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Rodrigo Mercado Fernandez

Erin Baker
University of Massachusetts Amherst

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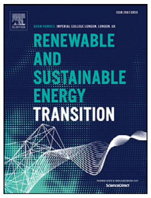

The sustainability of decarbonizing the grid: A multi-model decision analysis applied to Mexico

Rodrigo Mercado Fernandez[a,*], Erin Baker[b]

[a] Appalachian Energy Center, Appalachian State University, Boone, NC 28607, USA
[b] Mechanical and Industrial Engineering, University of Massachusetts Amherst, Amherst, MA 01003, USA

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ABSTRACT

Mexico recognizes its vulnerability to the effects of climate change, including sea level rise, increasing average temperatures, more frequent extreme weather events and changes to the hydrological cycle. Because of these concerns Mexico has a vested interest in developing sustainable strategies for mitigating climate change as it develops its electricity grid. In this study, we use a set of sustainability criteria to evaluate a number of model-derived pathways for the electricity grid aimed at meeting Mexico's climate goals. We use a multi-step approach, combining pathways from multiple large scale global models with a detailed electricity model to leverage geographic information into our multi-criteria sustainability analysis. We summarize the overall ranking of each expansion plan with the use of the weighted sum method. We find that the expansion plans with more than 20% of energy coming from carbon capture and storage (CCS) technologies tend to be less sustainable. While CCS technologies have low GHG emissions, they have high air pollution and water-use and require the development of extensive pipeline networks. In particular, these CCS characteristics pose concerns from an environmental justice perspective as high air pollution and water-use can significantly effect local communities: the plan with the most CCS has an extra 14 kg/GWh of weighted air pollution emissions and 199,000 liters/GWh of weighted water use compared to the plan with the most renewables. This analysis provides novel insights on tradeoffs that decisions makers must consider when looking at different sustainable development options to reach long term climate goals.

1. Introduction

Certain institutions within Mexico have recognized the country's vulnerability to the effects of climate change: preliminary assessments find that 13% of the country's municipalities are highly vulnerable to climate change, with a disproportionate impact in lower income areas [1]. Because of these concerns, Mexico has a vested interest in developing strategies for mitigation and adaptation to the negative effects of climate change. Mexico has developed policies and goals to address climate change at a national level in their 2012 General Law on Climate Change (LGCC) and the 2013 National Climate Changes Strategy (ENCC) [1,2] and at an international level with their Nationally Determined Contributions (NDC) established for the 2015 United Nations Climate Change Conference (COP21) in Paris.

The latest version of the NDC, released in 2020, sets Mexico national goals for adaptation and mitigation efforts up to the year 2030; these have slightly higher emissions than the previous version of NDC due to considering a different business-as-usual (BAU) scenario [41]. Mexico's NDC establishes unconditional and conditional greenhouse gas (GHG) emission reduction goals of 22% and 36%, respectively, by 2030 compared to a BAU baseline. These NDC emissions goals are consistent with Mexico's long-term goal of achieving a 50% reduction of national emissions from the year 2000 by the year 2050, as established in the LGCC [2]. If Mexico meets all the milestones set by these policies, it will be in line with the most aggressive mitigation scenarios set by the Intergovernmental Panel on Climate Change's (IPCC's) SR1.5C (2019) 1.5C scenarios [3]. It is important to note that recent analyses indicate that Mexico's current policies are not sufficient to reach the goals established in their NDC [40] or their 2050 climate goals in the LGCC [2]. To reach the goal in the LGCC of achieving 50% of 2000′s emissions in the year 2050, it is critical for Mexico to develop stronger policies, decarbonize the electricity grid and transition to cleaner technologies. In 2016 Mexico had 62 GW of installed generation capacity, of which 53% (33 GW) was natural gas. Clean technologies comprised only 26% of Mexico's installed capacity, including an 18% share for hydro and 5% for wind [4,5].

In this context, we evaluate the sustainability of a set of development pathways for the Mexican electricity grid, each aimed at reaching the goal set forth in the LGCC to reduce national emissions by 50% in 2050

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[*] Corresponding author.
E-mail address: mercadofernandezr@appstate.edu (R. Mercado Fernandez).

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compared to the year 2000. In efforts to provide better insight for to decision makers in the development of future energy policy, we evaluate these development pathways against a set of eight criteria, recognizing that sustainability is a multi-dimensional concept. A key contribution of this study is the incorporation of detailed geographic information on water use, air pollution, and transmission and carbon capture and storage (CCS) networks. Using detailed geographic information in the analysis allows us to combine environmental and societal impacts of climate mitigation efforts in a way that recognizes the importance of the distribution of benefits and burdens across communities. This study provides information that can be used by planners and policy makers working to reach long term sustainability and climate goals.

We implement a multi-step multi-criteria decision analysis (MCDA) methodology to evaluate a set of expansion plans. In this study, an *expansion plan* refers to all the necessary expansions to generation and transmission within the grid to reach the desired portfolio in 2050 as well as the annual power production plan for each power plant from 2016 to 2050. These expansion plans were derived from 6 large scale Integrated Assessment Models (IAMs) and one energy-system model. The seven expansion plans we analyze were originally developed in Veysey et al. [6], in which the models - EPPA, GCAM, IMAGE, Phoenix, POLES, TIAM and LEAP - were used to study optimal development pathways to reach Mexico's LGCC 2050 climate goal of achieving 50% of total emissions in 2000.

Historically, IAMs and other energy system models have been used to study climate related development pathways both at a regional and global level. IAMs combine economic, energy, technology, and climate models to better understand the interactions between these sectors and systems under different policy scenarios. Each of the models used in Veysey et al. [6], proposed significant proportions of clean energy in the electricity production in 2050; yet they varied in the generation technologies that were implemented. Here, we build on work in which these energy portfolios were soft-linked with a generation expansion model (PEGyT) to create detailed expansion plans for each of the development pathways [7]. Our study provides two key contributions to the existing literature: 1) we integrate detailed geographic information on the spatial distribution of air pollution and water consumption; 2) we include detailed information on the development of infrastructure, including the transmission system and CCS pipeline network, into the sustainability analysis.

There is a growing literature using multi-criteria approaches to evaluate electricity generation technologies and electricity systems. Table 1 presents a summary of key aspects of previous studies. One strand of the literature focusses on evaluating the sustainability of specific generation technologies across a variety of criteria; this includes Klein and Whalley [8] in the United States, May and Brennan [9] in Australia, Hartmann et al. [10] in Hungary, Shabban et al. [11] in Egypt, and Štreimikiene et al. [12] for Lithuania. Another strand develops this further, by evaluating various electricity *portfolios* rather than comparing individual generation technologies; these include Choi et al. [47] in Korea, Nock and Baker [13] in New England in the US, Aryanpur et al. [15] in Iran, Heinrich et al. [16] in South Africa, Brand and Missaoui [17] in Tunisia, Mirjat et al. [46] in Pakistan, Ribeiro et al. [18] in Portugal, and Volkart et al. [19] in Switzerland. An important subset of the studies that analyze electricity portfolios have focused specifically on Latin-America including Moreira et al. [14] and Santos et al. [42] in Brazil, Diaz and Cilinskis [43] in Colombia, and Santoyo-Castelazo and Azapagic [20] and Sheinbaum-Pardo et al. [21] in Mexico.

Our paper expands on these studies over several dimensions. One of the critical distinctions is that we use a detailed electricity model to derive the geographic location of generation and transmission from a series of model-derived scenarios. We incorporate this geographic information into the sustainability analysis, accounting for the important local effects of air pollution and water use. (See Section 2.3.1 for more details). Because of the spatial component of the social and environmental impacts of emissions, [22] highlights the importance of considering geographic distribution of effects in the development of effective environmental policy. We have found no papers in the literature that directly consider the geographic distribution of sustainability effects in their analysis of the electrical grid. Another contribution of our study is that we directly consider infrastructure in our analysis, including the transmission system and the CCS pipeline system. We found only four papers that include power transmission in their analyses. Aryanpur et al. [15], Heinrich et al. [16], and Volkart et al. [19] use models that include transmission networks (MESSAGE for the first, MARKAL for the other two). While the cost of the transmission network is included in total costs, there is no explicit metric to account for the geographic expanse of transmission networks. Given that the challenges to siting and developing transmission go beyond cost [23,24], we suggest that an explicit metric is important. Only Riberio et al. [18] includes a metric that directly addresses investment costs in the transmission network. In [18], however, the transmission network expansions are estimated based on generation technologies, rather than by implementing a power system network model.

Similarly, while some papers included CCS generation technologies in their analysis (such as Volkart et al. [19], Santoyo-Castelazo and Azapagic [20], and Diaz and Cilinskis [43]), we could find no papers that directly consider the CCS pipeline network that would need to accompany CCS power plants. In this paper, we build out the needed network of CCS pipelines and storage facilities for each expansion plan, using a mixed integer linear programming network expansion model presented in Section 2.2 and Appendix C. A review by Tcvetkov et al. [25] highlighted a number of concerns around CCS, including site selection and local conditions. Thus, we argue it is important to consider the implications that the development of CCS technologies and networks can have on the sustainability of each expansion plan.

Two studies have explicitly focused on Mexico. Santoyo-Castelazo and Azapagic [20], implements a MCDA to analyze the sustainability of the Mexican energy system in 2050, using 17 criteria to rank 11 generation portfolios for Mexico in 2050. This study differs from our paper in a number of aspects including: the lack of an electricity model, the selected scenarios are author generated, detailed geographic information isn't considered and they don't consider transmission or CCS networks. Sheinbaum-Pardo et al. [21] use eight criteria in their backward-looking study to analyze the energy system in two specific years, 1990 and 2008, before and after energy reforms. They conclude that the reforms did not have the desired effects on improving the sustainability of the energy sector.

The rest of the paper has the following organization. Section 2 presents our multi step MCDA methedology for analyzing the sustainability of each expansion plan. Section 3 presents the results from our MCDA analysis. Section 4 presents our insights and conclusions from the analysis. Detailed model descriptions and data can be found in Appendix A-D.

