equipment half way through its lifetime, T_i . Finally, capacity is phased out, DO_i , by the end of the lifetime of the particular technology. This approach is used in the original Moxnes model (1990), by including two vintages for installed equipment. Thus, these equations are:

$$\frac{dKN_i}{dt} = I_i - \frac{KN_i}{\frac{T_i}{2}} \quad (4)$$

$$\frac{dKO_i}{dt} = \frac{KN_i}{\frac{T_i}{2}} - \frac{KO_i}{\frac{T_i}{2}}. \quad (5)$$

From equation (5), the depreciation DO is the sum of depreciation for all sources i ,

$$DO = \sum_i DO_i = \sum_i \frac{KO_i}{\frac{T_i}{2}}. \quad (6)$$

To establish the investment function, we start with the total capacity of source i , which is defined as $K_i = (KN_i + KO_i)$; and thus, the total installed equipment is $K = \sum_i K_i$.

The model considers the total demand, ED , as exogenous. Following Abada et al., *“investment in new energy plants should be linked in some way to the observed discrepancy between demand and the installed capacity of existing energy plants”* (Abada et al., 2013, p. 242). The demand faces a dynamic adjustment, which consists of the time required to make adjustments, TI (Moxnes, 1990).

The investment function models the total investment as an increasing function of $ED - \frac{K}{TI}$, and the depreciation DO . Replacement of the retired capacity allows the model to maintain the current energy capacity. A function fulfilling these conditions has been proposed by Moxnes (1990) as shown in the following equation:

$$I = DO * f\left(\frac{ED-K}{TI*DO}\right), \quad (7)$$

where f is a piecewise continuous function given as:

$$f(x) = x + 1 \quad \text{if} \quad x \geq 0, \quad (8)$$

$$f(x) = e^{a \cdot x} \quad \text{if} \quad x < 0,$$

where a is a non-negative parameter, described further below. There are no adjustments when capacity equals demand, ($ED = K$); therefore, investments compensate for depreciation ($f(0) = 1$). On the one hand, when energy demand is higher than capacity ($ED > K$), investments lead to an increase in installed energy plants ($f(x) > 1$ if $x > 0$). On the other hand, even when energy demand is lower than capacity ($ED < K$), there is still some investment. Nevertheless, in this latter case, given that $I < DO$, there will be

a drop in the installed equipment ($f(x) < 1$ if $x < 0$). Capacity utilization, U , is defined in equation (9), as follow:

$$U = \frac{ED}{K}. \quad (9)$$

The model formulation takes into account that capacity utilization is similar across energy sources ($U_i = U$).

Finally, the simulated demand ($\hat{D}_i$) for energy source i , is:

$$\hat{D}_i = U_i K_i = ED \frac{K_i}{K}. \quad (10)$$

This completes the description of the model that we simulate in the next sections.

4.1. Data, model calibration, and model validation

We calibrate the model to the actual energy matrix in the period 1980 to 2012. During this period, Chile faced a number of difficult situations, such as severe drought that led to power rationing in the late 90s, unforeseen constraints on the supply of Argentine natural gas from 2004, and in recent years lower hydrology (CNE, 2012). The data used to calibrate the model consists of time series from the International Energy Agency (2012, 2014), BP Global (2013), and the Comisión Nacional de Energía de Chile (CNE) energy consumption data. The price data refer to the national end-use prices in U.S. dollars reported by the International Energy Agency (2012, 2014); a weighted average of industry and household prices is used, as we are modeling the aggregated energy matrix. Price information of "petroleum products", "coal" and "natural gas" comes from IEA Statistics: Energy Prices and Taxes (2011, 2013). All prices are in 2010 U.S. \$/toe. Capital costs, operating costs, and plant efficiencies are from the National Energy Commission (CNE, 2009), and IEA (2011). The cost assumptions of the model are summarized in Table 2.

According to Abada et al. (2013), the coefficient a in the function f for total investment (eq. 8) has been set to 0.231, which is an interpolation from the extreme left point from Moxnes (1990, p.8). In the same way TI is assumed to be equal to 1 year (Abada et al., 2013).