2. Methodology

Fig. 1 presents our multi-step multi-model MCDA approach to evaluate the sustainability of the seven electricity portfolios from Veysey et al. [6]. We build on the detailed expansion plans for the Mexican grid developed in [7]. For each expansion plan, we consider expansions to the long-distance transmission infrastructure, and we build out the CCS network. This information is used in our MCDA analysis to evaluate the sustainability of seven expansion plans, with the use of eight sustainability criteria. Of the eight sustainability criteria used in this paper, two of them, water use and air pollution, have a geographic component that we integrate into the analysis. This is further explained in Section 2.3.1.

In Section 2.1 we provide an overview of the model-derived expansion plans analyzed in this study, and in Section 2.1.1 we provide a description of the detailed electricity model PEGyT. In Section 2.2 we present an overview of the model used to create the CCS networks, and

Table 1
Overview of literature on MCDA sustainability analysis of generation technologies and electricity systems.

Study	Country / Time Frame	Scenario Generation	# of Criteria	Electricity Model	Geographic Information, CCS Network or Transmission Networks
May and Brennan (2006)	Australia 2050	N.A.	21	N.A.	N.A.
Moreira et al. (2015)	Brazil 2010–2016	historic data from (2010–2016)	7	N.A.	N.A.
Santos et al. (2017)	Brazil 2050	5 scenarios (developed by IAMs)	15	N.A.	N.A.
Diaz and Cilinskis (2019)	Colombia 2050	3 scenarios (GCAM, TIAM, PHOENIX)	5	N.A.	N.A.
Shaaban et al. (2018)	Egypt Current	N.A.	13	N.A.	N.A.
Hartmann et al. (2017)	Hungary 2020	N.A.	5	N.A.	N.A.
Aryanpur et al. (2019)	Iran 2015–2050	10 scenarios generated. Non hydro renewables range from 12%−48% in scenarios	18	MESSAGE Model	MESSAGE includes transmission. But no specific criteria for transmission
Choi et al. (2020)	Korea 2030	4 government policy scenarios	7	multi-objective goal-programming electricity systems model	N.A.
Streimikiene et al. (2015)	Lithuania Current	N.A.	20	N.A.	N.A.
Santoyo-Castelazo and Azapagic (2014)	Mexico 2050	11 scenarios. 2 scenarios based on previous studies the rest are defined by author.	17	N.A.	N.A.
Sheinbaum-Pardo et al. (2012)	Mexico 1990/ 2008	historic data for 1990 and 2008	8	N.A.	N.A.
Mirjat et al. (2018)	Pakistan	4 scenarios with differen fuel mixes. Reference (REF), Renewable Energy Tech (RET), Clean Coal Maximum (CCM), Energy Efficiency and Conservation (EEC)	17	LEAP	N.A.
Ribeiro et al. (2013)	Portugal 2020	5 scenarios representative of different energy policy trends. BAU, Natural Gas, Hydro-Gas, Max renewables	13	MILP in GAMS	Considers a criteria for transmission network investment
Heinrich et al. (2007)	South Africa Current	24 scenarios. Scenarios generated by considering representative probability distribution for a set of uncertain parameters.	4	MARKAL Model	N.A.
Volkart et al. (2017)	Switzerland 2010–2035	3 scenarios. Ref scenario (no climate policy), Clim scenario (20% red 2020, 40% red by 2035) no CCS, Clim+CCS scenario same as Clim but with CCS	12	MARKAL Model	MARKAL includes transmission. But no specific criteria for transmission. Explicitly addresses sustainability impacts of CCS Technology.
Brand and Missaoui (2014)	Tunisia 2010–2030	5 scenarios defined by key stakeholders of Tunisian power sector	13	Linear optimization of power plant dispatch and investment model	N.A.
Klein and Whalley (2015)	United States Current	N.A.	8	N.A.	N.A.
Nock and Baker (2019)	US (New England) 2035	15 portfolios analyzed that reflect discussions and arguments in NE	8	Merit Order Dispatch Electricity Model	N.A.

in Section 2.3 we define the sustainability criteria that we implement in this paper.

2.1. Model-Derived expansion plans

IAMs are used to study the interactions between human and natural systems under different policy scenarios by combining economic, technology, energy, and climate models [44]. IAMs can be divided into two categories: top-down models, which perform optimization based on aggregated representations of the economy, and bottom-up models, that simulate the economy with detailed technological models [45]. Energy system models, such as LEAP, include detailed energy and technology models with simplified economics and little interaction with other sectors. Each of the models used in Veysey et al. [6], produces a vastly different optimal electricity portfolio across the 2016–2050 planning period both in terms of total electricity consumption and generation technology mix. Fig. 2 summarizes the results from Mercado et al. [7]. The left-hand bars show the optimal installed capacity in 2050; the right-hand bars show the composition of total electricity production during the period of 2016–2050. Both are for the 50% of 2000 emissions in 2050 abatement goal established in the LGCC.

The models produce vastly different electricity portfolios in 2050 because they differ on many factors and assumptions, including economic modeling approach, spatial resolution, representation of generation technologies, cost and input data, macro-economic parameter assumptions, and the availability of renewable resources [26,27]. A particularly important factor is how each model represents competition between technologies and how technology changes over time, which have important impacts on the resulting pathways. This results in some of the expansion plans relying heavily on CCS technologies, including EPPA, GCAM and IMAGE; while Phoenix, TIAM and POLES depend more heavily on renewables, solar and wind; LEAP has the most var-

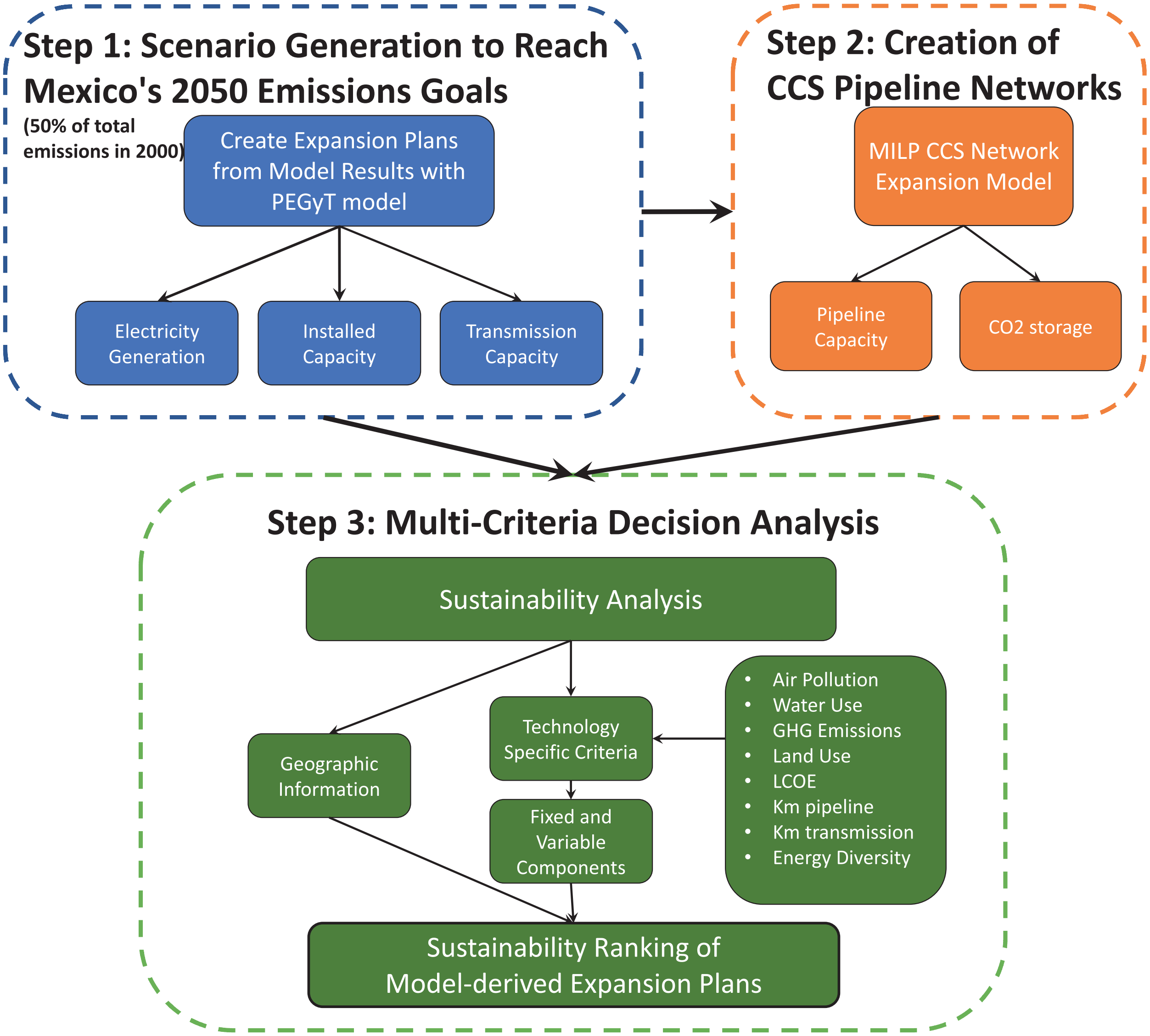

Fig. 1. Multi-step sustainability analysis with multi-criteria decision making.

ied electricity portfolio with a mix of renewable, CCS and conventional technologies.

Another significant difference between the expansion plans is their total electricity demand in 2050. These differences in electricity demand are driven by a variety of assumptions across the models including energy policy, energy efficiency initiatives, electrification of other sectors, and economic growth. An example is the POLES expansion plan, which has the highest electricity demand in 2050, attributed to its projected GDP growth and to the fact that it has the highest rate of electrification in the transportation sector. An important assumption for our study is that the differences across expansion plans in total electricity demand *do not reflect differences in access to electricity or quality of life*.

In this paper the sustainability of each expansion plan will depend on the expansions to transmission capacity, carbon capture and storage networks, installed generation capacity and electricity production per technology across the entire expansion plan from 2016 to 2050. While all the electricity portfolios have between 80 and 100% of electricity production coming from clean energy in the year 2050, they still have a significant contribution from natural gas, ranging from 30 to 50% of the total electricity produced from 2016 to 2050, as can be seen in the right hand bars of Fig. 2. This highlights the critical role that natural gas will have in the transition of the Mexican grid to cleaner portfolios.

2.1.1. Generation expansion model (PEGyT)

The model-derived expansion plans for the Mexican electrical grid were developed through an iterative process in [7] using the Planning of Integrated Expansion of Generation and Transmission (PEGyT) model. The iterative process in [7] takes the energy portfolios proposed by the models in Veysey et al. [6] and determines the optimal expansion to installed capacity and transmission to transition from the 2016 Mexican grid to the desired electricity portfolio in 2050. PEGyT is a linear programming cost minimization model that uses CPLEX [28] and was developed by the National Institute of Electricity and Clean Energy (INEEL) in Cuernavaca, Mexico. A more detailed description of the PEGyT model is presented in Appendix B.

2.2. Carbon capture and storage networks

The portfolios analyzed in this study incorporate various amounts of CCS technologies. To be able to incorporate significant amounts of CCS technologies it is necessary to develop the proper CO_2 transportation and storage infrastructure. Here we develop a cost minimization Mixed Integer Linear Program (MILP) network expansion model for the creation of CCS networks, which is run through CPLEX 12.9. This model

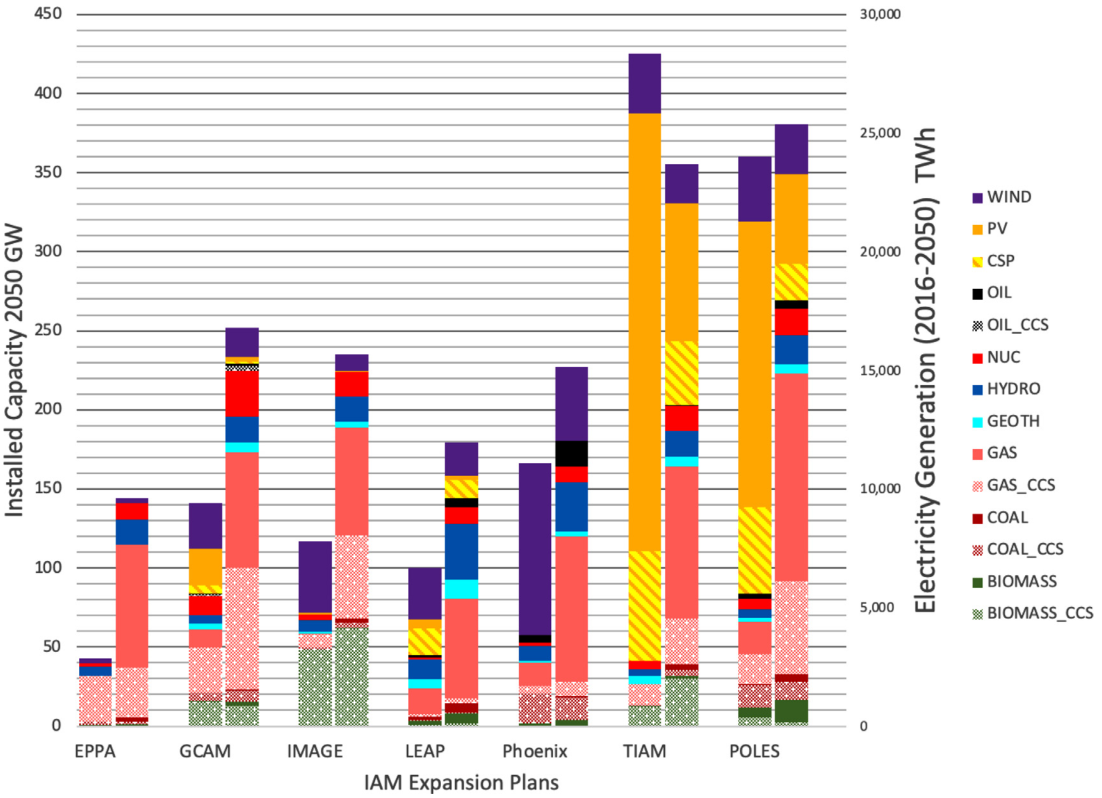

Fig. 2. Installed capacity by expansion plan in 2050 and electricity generation 2016–2050 by expansion plan for the 50% of the year 2000 emissions in 2050 abatement goal established in the LGCC. Left bar indicates installed capacity in 2050 based on the PEGyT expansion plans (see [7]); and the right bar indicates energy produced per technology from 2016 to 2050 (see [7]).

Table 2
Summary of CCS network expansion model results.

Expansion Plans	Km of Pipeline	Cap* Length (kTons/hr*km)	CO_2 Stored (Mtons)
IMAGE	3,231	3,689,483	1,834
Poles	3,035	2,032,789	909
GCAM	2,944	2,328,985	1,281
Phoenix	2,630	1,316,940	368
EPPA	2,630	1,204,396	365
TIAM	2,414	1,907,430	978
LEAP	996	154,582	87

is applied to the detailed expansion plans (2016–2050) developed in Mercado et al. [7].

The CCS network model is cost minimizing and optimizes 1) where and when to build new, or expand existing, pipelines; 2) the capacity of each line (*kilo*Tons of CO_2/hr); and 3) which storage sites the CO_2 will be moved to depending on the amount of CO_2 emitted within the grid at each time period. The optimization of the CCS networks is subject to constraints on conservation of mass throughout the network and maximum available storage capacity at each node. The full model formulation is presented in Appendix C. The network expansion model consists of 23 nodes as potential locations for CCS generation plants and 9 storage sites, as shown in Fig. 10 in Appendix C. The 9 storage sites were obtained from [29] in which preliminary studies estimate that Mexico has the capacity to store 100 Gigatonnes of CO_2 in saline formations within its territory. Table 7 in Appendix C gives the estimated storage potential for the different regions of Mexico.

The CO_2 emitted at each node is an input determined by the expansion plans in [7] that reflects how much electricity is produced with CCS generation technologies (gas, coal, oil and biomass), as shown in the right-hand columns in Fig. 2. A summary of the CCS network expansion model results are presented in Table 2; the resulting CCS networks created for each of the seven expansion plans can also be found in Apendix C Fig. 11.

2.3. MCDA criteria definition

Table 3 presents the set of eight criteria we use to evaluate the sustainability of each expansion plan. The sustainability criteria implemented in this study are intended to support decision makers in analyzing the tradeoffs between different energy portfolios. In this paper we calculate the sustainability of each expansion plan with a linear additive value function, also known as the weighted sum method, across a series of linear individual value functions for each criteria. (See Apendix D for more details). This is a similar approach as in [8] and is the most common method used when looking at sustainable energy MCDA [30]. A linear additive value function method was selected due to its relative simplicity, which allows stakeholders and decision makers to understand the outcome of the analysis more easily and hence is more likely to be trusted. This method is valid if a decision maker exhibits preferential independence between the criteria, which means that the preference for one sustainability criteria does not depend on a specific level for another the criteria. More formally, this functional form is valid

Table 3
Sustainability criteria for expansion plans 2016–2050.

Criteria	Unit	Description
Air Pollution Emissions	kg/GWh	Sum of life cycle emissions of SO_2, NO_x, PM
Water Use	L/GWh	Water withdrawn by power plant from the environment that is not returned to its original water source.
Life Cycle GHG Emissions	kg CO_2eq/GWh	Life cycle emissions of CO_2, CH_4 and NO_2, measured in CO2 equivalence
Land Use	m^2/GWh	Land associated with the construction of a new generation plant and land use for fuel extraction and production
Levelized Cost of Energy	$/MWh	Sum of the discounted overnight capital, generation and O&M costs divided by the total amount of electricity generated in the planning period.
Kilometers of Pipeline Built	$m * \frac{kiltons}{hr} / GWh$	Total volume of CO_2 pipeline referring to the length of pipelines in meters multiplied by the capacity of the pipelines
Kilometers of Transmission Expansion	$m * MW/GWh$	Length of the transmission connections in meters multiplied by the transmission capacity expansion
Energy Diversity	0–1 (dimensionless)	Measure of the diversity of fuel sources used in the energy portfolio. Based on Shannon-Wiener index

if the decision maker satisfies additive independence and there are no interaction between preferences [35]. A full preference elicitation would be required to determine the most appropriate functional form; this is left for future research.

The preference weights w_j given to each criteria capture the relative value of the tradeoff, for the decision maker, of going from the best to worst value relative to the other criteria. Quantitative examples of these tradeoffs are given in Section 3.2. In Section 3.1 we analyze the rankings of the expansion plans under an equal weights' scenario and in Section 3.2 we perform a sensitivity analysis on the rankings of the expansion plans under various illustrative decision maker preference scenarios.

The eight sustainability criteria presented in Table 3 are meant to reflect the most important factors for decision makers and planners in Mexico based on the 2014–2028 National Energy Strategy [31] and their NDC [41], including sustainability in the energy sector, energy security and social inclusion. We implement four environmental criteria (air pollution, water use, GHG emissions, land use) and an economic criteria (LCOE), which are based on previous work by Klein and Whalley [8]. A key contribution of this paper is the integration of geographic information with water use and air pollution. This allows us to capture the social aspect of these environmental criteria, permitting the decision maker to consider the distribution of benefits and consequences of various scenarios in relation to the population. In addition to the above criteria, we include measures of the extent of the CCS pipeline network and the transmission network. These criteria are relevant to potential social concerns related to the development of new infrastructure. Finally, energy diversity is considered a social criteria that decision makers can use to address concerns related to energy security. These criteria are further explained in Sections 2.3.1 and 2.3.2.

Each generation technology used in the expansion plans will have an impact on the sustainability criteria presented in Table 3. We build on the work of [8], which defines the impacts to sustainability criteria in a per unit of energy basis, and [13], where the effects of each sustainability criteria are broken into a fixed and variable component. The fixed component of these criteria captures the impact of the installed capacity of each generation technology; while the variable component is related to how much electricity is produced by each generation technology. This break-down into fixed and variable contributions to sustainability criteria permits us to accurately capture the overall sustainability of each expansion plan.