	Year	Coal	Oil	Natural Gas	Hydro	NCRE
Capital costs - CC_i (\$/toe per year)	All	6639	706	1627	2990	3232
Payback time - PBT_i (years)	All	5	5	5	5	5
Other operating costs - OO_i (\$/toe per year)	All	492	1274	1167	46.52	112
Efficiencies - E_i (% useful)	All	42	41	50	96	70
CO₂ emission factor Q_{i,CO_2} (tCO₂/toe)	All	7.43	8.35	4.30	0.10	0.35

Source: Comisión Nacional de Energía (2009), WEC (2008), International Energy Agency (2005-2008)

Table 2. Cost assumptions for energy sector

For calibration we use a procedure to minimize the deviation between the simulated outcome and historical data (Abada et al., 2013). For the economic evaluation, we use an approach proposed by Vanni et al. (2011). All available information has thus been used e.g. costs, efficiencies of the energy plants, etc., and the calibration procedure has only been applied to adjust the value of the most uncertain parameters, i.e. initial values of the state variables, α , and premiums (Moxnes, 1990; Abada et al., 2013). We specify an error function to measure the distance between the empirical and simulated demand. For each energy source i , the distance between historical D_i^t and simulated $\widehat{D}_i^t$ consumption is defined by the model's error function, the sum of squared errors, i.e.:

$$e = \sum_i \sum_t |D_i^t - \widehat{D}_i^t|^2. \quad (11)$$

Table 3 reports the calibrated values for Chile. The relatively large values of the oil premiums, compared with those for natural gas and coal, reveal a strong preference for oil, indicating the historic background for the current dependence on oil. In addition, the negative value of the NCRE premium shows the need to create incentives, in order to

decrease the costs of investment in NCRE sources, if one wishes to diversify energy sources away from imported oil and its environmental impacts.

Calibrated values of the parameters (Mtoe/year)									
KN_{Coal}	KO_{Coal}	KN_{Oil}	KO_{Oil}	$KN_{Nat.Gas}$	$KO_{Nat.Gas}$	KN_{Hydro}	KO_{Hydro}	KN_{NCRE}	KO_{NCRE}
3.88	1.29	18.30	2.51	2.81	1.86	1.18	4.59	0.043	0.005

Alpha (toe/\$)		Premium (\$/toe)			
α	PR_{Coal}	PR_{Oil}	$PR_{Natural\ Gas}$	PR_{Hydro}	PR_{NCRE}
0.0015	590.42	1502.71	926.75	0.0	-1071.25

Table 3. Calibrated values of the parameters

Metric	Equation	Coal	Oil	Natural Gas	Hydro	NCRE
MSE	$MSE = \frac{1}{n} \sum (X_m - X_d)^2$	0.62	2.39	2.53	1.43	0.038
Theil index	$U^M = \frac{(X_m - X_d)^2}{MSE}$	0.03	0.02061	0.03	0.14	0.19
	$U^S = \frac{(S_m - S_d)^2}{MSE}$	0.15	0.18	0.30	0.19	0.03
	$U^C = \frac{2(1-r)S_m S_d}{MSE}$	0.82	0.81	0.67	0.67	0.78

Table 4. Error analysis of the model

 Insert figure 1 about here

Two dimensions are considered for validation of system dynamics models: structural validity and behavioral validity. Structural validity establishes whether the implemented model structure is an adequate representation of the phenomenon being modeled, and behavioral validity compares the model-generated behavior with the empirical behavior, i.e. the capacity of the model to reproduce past behavior (Barlas, 1996). This model has been built based on the relevant literature, and from Moxnes, (1990) and Abada et al. (2013).

Focusing our discussion on the behavioral validity. Figure 1 shows the historical demand behavior compared with the simulation results for the Chilean case. A visual inspection of the figure indicates that the model is able to capture the main trends not only in the aggregated demand but also for each of the fuel sources. Additionally, Table 4 presents the statistical tests performed to confirm the validity of the constructed model. We use the Theil inequality statistics (Sterman, 1984), which provide a decomposition of the mean square errors in terms of bias (U^M), unequal variation (U^S), and unequal co-variations (U^C). Looking at Table 4, we observe that the largest share of the MSE can be attributed to U^C , the imperfect covariation component of the Theil inequality statistics. Based on the low bias and variation components, we can assume that the errors are unsystematic, implying that the model replicates the empirically observed behavior. Therefore, our simulation model does a good job of reproducing the inter-fuel substitutions. Thus, we confirm the validity of the model.

5. Simulation results

We now turn to the discussion of the simulation experiments with the model. We start by providing the base case simulation and continue with a series of different set scenarios. The behavior of the energy matrix is generated through changes in the prices for the fuels (oil, natural gas, and coal) that constitute the different sources for energy supply, and through changes in the demand, as we explained in the previous sections. The base case was chosen to keep the status quo in Chile. Demand forecasting is done by constructing a single-equation demand function that captures the dynamic adjustment of the different energy sources' consumption resulting from changes in fuel prices (Abada et al., 2013). The selection of this base-run scenario was inspired by Abada et al. (2013), where future fuel prices are generated assuming that prices are random variables that follow a uniform distribution in the interval $[0,200]$ \$/toe. We performed 1000 iterations for the

construction of each different pricing scenario, and one was chosen randomly for the base-case scenario. This scenario serves as a reference point to compare with changes in energy demand, as prices and policies are changed in the other scenarios.

Simulation results for the base case are presented in Figure 2, given in terms of the capacities of energy plants by energy sources in the period 2013-2030. The figure shows that the energy matrix continues with the same trend, where the main energy source is oil, followed by hydro and natural gas, and the smallest contribution is from coal and NCRE. Under the base-case conditions, differences in the Chilean energy composition are lower than 5% compared with the reference year (2012). The simulation shows that the country will continue its dependence on the external energy supply, as oil has the largest market share, 41.2%, by 2030. We assume implicitly that there are no problems with the availability of oil; while the last few years have shown large fluctuations in the price there has not been any supply shortage.

The resulting change in the energy matrix is shown in Table 5. Oil continues to be the dominant source of energy, although by 2030 its market share will have fallen by 5 percent in terms of the total demand. However, the total amount of oil consumed by 2030 is higher than in 2012 due to the overall increase in consumption. There is a dynamic substitution due to the effects of the price scenarios and feedbacks, where the loss of market share for oil is approximately equal to the gain in market share for hydro; where in 2012 the market share of hydro was half of that of oil, by 2030 it is only 30% lower than that of oil. The other energy sources do not show any significant changes between 2012 and 2030, although we can observe a small shift away from coal towards natural gas and NCRE. The overall implication is that Chile will not free itself from its dependence on imported energy. What we observe is a common, but important, inertia in changing an energy system, which is expected as changes often take a long time to be implemented

for most energy systems. As we observe in the base case, there is no long-term significant change as the incentives are not able to overcome the inertia.

 Insert figure 2 about here

Energy Source	Capacity 2012 (% of total capacity)	Capacity 2030 (% of total capacity)
Natural Gas	17	18
Hydro	23	28
Coal	11	9
Oil	46	41
NCRE	3	4

Table 5. Capacity by energy sources 2012-2030

Next, we compare different policy options for diversifying the energy mix with the base-case, to understand which conditions will reduce the dependence on fossil fuel and increase the share of renewable energy, and understand the underlying reasons for the changes. These changes include different developments in prices and demand; we also simulate strategies that have been suggested by different energy agencies in Chile, e.g. CNE. We are particularly interested in which regulatory policies might be used to reduce Chile's dependence on external fuels, particular fossil fuels. Is it possible to find a set of policies that will significantly reduce the dependence on fossil fuel in the medium term?

We simulated five sets of policies:

- Price policy: represents how different pricing scenarios influence demand, and the energy-source substitution dynamics. We built three different price scenarios: (i) *stochastic*, where the future fuel prices are generated from two different distribution functions adjusted to the historical prices. We used the @Risk

program to select the distributions with the best fit (the distributions are triangular for natural gas, and exponential for oil and coal). (ii) For the *decreasing* prices scenario, we took an interval from the historical prices where they show the most significant downward trend and based the future prices on that interval. (iii) Similar to the *decreasing* prices scenarios, we created the *increasing* prices scenario, by taking an interval from the historical prices where they exhibited an upward trend. In all cases, including the base case, we performed 1000 iterations for the three price scenarios. Table 7 provides more information about the prices in the different scenarios.

- Market policy: investment decisions are in place, based on the market opportunities. Thus, the expected return on an energy source investment is based on the estimated payback time (PBT_i).
- Non-conventional and renewable policy: provides incentives for the investment in NCRE capacity in the Chilean energy matrix. This is the scenario where we assume that the intention of law 20.257 will be fully implemented.
- Cost policy: changes in investment and operating costs leads to a new configuration of the energy mix.
- Combination policy: implements both the market policy and the non-conventional and renewable policy above.

Tables 6 and 7 provide information about the assumptions in the different scenarios. Table 6 includes a comparison between the base case scenario and the policies applied in each of the three scenarios as well as the percentage each scenario varies from the base case by the end of the simulation. Table 7 provides the average price during the period and the change compared to the base case. This information helps us to understand the actual reasons for differences in behavior.