A challenge in comparing the sustainability of the different expansion plans produced by the different models is that they produce vastly different amounts of energy in the year 2050. It is not possible to directly compare most criteria such as water use, emissions, land use, investment costs and kilometers of pipeline built without unfairly penalizing expansion plans that produce larger amounts of electricity in 2050. We also do not want to favor expansion plans that produce higher amounts of electricity by assuming that higher electricity production is correlated to a higher quality of life. The models have different electricity productions due to their assumptions on economic and population growth, energy saving initiatives and electrification of other industries [6].

Because of this all of the criteria in Table 3, with the exception of energy diversity, will be evaluated on a per unit of energy basis, to allow for a more direct comparison between expansion plans. The criteria are presented in a per unit energy basis by calculating the value of the criteria for the entire planning period (2016–2050) and then dividing by the total amount of energy produced in the expansion plan. Thus, we are implicitly using a discount rate of 0 for the sustainability criteria, meaning that we care the same about the effects of emissions, water use, etc. in the year 2050 as to those in 2016. The one exception to this is LCOE, which uses a discount rate of 9%.

2.3.1. *Sustainability criteria with geographic component*

A novel aspect of our study is that we integrate geographic information into specific criteria when evaluating the sustainability of an expansion plan. We consider the local effects on sustainability by using nodal weights for air pollution emissions and water consumption. Previous studies have looked at the damages from air pollution emissions from power plants and the importance of considering the geographic distribution of effects [22]. Other studies have also recognized the importance of the interactions between electricity generation with limited regional water resources with the development of the grid [32]. Thus, we provide relevant information on these topics.

Air pollution emissions: Air pollution emissions are calculated as the combined life cycle emissions of SO_2, NO_x and particulate matter (PM) as in [8]. The emissions are calculated based on the annual installed capacity and electricity produced per technology at each node. We multiply the air pollution emissions at each node by a weight that reflects the percentage of the total national population at that node to obtain the weighted air pollution emissions per unit of energy (kg/GWh) for expansion plan i. Our metric x_{ai} is the summation of weighted air pollution emissions for all nodes n, a_{in}. We give a higher weight to nodes with larger populations as this implies more people are exposed to the air pollution and there will be more adverse health effects. We define the weighted cumulative air pollution emissions per unit of energy x_{ai} with Eqs. (1) and (2):

$$\mathrm{a_{in}} = \sum_{t=1}^{T} \sum_{g=1}^{G} k_{tngi} a_g^f + \epsilon_{ntgi} a_g^v, \ \forall i = 1, \dots, B_e \tag{1}$$

$$x_{ai} = \frac{\sum_{n=1}^{N} \omega_n a_{in}}{\epsilon_i^{total}}, \ \forall i = 1, \dots, B_e \tag{2}$$

Where a_{in} are the total pollution emissions for the expansion plan i at node n, k_{tngi} is the new installed capacity at node n in year t of generation technology g in expansion plan i, a^f_g are the fixed pollution emissions for generation technology g, per unit of capacity (kg/MW). ε_{ntgi} is the electricity produced at node n at year t by generation technology g in expansion plan i, a^v_g are the variable pollution emissions for generation technology g, per unit energy (kg/GWh). In Eq. (2), ω_n is the population weight for node n. The population weight for each node is defined as the percentage of the total population at node n. ε^{total}_i is the total cumulative electricity production for expansion plan i and B_e is the total number of expansion plans in this study. The population weights ω_n, a^v_g and a^f_g can be seen in the data section in the Appendix A.

Water use: Our metric x_{ci} is total weighted water use per unit energy (L/GWh) for each expansion plan i. We define water use as water withdrawn from the environment that isn't returned to its original source [8]. Water use is calculated using the annual installed capacity and energy produced per technology at each node, similarly to air pollution. The water consumption at each node is multiplied by a weight that reflects the area's water scarcity. The water scarcity for each area is defined as the amount of water withdrawn relative to the amount of local renewable water, as presented in Eq. (3). The higher the weight, the more severe the local scarcity, hence being less sustainable. We define the weighted total water consumption per unit of energy x_{ci} with Eqs. (4) and (5):

$$\mu_n = \frac{H2O^{withdrawn}_n}{H2O^{available}_n} \tag{3}$$

$$c_{in} = \sum_{t=1}^{T}\sum_{g=1}^{G} k_{tgi}c^f_g + \varepsilon_{ntgi}\, c^v_g,\ \forall i = 1,\dots,B_e \tag{4}$$

$$x_{ci} = \frac{\sum_{n=1}^{N} \mu_n c_{in}}{\varepsilon^{total}_i},\ \forall i = 1,\dots,B_e \tag{5}$$

Where c_{in} is the total water consumption of node n in expansion plan i, x_{ci} is the total weighted water consumption per unit of energy for expansion plan i (L/GWh), μ_n is the water scarcity weight for node n, c^f_g and c^v_g are the fixed and variable water consumption for generation technology g per installed capacity (L/MW) and per unit of energy (L/GWh). The weights for μ_n are given in the data section in the Appendix A.

2.3.2. Sustainability criteria without geographic component

Life cycle GHG emissions: For each expansion plan we will consider x_{ei} the total cumulative life cycle GHG emissions, as CO_2 equivalent emissions per unit of energy, for all generation technology including the upstream, O&M and downstream CO_2, CH_4 and NO_2 emissions as in [8]. This criteria considers IPCC 100 year global warming potential (GWPs) of 25 for CH_4 and 298 for NO_2 [8]. These GHG emissions are also calculated based on a fixed and variable component. The fixed and variable component for GHG emissions for each technology are presented in the data section in the Appendix A. The total GHG emissions per unit of energy are obtained with Eqs. (6) and (7):

$$e_{in} = \sum_{t=1}^{T}\sum_{g=1}^{G} k_{tgi}e^f_g + \varepsilon_{ntgi}\, e^v_g,\ \forall i = 1,\dots,B_e \tag{6}$$

$$x_{ei} = \frac{\sum_{n=1}^{N} e_{in}}{\varepsilon^{total}_i},\ \forall i = 1,\dots,B_e \tag{7}$$

Where e_{in} are the total ghg emissions for node n in expansion plan i, x_{ei} are the total ghg emissions per unit energy for the expansion plan i, e^f_g are the fixed GHG emissions for generation technology g per installed capacity (kgCO_{2eq}/MW) and e^v_g are the variable GHG emissions for generation technology g per unit of energy (kgCO_{2eq}/GWh).

Land use: For each expansion plan we will calculate the total life cycle land use x_{Li} for all generation technologies in terms of m^2/GWh. This criteria considers the land associated with the construction of a new generation plant and land use for fuel extraction and production which can be significant across the lifetime of the power plant. We take the maximum life cycle land use of power plants from Klein and Whalley [8]. Land use is of importance to our study due to the environmental and social impacts that the development of new power plants can incur. From a social aspect land use can also be a concern as energy projects can have pushback from communities close to where these projects are being developed. For this study we consider that the lower the land use an expansion plan has the higher its sustainability score. The land use for each expansion plan is calculated using Eq. (8):

$$x_{Li} = \frac{\sum_{n=1}^{N}\sum_{t=1}^{T}\sum_{g=1}^{G} k_{tngi} L^f_g}{\varepsilon^{total}_i},\ \forall i = 1,\dots,B_e \tag{8}$$

Where L^f_g is the fixed land use for generation technology g in m^2/MW. Values for land use per technology were obtained from [8] and are presented in the data section in the Appendix A.

Levelized cost of energy (LCOE): We calculate the LCOE in \$/MWh for each expansion plan across the planning period (2016–2050) with Eq. (9):

$$x_{LCOEi} = \frac{\sum_t \frac{I^{total}_{ti}}{(1+d)^t}}{\sum_t \frac{\varepsilon^{total}_{ti}}{(1+d)^t}} \tag{9}$$

Where x_{LCOEi} is the LCOE for expansion plan i, I^{total}_{ti} represents the total investment in 2016 US dollars for period t in expansion plan i which includes overnight investments in generation and transmission capacity as well as O&M and fuel costs and d is the discount rate. We use a discount rate of 9% in this analysis. This allows us to better capture the LCOE of the entire expansion plan rather than for individual technologies within the grid.

Kilometers of pipeline built: Our metric represents the total volume of CO_2 pipeline: the length of pipelines in meters multiplied by the capacity of the pipelines. A lower volume is preferred. The units of this metric are $m\frac{kiltons}{hr}/GWh$. The metric is expressed in Eq. (10):

$$x_{\mathcal{L}i} = \frac{\sum \mathcal{L}_{nmi} * F^{exp}_{nmi}}{\varepsilon^{total}_i},\ \forall i = 1,\dots,B_e \tag{10}$$

Where $\mathcal{L}_{nmi}$ is the length of pipeline from nodes n to m in the CCS network in expansion plan i, F^{exp}_{nmi} is the capacity expansion to line n to m by 2050 in *kilo*Tons/hr in expansion plan i. The metric, $x_{\mathcal{L}i}$, is the total length of added pipelines multiplied by the capacity of the pipelines per unit energy for the expansion plan i.

Kilometers of transmission expansion: Our metric for Transmission Expansion represents the total expansions to transmission capacity $m * MW/GWh$ which represents the length of the transmission connection in meters multiplied by the transmission capacity expansion. A lower value is preferred for this metric as larger expansions to transmission infrastructure can have strong social and environmental impacts and pushback [23,24], and it can be expressed by Eq. (11):

$$x^T_{\mathcal{L}i} = \frac{\sum \mathcal{L}^T_{nmi} * F^{Texp}_{nmi}}{\varepsilon^{total}_i},\ \forall i = 1,\dots,B_e \tag{11}$$

Where $\mathcal{L}^T_{nmi}$ is the length of transmission line from nodes n to m in the gird in expansion plan i, F^{Texp}_{nmi} is the capacity expansion to line n to m by 2050 in *MW* in expansion plan i. The metric, $x^T_{\mathcal{L}i}$, is the total length of added transmission capacity multiplied by the added transmission capacity in the grid per unit energy for the expansion plan i.