Energy Source	Market		NCRE			Cost			Combined			
	Payback time (PBT _i)	Payback time (PBT _i)	Premium (PR _i)	Premium (PR _i)	<i>Change</i>	Capital Costs (CC _i)	Capital Costs (CC _i)	<i>Change</i>	Payback time (PBT _i)	Payback time (PBT _i)	Premium (PR _i)	Premium (PR _i)
	Base Case	Policy	Base Case	Policy		Base Case	Policy 2030		Base Case	Policy	Base Case	Policy
Coal	5	10	590.4	628.6	6.4%	6639.5	3201.0	-51.7%	5	8	590.4	628.6
Oil	5	10	1502.7	1502.4	-0.02%	706.0	706.0		5	8	1502.7	1502.4
Natural Gas	5	10	926.7	890.8	-3.8%	1627.8	1329.8	-18.3%	5	8	926.7	890.8
Hydro	5	10	0	0.1		2990.5	2658.2	-11.1%	5	8	0	0.1
NCRE	5	10	-1071.2	506.6	147.3%	3232.6	960.7	-70.2%	5	8	-1071.2	506.6

Table 6. The assumptions in the different scenarios.

Average Simulated Prices (2013 to 2030)							
Energy Source	Base Case	Stochastic		Decrease		Increase	
	Price	Price	<i>Change</i>	Price	<i>Change</i>	Price	<i>Change</i>
Coal	101.72	74.71	-26.55%	35.32	-65.27%	234.11	130.14%
Oil	83.22	72.23	-13.20%	21.95	-73.63%	113.46	36.34%
Natural as	112.89	85.70	-24.08%	53.90	-52.25%	145.82	29.17%

Table 7. Average simulated prices in the scenarios.

The first four policies are based on the report "Energy Scenarios Chile 2030 (Comité Técnico de la Plataforma Escenarios Energéticos 2030, 2013), while the fifth is a mix of the proposed policies for an integrated analysis. We start by investigating the effect of price on the development of the energy matrix, which is the main variable driving substitution. We ran three different policies, one with an increase in prices for oil, coal and gas, one with a decrease in the prices, and finally one with stochastic prices where the mean of the price is the same as in the base case. Table 7 shows the changes in the prices for the three simulated scenarios. For example, in the decreasing price scenario, the fuel prices vary on average between 21.95 to 53.90 U.S. \$/toe. Table 8 shows the results of the different simulations for the market share of each fuel at the end of the period (2030).

Energy Source	Base Case	Decrease in Prices (% of total capacity)	Increase in Prices (% of total capacity)	Stochastic Prices (% of total capacity)
Natural Gas	18	19	16	17
Hydro	28	26	30	28
Coal	9	10	7	9
Oil	41	45	43	43
NCRE	4	3	4	4

Table 8. Effect of different price policies on the energy matrix by 2030

As we can observe in Table 8, oil retains the dominant position as a percentage of capacity. In all the three cases, the percentage of oil is higher than in the base case, but there is generally no significant difference between the three scenarios as it varies from forty-three to forty-five percent of total capacity. We can also see that the share of renewables, i.e. hydro and other NCRE, is more or less stable across the different scenarios. The only slight variation is in the case of increasing prices where hydro reaches thirty percent of the total demand, and thus, a potential scenario with very high fuel prices may lead to a higher (but still modest) renewables share, because of slight variation in the

strong inertia of the fuel's dynamic substitution. In fact, we performed a sensitivity analysis where natural gas prices are increased by up to ten times (not reported here), however, the simulations show no changes of renewables by 2030 as a result of increasing the price of natural gas.

In the case of decreasing prices, hydro loses market share due to its relatively high investment cost. We have to conclude from this that the changing fuel prices will not deliver the goal of making Chile less dependent on imported fuel; even in the “best” case, it will only lower Chile's dependence on (imported) fuel marginally, and most likely at a significantly higher cost than the base case.

In the market policy scenario (Table 9), investments are made according to current market practices, i.e., investments are made based on feasibility in terms of the estimated payback time. First, we perform a sensitivity analysis of the PBT_i parameter, with a particular focus on the share of NCRE. This is interesting, as one of the main policies of the Chilean government is to diversify the energy mix towards greater participation of NCRE. Simulations show that the largest share that it was possible to obtain for NCRE sources was 5%, with a PBT_i of 10 years. Simulation with a PBT_i of 10 years leads to the shares of the other energy sources. The results show that oil (42%) remains, at the end of the period, the source with the largest share, followed by hydro (28%) and natural gas (16%), similar to that presented in the base case situation. Thus, the market policy leads to very minor changes in the energy matrix as shown in Table 9, with variations lower than 5% for each source.