Energy diversity: Mexico has been implementing energy reforms and policy to promote energy diversification and increased renewable integration in response to concerns regarding climate change and energy security [6]. Ideally a portfolio will have a balance between diversity of energy sources and contributions from renewables [20]. Other studies have stated the importance of energy diversity's role in helping with energy security by minimizing unknown threats [33].

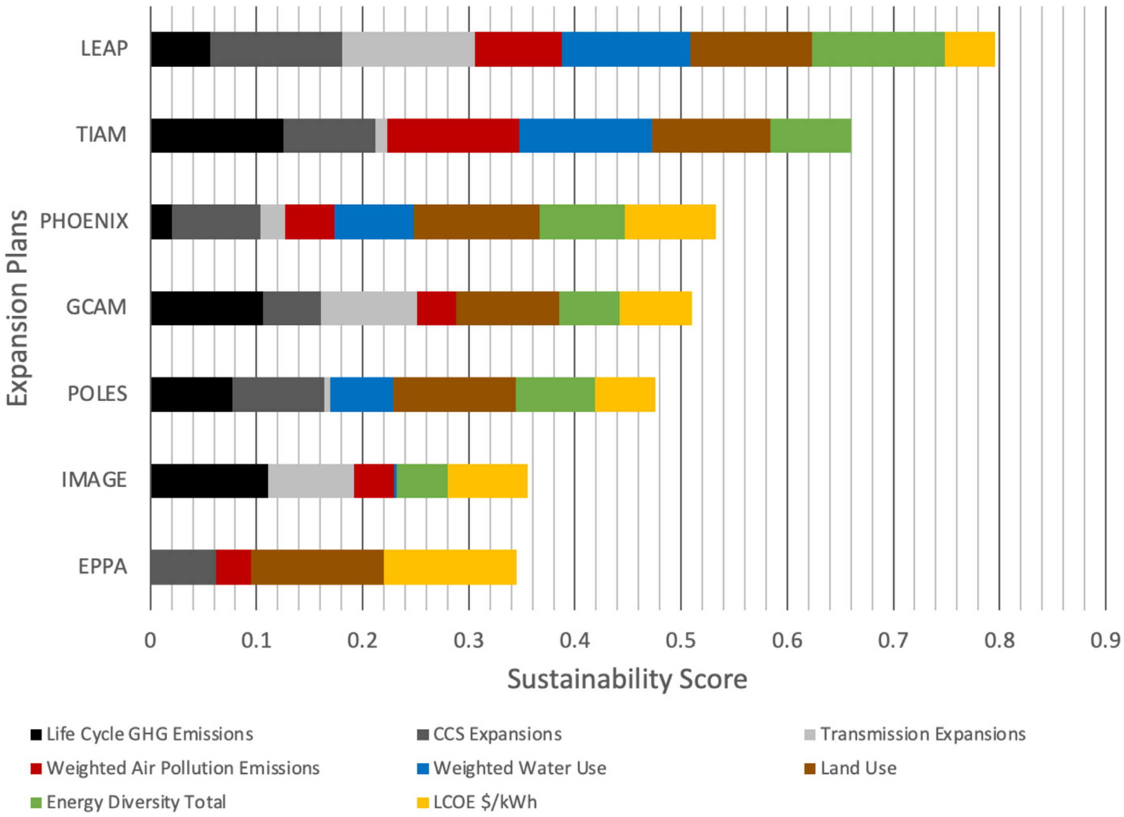

Fig. 3. .Sustainability score for expansion plans 2016–2050.

For this study the Shannon-Wiener Index will be used to measure and compare the energy diversity for all the electricity produced per technology across the entire planning period for each expansion pathway. We use the Shannon-Wiener index because it can measure the diversity and balance of the electricity portfolio [34]. We will measure the diversity in each expansion plan in regard to the number of fuel sources used and their contributions to the electricity portfolio. The Shannon-Wiener Index is expressed in Eq. (12) where a higher value of the index implies higher diversity:

$$x_{Hi} = e^{-\sum_{f=1} p_{fi} \ln p_{fi}} \tag{12}$$

Where p_{fi} is the proportion of energy produced by fuel source f for expansion plan i, x_{Hi} is the Shannon-Wiener Index for expansion plan i.

3. Results and discussion

3.1. Sustainability ranking of expansion plans using equal weights

We initially analyze the sustainability results for the expansion plans with the assumption of equal weights for the decision maker. Using equal weights allows us to clearly identify the effects of each criteria on the expansion plans. Table 4 and Fig. 3 present the expansion plans ranked from highest to lowest for overall sustainability score, when equal weights are considered with the linear additive value function, as well as showing the raw scores for each sustainability criteria.

We have highlighted the best score for each criteria in Table 3. We see that LEAP, TIAM, and EPPA each score best on some of the criteria. This means that if, for example, Mexico highly prioritized LCOE and land use, then EPPA would be the best expansion plan. With the equal weights' scenario, we find that EPPA, IMAGE, POLES and GCAM have the lowest overall sustainability score. Of these expansion plans IMAGE and GCAM are nearly dominated by TIAM, aside from TIAM's high LCOE and high requirement for transmission expansions. One key contributing factor to EPPA, IMAGE, POLES and GCAM's sustainability scores is their relatively high use of CCS technologies, ranging between 20 and 50% of the total electricity production from 2016 to 2050. While CCS technologies can be an attractive option to reduce CO_2 emissions without having to drastically change the electricity system, they retain many of the drawbacks of conventional natural gas, coal or oil plants: they do not reduce air pollution emissions of gasses such as SO_2, NO_x or particulate matter, they have high water consumption rates compared to renewable technologies, and have high operational costs due to fuel consumption. Apart from this, CCS technologies affect the overall sustainability of an expansion plan directly by requiring the development of large CO_2 transportation and storage networks.

The expansion plans with the highest overall sustainability scores are TIAM and LEAP. These expansion plans benefit from having the lowest levels of electricity production from CCS technologies and fossil fuels (2016–2050), with TIAM at 18% and LEAP at 3% for CCS use and TIAM at 37% and LEAP at 44% for fossil fuels. By incorporating higher levels of renewable and nuclear electricity generation, these expansion plans have lower levels of air pollution emissions, water use and km of pipeline built. LEAP and TIAM avoid using CCS technologies by producing half of their electricity with a balanced mix of renewable technologies, nuclear and hydro. This mix of clean generation technologies also gives LEAP the highest energy diversity score. We find that, for equal weights scenario, energy diversity is the best indicator for overall sustainability of an expansion plan. The main disadvantage of the TIAM and LEAP expansion plans are their high LCOE due to their investments in high levels in renewables. TIAM's LCOE, at $73/MWh, is nearly 3 times the cost of EPPA's LCOE.

A novel aspect of our paper is that, because we use a detailed electricity model, we can integrate geographic information into our sustainability analysis. It's important to note that this geographic information is

Table 4
Per unit of energy scores for each sustainability criteria for expansion plans.

Expansion Plans	Weighted Air Pollution Emissions (kg/GWh)	Weighted Water Use (thousand L/GWh)	Land Use (m^2/GWh)	Life Cycle GHG Emissions (tons CO_2eq/GWh)	LCOE ($/MWh)	Energy Diversity Total	CCS Network Exp. ((kiloton/hr*m)/MWh)	Trans. Network Exp.	Sust. Score(0–100)
LEAP	46	218	121	208	55	6.4	13	90	80
TIAM	39	211	132	135	73	4.8	80	883	66
PHOENIX	52	292	108	247	40	5.0	87	796	53
GCAM	53	414	179	156	47	4.2	138	325	51
POLES	59	317	118	186	51	4.8	80	922	48
IMAGE	53	410	503	151	44	3.9	235	395	36
EPPA	54	414	87	268	25	2.4	125	958	34
Max	59	414	503	268	73	6.4	235	958	80
Min	39	211	87	135	25	2.4	13	90	34
Std. Dev.	6	90	146	51	15	1.2	69	347	15