Energy Source	Base Case	NCRE (% of total capacity)	Cost (% of total capacity)	Market (% of total capacity)
Natural Gas	18	13	16	16
Hydro	28	24	27	28
Coal	9	7	12	8
Oil	41	35	40	42
NCRE	4	21	5	5

Table 9. Effect of the NCRE, Cost and Market Scenario's on the energy matrix by 2030

For the third scenario (NCRE scenario), we look at the possibilities of significantly increasing the share of NCRE. It is a political priority to increase the share of NCRE in the energy matrix and there has been both internal and external pressure on Chile to support this policy. The policy will both support the aim of reducing dependence on imported fossil fuel and also help to lower emissions. This has led to the "meta 20/25" bill, i.e., that 20% of electricity generation by 2025 has to come from NCRE (Comité Técnico de la Plataforma Escenarios Energéticos 2030, 2013). The third scenario aims at achieving this through incentives for investment in NCRE. As the model here is based on a cost approach, the premium parameter, PR_i , for each energy source was manipulated to achieve a 20% participation of NCRE by the end of the simulation period. In this way, the premium parameters are used to reduce the total costs of NCRE, which in turn will encourage investment in these sources. The increase in the PR_i can then be seen as incentives proposed by the Government to reduce costs in these energy sources, e.g., tax incentives, feed-in tariffs etc. For example, Table 6 shows that the PR_i of the NCRE increases 147.30%, which reduces the total costs of NCRE sources and thus can be seen as a way to incentivize investment in those energy sources. In the base case, the share of NCRE was 4% while in this case, with incentives, we achieve an NCRE participation of 21%. Although oil still represents the largest share of total capacity, its share has decreased from the base case by six percentage points, while natural gas has decreased by five percentage points; however, hydro has also decreased, by four percentage points,

which should be offset against the 21% share of NCRE. The NCRE policy manages to increase the share of renewables, but most likely at a relatively high cost as it is heavily subsidized and Chile is still dependent on imported fossil fuel for more than fifty percent of its generation.

For the fourth scenario, we turn to the future investment cost of the different energy sources, as they have a significant influence on the choice of which technology to invest in, and therefore on the composition of the energy matrix. While it might be difficult to predict the future cost of a technology, we use the “official” data from the “Chile Energy Scenarios 2030” and implement them in our model for the period 2013-2030. However, in this study there are only the capital costs for natural gas and coal. Oil costs were not projected, so the initial-cost model for both historical and simulated periods was assumed. The projected costs in this policy decrease as compared with the base case. Table 6 shows the capital costs used in the base case and the capital costs at the end of the scenario in 2030. It should be noted that we assume that the cost will decline over the period. The outcome of this policy is again, as in two of the previous three policies, that the energy matrix is surprisingly stable, as the share of the different energy sources changes relatively little, as can be seen in Table 9. Oil continues to have the largest share of total capacity, by source, at the end of the simulated period, followed by hydro and natural gas, very similar to the base case. Although the proposed policy raises the costs of thermal energy so that other energy sources such as renewable can participate, the results indicate that by 2030 the renewables do not have a representative participation in the Chilean energy matrix.

For the final scenario, we combine two of the above policies: the market and non-conventional renewable energy policy scenarios. By doing this we create a very optimistic scenario regarding the penetration of NCRE, where the non-fossil fuel generation is

advanced as much as possible, using both incentives and government regulation. The results are presented in Table 10. The outcome of this would be an increase of NCRE to 22.3% and a reduction of the share of fossil fuels to just over half of the total fuel consumption in Chile's energy matrix, by 2030. The main reduction in fossil fuels would come from the decrease in the use of oil. However, if we compare the results with the NCRE policy alone, then there are no significant gains, only about one percentage point.