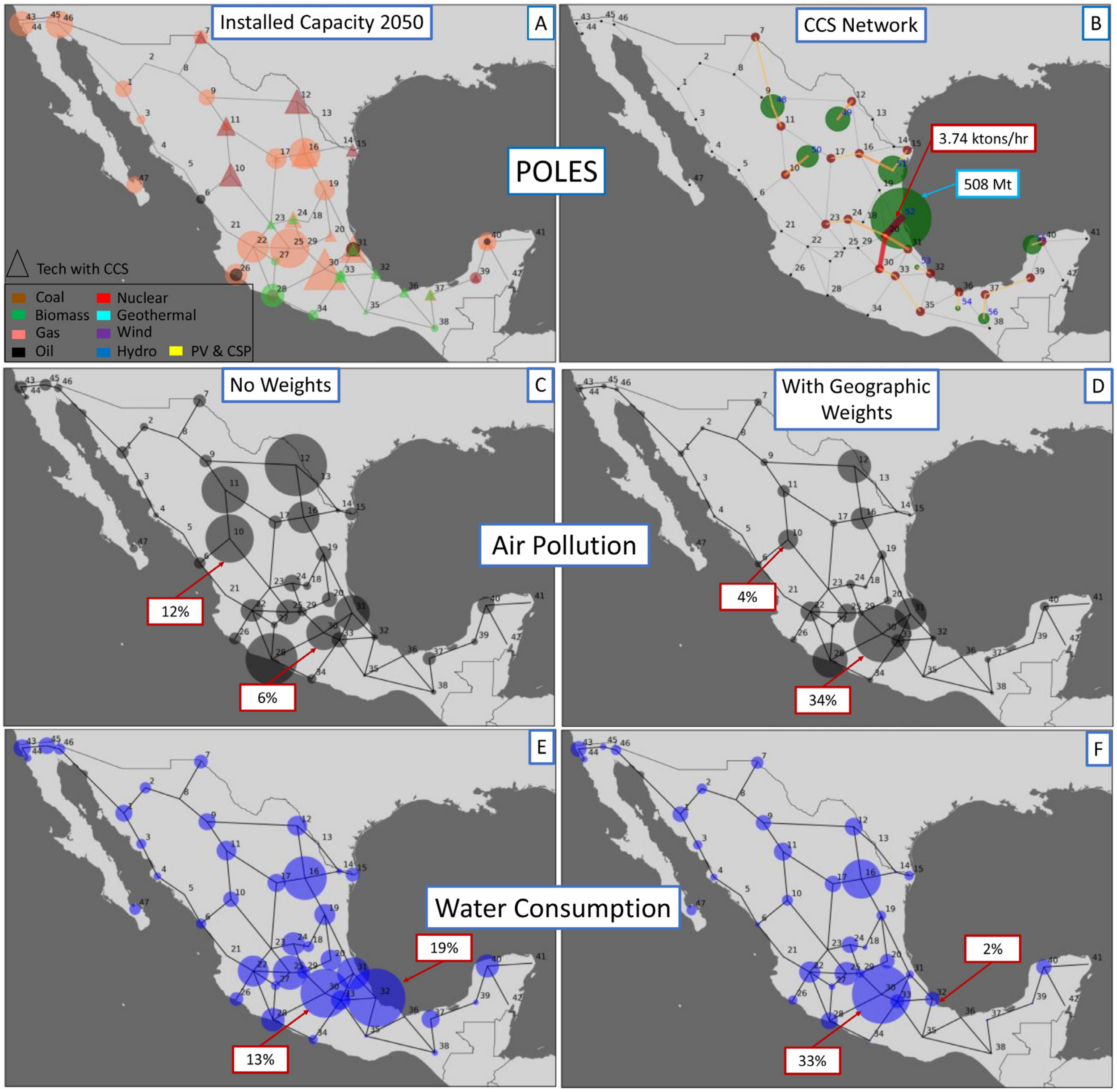

Fig. 4. Comparison of air pollution and water consumption per node (2016–2050) for the POLES expansion plan with and without geographic weights. Section (A) presents the installed capacity of conventional and CCS plants in 2050. The color of node indicates generation technology, a triangle indicates a CCS plant and the size of the node reflects the size of the power plant. Section (B) presents the CCS pipeline network in 2050 for POLES. Red nodes indicate nodes with CCS generation plants. Green nodes indicate CO_2 storage sites and the size represents the amount of CO_2 stored there. gray lines indicate connections within the transmission system and red lines indicate connections within the CCS pipeline network. Sections (C) and (D) present the distribution of air pollution emissions per node with and without geographic weights, respectively. The red boxes give the percentage of the total air pollution emissions at that node. Sections (E) and (F) present the distribution of water use per node with and without geographic weights, respectively. The red boxes give the percentage of the total water use at that node.

sufficient to change the rankings of some the expansion plans. In Fig. 4, we highlight the impacts of considering and not considering the geographic weights for air pollution and water use per node for the POLES expansion plan. On the right, we show the impact of considering weights for population and water shortages for each node. Note node 30, which is Mexico City is of particular interest. In POLES, only 6% of air pollution emissions are in Mexico City; yet with the high population, it has 34% of total emissions *impact*, as shown in Fig. 4, C and D. We see a similar result for water use at this node, with the impact of water use in Mexico City far outweighing the actual water use. In this case, the relative importance of the water use in Mexico City increases because this area has a high water scarcity value, as shown in Fig. 7 in the Appendix A.

3.2. *Sensitivity analysis over decision maker preferences*

In this section we consider other weightings scenarios as different decision makers will have different preferences. We analyze the sustainability rankings under various decision maker preferences, as shown in Table 5. In addition to equal weights, we use seven preference scenarios, in which different subsets of criteria are given larger weights. We use 4 decision maker preference scenarios that were previously defined in Nock and Baker [13] and Klein and Whalley [8]: climate change, environment, climate economics, and economics. In the climate change scenario, there is a strong preference for reducing GHG emissions while climate economics has higher weights for GHG emissions and LCOE. The environment scenario has a higher value on reducing air pollution,

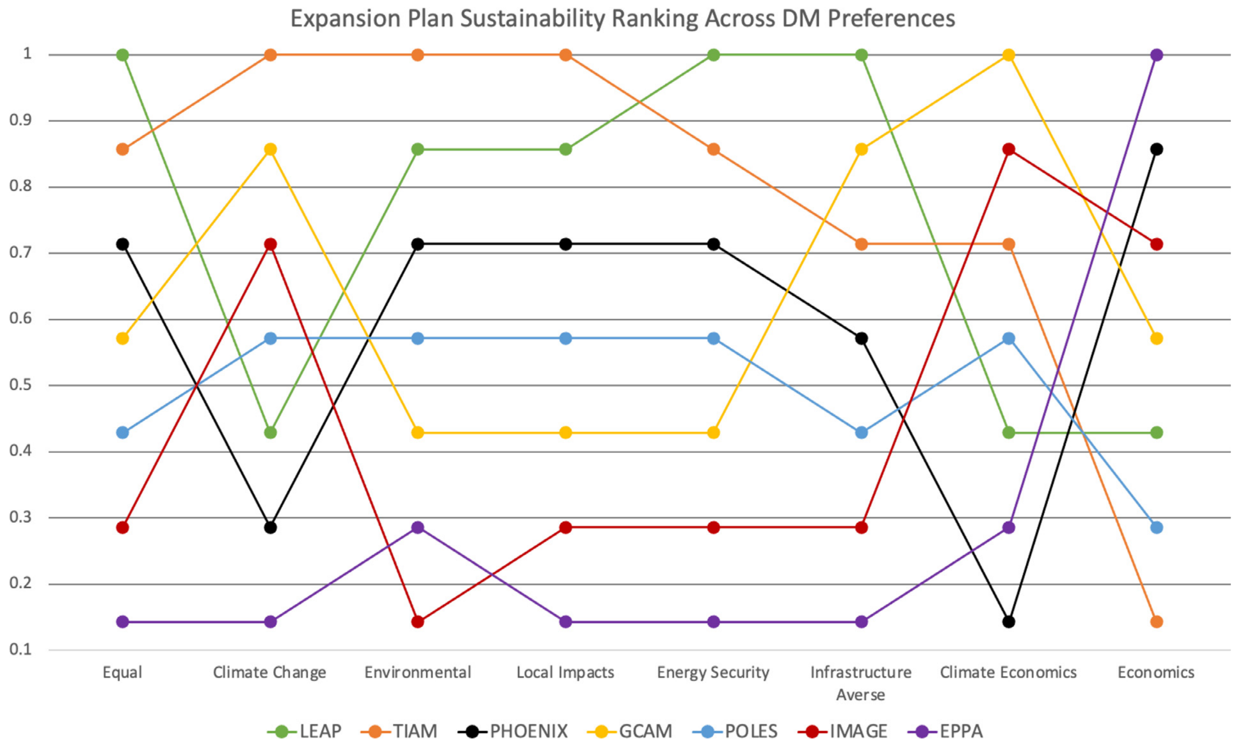

Fig. 5. Expansion plan sustainability ranking across decision maker preferences.

Table 5
Weights for various decision maker preferences.

DM Preferences	Air Pollution	Water Use	Land Use	GHG	LCOE	Transmission	Energy Diversity	CCS Network
Equal	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Climate Change	0.029	0.029	0.029	**0.8**	0.029	0.029	0.029	0.029
Environment	**0.2**	**0.2**	**0.2**	**0.2**	0.05	0.05	0.05	0.05
Local Impacts	**0.4**	**0.4**	0.033	0.033	0.033	0.033	0.033	0.033
Energy Security	0.029	0.029	0.029	0.029	0.029	0.029	**0.8**	0.029
Infrastructure Averse	0.033	0.033	0.033	0.033	0.033	**0.4**	0.033	**0.4**
Climate Economics	0.033	0.033	0.033	**0.4**	**0.4**	0.033	0.033	0.033
Economics	0.029	0.029	0.029	0.029	**0.8**	0.029	0.029	0.029

water use, land use and GHG emissions. The economics scenarios puts a high weight on LCOE. We also propose 3 new decision maker preferences: energy security, infrastructure averse, and local effects. In the energy security scenario, the decision maker has a high priority on energy diversity due to its links to energy security [6,20,33]. In the infrastructure averse scenario, higher weights are put on minimizing expansions to the transmission and CCS networks. Finally, in the local effects scenario, the decision maker has greater concerns for air pollution and water use, which can have significant effects on local communities. It is important to note that these decision maker preference scenarios are illustrative as we were not able to perform preference elicitation. While these preference scenarios are illustrative, we believe that they provide valuable insights on how changes in preferences can change the ranking of development pathways. In Fig. 5 we present how the sustainability ranking of the expansion plans change under the various decision maker preference scenarios.

We can quantify the relative value of the tradeoffs between the sustainability criteria given that we are using a linear additive utility function. This can help to better understand the implications for various decision maker preferences. For example, in the equal weights' scenario the decision maker is indifferent between having a weighted air pollution of 59 kg/GWh (worst value) and a weighted water use of 211.4kL/GWh (best value) compared to having a weighted air pollution of 39 kg/GWh (best value) and a weighted water use of 415 kL/GWh (worst value). Or, put another way, equal weights implies that reducing one kg/GWh of air pollution is equivalent to reducing 10 kL/GWh of water usage. The values presented in this example were taken from Table 4.

LEAP and TIAM rank highest across 3 preference scenarios each, as shown in Fig. 5, making them somewhat robust to the DM preferences presented in this paper. On the other hand, EPPA is the lowest ranking expansion plan under 5 preferences scenario and ranks well only in the economic scenario. LEAP and GCAM never rank lower than 5th in any preference scenario, while most of the other expansion plans rank last at least once. This may make these two expansion plans good compromise choices. GCAM might be preferred if climate and economics are the primary concerns; while LEAP is better across most environmental aspects.

Here we illustrate what some of these tradeoffs mean, focusing on LEAP, TIAM, and GCAM due to their overall performance across preference scenarios. For LEAP and TIAM, we investigate the tradeoffs between local effects (air pollution and water use) and infrastructure (expansions to transmission and CCS networks) that would cause the decision maker to be indifferent between the two development options. Starting from the equal weights' scenario, we increase the weights for local effects and decrease the weights for infrastructure until LEAP and TIAM have the same sustainability score. In the equal weights' scenario, all criteria have a weight of 0.125; through an iterative process we find that when air pollution and water use have a weight of 0.21 and transmission and CCS expansions have a weight of 0.04 LEAP and TIAM have the same sustainability score. These new weights imply that for a decision maker to prefer TIAM, they must feel that decreasing CCS network expansions by 1 $\frac{kiloTons}{hr} * {}^{km}/_{GWh}$ is equivalent to decreasing air pollution by 17.2 kg/GWh. Put another way, if we assume a capacity of 1 kTon/hr, then in order to prefer TIAM to LEAP, the decision maker is willing to add 1000 km of CCS pipeline in return for reducing 17.2 kg/GWh of air pollution. To put this into perspective, in 2016 the air pollution intensity for the Mexican grid was 66 kg/GWh.

We can also look at the tradeoffs necessary between GCAM and LEAP, in this case decreasing the weights for local effects and increasing the weights for climate economics until LEAP and GCAM have a similar sustainability score. We find that, in this case, changing these weights alone cannot make GCAM equivalent to LEAP. Weights of 0.249 for LCOE and GHG emissions and 0.001 for air pollution and water use, result in a sustainability score of 70 for LEAP and 65 for GCAM. Under the equal weights scenario, reducing 1 kg/GWh of air pollution is worth 2.40 $/MWh; for GCAM to approach LEAP in sustainability then reducing 1 kg/GWh of air pollution emissions must be worth less than 0.01 $/MWh.

3.3. Discussion

3.3.1. Tradeoffs between CCS and other technologies

When evaluating the sustainability of each of the seven proposed expansion plans, we found that none are dominated. Because of this, decision makers must carefully consider the tradeoffs between the proposed expansion plans that rely heavily on CCS technologies or renewables and nuclear. We find that under equal weights, expansion plans with a large deployment of CCS technologies tend to have lower overall sustainability scores. This can be attributed to the fact that, while CCS generation can be an attractive option to easily lower CO_2 emissions, they retain many of the drawbacks of conventional generation technologies, such as high air pollution emissions, water use, land use and require the creation of a CO_2 transportation and storage network. Furthermore, CCS technologies can also present energy justice concerns due to their high air pollution and water use, which are problematic to the mostly low-income communities who are disproportionality located close to power plants [36]. Our findings regarding CCS are consistent with the results in Volkart et al. [19], Santoyo-Castelazo and Azapagic [20], and Diaz and Cilinskis [43]. Volkart et al. [19] note that the scenario with CCS has many of the co-benefits and drawbacks of an energy system dominated by fossil fuels, except for GHG emissions. They observe that the deployment of CCS generation decreases the use of renewables, can lead to societal conflicts due to the storage of CO_2 and produces higher chemical waste [19]. Although not directly stated in the conclusions or analysis of Santoyo-Castelazo and Azapagic [20], also applied to Mexico, we note that the 3 highest ranking electricity portfolios in that paper were the ones with the lowest levels of CCS, ranging between 0 and 12%, and the worst ranking portfolios were the scenarios with the highest levels of CCS generation and fossil fuels. Similarly, in Diaz and Cilinskis [43], the scenario with the most renewables and lowest reliance on CCS technologies is the highest ranked in terms of reducing CO_2 and maintaining economic growth.

Morever, we found LEAP and TIAM expansion plans are somewhat robust across preference scenarios, with each expansion plan ranked highest in 3 preference scenarios, due to their high use of renewables, high energy diversity and relatively low use of CCS technologies. For the expansion plans with high CCS to be preferred, GCAM and IMAGE, decision makers would need to highly prioritize reducing both GHG emissions and LCOE over other environmental concerns.

3.3.2. Energy diversity as an overarching metric

We found that the metric for energy diversity was the best predictor for overall expansion plan ranking under the equal weights scenario. We speculate that energy diversity may be a good proxy for overall sustainability because of the many benefits that it can bring to the energy system including: addressing energy/fuel supply security concerns; hedging ignorance; promoting competition; accommodating plural interests; fostering innovation; nurturing context sensitivity; and mitigating lock-in among other factors [33]. These are the kind of tradeoffs in sustainability analysis that must be carefully evaluated by the decision makers, taking into account the potential benefits and drawbacks of each development pathway.

3.3.3. Limitations

There are two key limitations to keep in mind for this study. We use a linear additive value function to calculate the overall sustainability of each expansion plan to the electrical grid. This method allows us to assign different weights to each of the sustainability criteria to reflect different preferences of decision makers. We did not explicitly elicit preferences from decision makers in Mexico; rather we have evaluated the results of a series of predefined preference scenarios. Further work can look into capturing actual decision maker preferences over the sustainability metrics.

Additionally, the electricity generation characteristics for each of the sustainability criteria obtained from [8,13] are based on data from the US. This data might not reflect the same conditions for Mexico or other countries. Incorporating region-specific data could help improve the reliability of the sustainability analysis and ranking to better reflect the Mexican system.

4. Conclusions

The multi-model multi-step methodology presented in this paper is meant to guide decision makers in Mexico as they consider the sustainability tradeoffs for different development pathways for the electricity grid to meet 2050 climate goals. We use a MCDA approach to evaluate the sustainability of a series of detailed expansion plans with a linear additive value function considering eight sustainability criteria. We demonstrate the usefulness of incorporating geographic information with water use and air pollution emissions data in addressing social concerns and quantifying the spatial distribution of effects for sustainable development pathways. Similarly, by incorporating criteria for the transmission system and the carbon capture and a storage network into the sustainability analysis decision makers can better address social components for the development of energy infrastructure. These contributions are enabled as we translate the top-down results from high level models into PEGyT, a detailed model of the Mexican electrical grid.

A key result from our analysis is that for a decision maker to be indifferent between the GCAM (40% CCS and 29% renewables + nuclear) and LEAP (3% CCS and 52% renewables + nuclear) expansion plans, the tradeoff of reducing 1 kg/GWh of air pollution emissions must be worth less than 0.01 $/MWh. In other words, if 1 kg/GWh of air pollution emissions is worth more than 0.01 $/MWh then it is unlikely that they will develop CCS technologies as the economic benefits of CCS technologies would be outweighed by the increased air pollution emissions. Another key tradeoff identified between local effects (air pollution and water use) and infrastructure (expansions to transmission and CCS networks) for the LEAP (3% CCS and 52% renewables + nuclear) and TIAM (18% CCS and 45% renewables + nuclear) expansion plans suggest that decreasing CCS network expansions by 1000 km/GWh is equivalent to decreasing air pollution by 17.2 kg/GWh. Finally, we observed that the energy diversity metric was the best proxy for the overall ranking of the expansion plans under equal weights scenario.

The sustainability framework proposed in this paper helps to better understand the macro effects of different development pathways in the electricity system and their potential tradeoffs. This analysis would

Table 6
Sustainability criteria input data.

Generation Technology	Life Cycle GHG		Air Pollution Emissions		Water Consumption		Land Use
	Fixed (kgCO_2eq/ MW)	Variable (kgCO_2eq/ GWh)	Fixed (kg/ MW)	Variable (kg/ GWh)	Fixed (L/ MW)	Variable (L/ GWh)	Fixed m^2/ MW
Hydro	53	0.0	0.419	0.0	16,587	208	190,606
Wind	39	0.0	0.345	0.0	11,048	2020	3,950
Nuclear	95	0.0	1.672	0.0	16,587	2,415,000	1,024
Solar PV	92	0.0	1.528	0.0	72,952	0.0	1,561
CSP	153	0.0	0.722	0	7000	500	2,715
Geothermal	49.9	0.0	1.090	0.0	18,000	500,000	18,391
Natural Gas	0.0	449,000	0.0	988	16,587	815,000	2,308
Natural Gas CCS	0.0	44,900	0.0	988	16,587	1,457,384	2,308
Oil	0.0	752,000	0.0	2,668	16,587	795,000	2,308
Oil CCS	0.0	75,200	0.0	2,668	16,587	1,351,500	2,308
Coal	0.0	768,000	0.0	19,260	16,587	1,211,332	11,020
Coal CCS	0.0	76,800	0.0	19,260	16,587	2,081,976	11,020
Biopower	0.0	35,000	0.0	1,099	16,587	553,000	120,236
Biopower CCS	0.0	3,500	0.0	1,099	16,587	940,100	120,236

Sources: [8,13].

Table 7
Estimated CO_2 storage potential per site. Source: [29].

Geological Province	Estimated Storage Potential Giga-Tones of CO_2	Node(From Fig. 11)
Chihuahua	<1	48
Coahuila	13	49
Central	<1	50
Burgos	17	51
Tampico Misantla	10	52
Veracruz	15	53
Southeastern	24	54
Yucatan	14	55
Chiapas	6	56
Total	100	

ideally be part of an iterative process where models inform decision makers who are communicating with local communities on the potential tradeoffs of various development pathways. At the same time, the concerns and needs of the community should inform decision makers and the models. While the sustainability methodology proposed in this paper was applied to the Mexican electrical grid, this methodology can be expanded to other countries and regions. Future work will focus on leveraging the sustainability methodology and detailed geographic information proposed here to incorporate a detailed equity analysis.

Declaration of Competing Interest

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

CRediT authorship contribution statement

Rodrigo Mercado Fernandez: Conceptualization, Methodology, Software, Visualization. **Erin Baker:** Conceptualization, Resources.

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Appendix A - Data

Table 6. provides the fixed and variable components for each generation technology for each sustainability criteria; based on data from [8,13].

Air Pollution Weights

Fig. 6. presents the air pollution weights ω_n for each node, which represent the percentage of the total population at node n.