Energy Source	Base Case (% of total capacity)	Combined (% of total capacity)
Natural Gas	18	12
Hydro	28	25
Coal	9	9
Oil	41	32
NCRE	4	22

Table 10. Effect of the Combined policy on the energy matrix by 2030

As one of the main governmental objectives is to decrease the dependence on fossil fuel, in particular imported oil, Table 11 shows the share of fossil fuel and renewables in the base case and the six scenarios that we have run. Looking at the table, the first observation we might make is that in all cases, fossil fuels maintain more than a fifty percent share of the fuel; even in the most optimistic scenario it has a fifty-three percent share. In the scenarios where there are no explicit policies for introducing incentives or regulation for the NCRE the share of fossil fuel is close to seventy percent of the fuel in the energy matrix. Except in the cases of the NCRE and Combined scenario, there is a very limited penetration of NCRE sources for generation, and the renewables are mainly made up by the hydro capacity, which managed to maintain an almost stable share of the energy matrix across all the scenarios. It is worth noticing, as mentioned above, that the combination of the NCRE and the market scenario seems to have little effect as a

“multiplier” on the NCRE sources. In other words, a combination of these scenarios has little effect on the reduction of fossil-fuel dependence.

Scenario	Fossil (% of total capacity)	Renewable (% of total capacity)
Base Case	68	32
Increase in Prices	66	34
Decrease in Prices	71	29
Stochastic Prices	68	32
NCRE	55	45
Cost	68	32
Market	67	33
Combined	53	47

Table 11. Share of fossil and renewable fuel in the different scenarios

The model results show that diversification of the Chilean energy matrix requires policies that attract investment in renewable energy, i.e. policies that increase the revenues from NCRE or that reduce the investment costs are the only ones that enable NCRE to attain a significant participation in the energy matrix. We observe a resistance to increasing the market share of renewables, which is due to the lack of highly aggressive incentives to allow them to overcome the economic barriers. Such an observation is consistent with the current environmental paradox in the Latin-American electricity sector, where we observe an increase in thermal generation (Arango and Larsen, 2010). Thus, the model shows strong inertia, resulting from the feedback structures in the model and the results end in a path-dependence pattern, currently observed in many energy systems (Fouquet, 2016).

6. Conclusions

We developed a behavioral simulation model that represents the dynamic substitution of energy sources in a national (or possibly regional) energy matrix. We calibrated the model to the energy matrix of Chile and investigated a number of scenarios in order to understand how the representation of energy sources might change over time, given different pricing and regulatory policies. For the calibration, we used a method proposed by Vanni et al. (2011), which allowed us to obtain simulation results closely aligned with the actual evolution of the energy matrix from 1980 until 2012, indicating that the model can realistically capture the changes that took place over this period. The scenarios represent market forces, i.e. changes in relative prices among fuels and investments, and regulatory interventions, which are incentives for investing in NCRE sources. The model can support decision making by policy makers and potential investors in the Chilean energy sector, considering that the electricity sector is included within the energy sector.

Simulation results provide a number of insights, particularly about the introduction of renewables, or NCRE, in Chile. The base case scenario showed the “business as usual” scenario with no major changes. In this first scenario, we observe a trend where the current heavy dependence on imported fossil fuel continues and only minor changes occur in the energy composition, as compared with the reference year, 2012. Moreover, there is no change in the energy matrix composition towards the stated goals of the government, which is seeking greater security of supply, reduced dependence on imported fuel, and more environmentally friendly production. We ran simulations with changes in fuel prices and investment costs, where there were no significant changes from the base case scenario. In fact, a decrease in imported fossil fuel prices actually increases the share of fossil fuel, a scenario that is currently being played out in the global oil-markets during a sharp decrease in oil prices. Moreover, higher energy prices have a relatively small

influence on the share of NCRE in the matrix. From our simulation experiments we conclude that the market, almost independent of what happens to prices and investment cost, may not be able to bring about the desired change in the composition of the energy matrix in Chile.

Given the robustness of the energy matrix to market forces, we need to turn to regulation to be able to observe any changes in the energy matrix. The two remaining simulation experiments, the NCRE and Combined scenarios, are examples of regulation. In these scenarios, we assume a significant government intervention to reach the desired goals. Simulations have shown that both interventions lead to changes in the composition of the energy matrix. In both cases, we increase the renewable share to almost fifty percent (hydro and other NCRE), leaving fossil fuels with the remaining share of just over fifty percent of the energy matrix, a significant improvement over the previous cases. Such intervention policies have been used in Europe over the last decade to increase the share of renewables, in some cases with great success. Germany managed to increase the share of renewables by using feed-in-tariffs and other initiatives from the German regulator and government (Würzburg et al., 2013); however, the downside of this is the increase in the cost of electricity for German industry and consumers. Thus, there exists a trade-off that Chile should consider, as it could have implications for economic growth. Our results indicate that this might be the only way in which Chile could move closer to the desired composition of the energy matrix.

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