Water Consumption Weights

Fig. 7. presents the water scarcity weights μ_n for all the nodes in the model:

In Mexico in 2015 the water use per sector was: 14.6% public use, 76.3% agriculture, 4.8% electricity sector excluding hydro generation, and 4.3% Industry, with a total water consumption of 266,559 hm^3 [37]. Fig. 7 [37] shows the water scarcity for the different hydrological resources in Mexico in 2016. At a national level the water scarcity is considered to be low at 19.2%. But most of Mexico's major population centers are located in regions with a high degree of pressure on its hydrological resources as shown in Fig. 7 [37]. This figure helps to highlight areas such as the State of Mexico, containing Mexico City, as a critical area in terms of water use as their water consumption is already larger than the local area's renewable water capacity.

Appendix B – PEGyT model

The PEGyT model represents the Mexican electrical grid with a reduced network consisting of 47 nodes, 9 areas of operation and 64 aggregate lines as shown in Fig. 8. The topology of the long-distance transmission infrastructure in the PEGyT model is used by the INEEL in [28] and uses data from the Secretary of Energy Annual report [4]. (For a more detailed description of the PEGyT model and expansion plans see [7]). The PEGyT model creates an optimal expansion plan for the Mexican electrical grid that minimizes investment and operating cost for the generation and transmission expansion problem across the planning horizon. Each expansion plan presented in this paper covers 2016–2050 and satisfy Mexico's General Law for Climate Change goal for 2050 of reaching 50% of emissions from 2000 [2].

Appendix C – Carbon capture and storage model

The carbon capture and storage network expansion model chooses when to build new connections or expand existing pipelines. The key

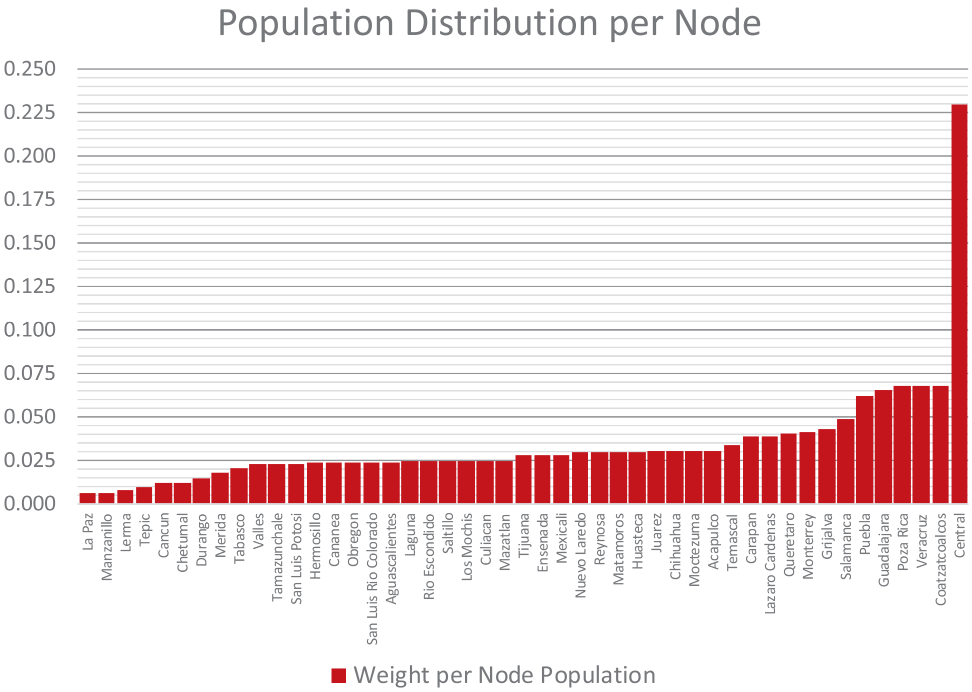

Fig. 6. Population distribution per node.

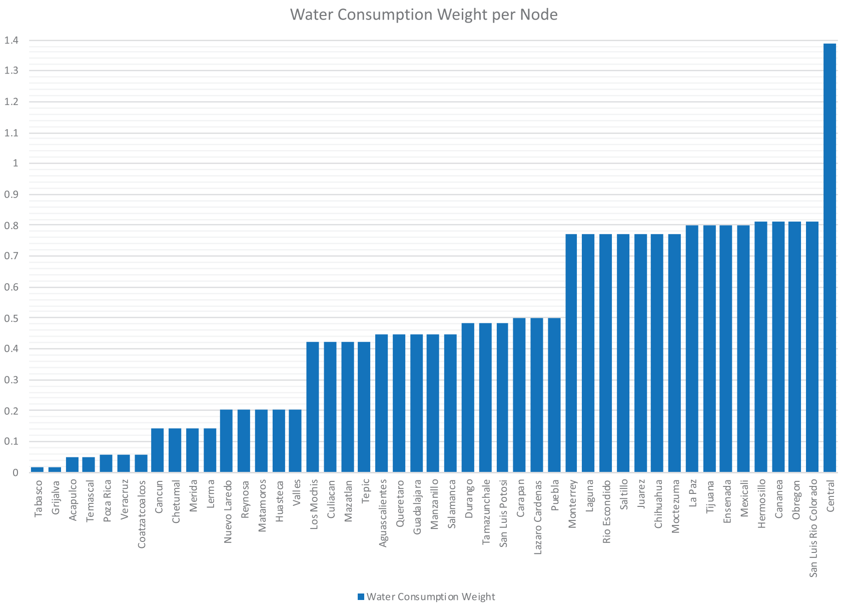

Fig. 7. Water scarcity weight per node. Source: SEMARNAT and CONAGUA, "Estadisticas del Agua en Mexico edicion 2016," 2016 [37].

decision variable in the model is F_{nmt}^{exp}, which denotes the expansion of the line between nodes n and m at time period t in *kilo*Tons/hr of CO_2. This decision variable dictates the diameter of the pipelines within the system. N is the set of nodes within our system, F is the set of possible connections within the system and T is the set of time steps, which are the individual years from 2020 to 2050. Where E_{nt} is the CO_2 entering the system at node n in *kilo*Tons of CO_2 at time period t and S_n^{max} as the maximum storage capacity at node n *in kilo*Tons. If a node n has CO_2 entering the system, because of electricity production from a CCS plant, we will refer to it as a source node and it will have $E_{nt} > 0$ *and* $S_n^{max} = 0$. This means that source nodes in the system do not have storage capacity. If a node n has storage capacity for CO_2, due to its geological characteristics, then we will refer to it as a storage node and it will have $E_{nt} = 0$ *and* $S_n^{max} > 0$. Fig. 10 shows all the possible source and storage nodes within Mexico that are considered within this study.

The other decision variables within the model are: f_{nmt} the flow from node n to m in *kilo*Tons/hr at time period t, F_{nmt}^{max} maximum flow capacity in *kilo*Tons/hr from node n to m at time period t, s_{nt} new CO_2 stored at node n in kilotons at time t, S_{nt} the cumulative CO_2 stored at node n in kilotons and time period t. B_{nmt} is a binary decision variable that indicates if a line from node n to m is constructed (1) or not (0) at time t, and D_{nm} is the diameter of the pipeline in meters. The D_{nm} of each pipeline is determined by the maximum flow f_{nmt} between each pair of nodes. The relationship between the flow and diameter is nonlinear (see Eq. (15) below); thus we implement a piecewise linear function to approximate the pipeline diameter.

The MILP model formulation is presented below:

Objective Function:

$$\min_{F_{nmt}^{\exp}} \sum_{t\in T} \sum_{n\in N} \sum_{m\in M} \frac{C * D_{nm} * l_{nm} + B_{nmt} * C_{fixed} * l_{nm}}{(1+r)^t} \tag{13}$$

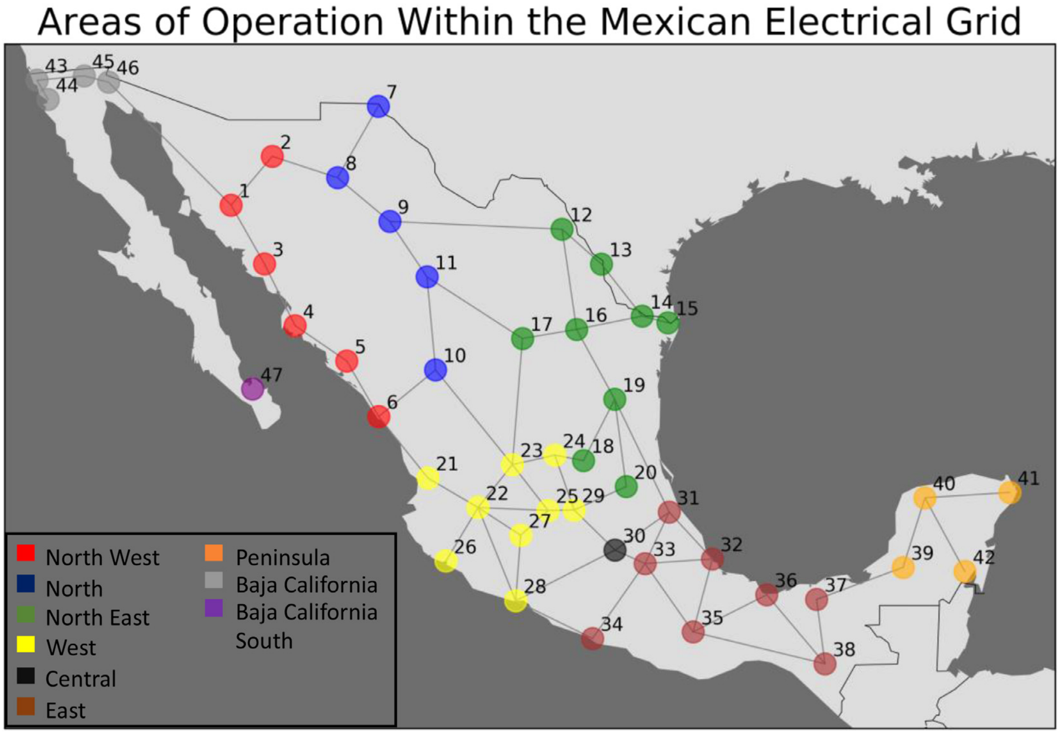

Fig. 8. Mexican electrical grid in PEGyT model. Small numbers at each node indicate demand or production points within the system, color indicates area of operation.

s.t.

$$E_{nt} + 8760hr\left(\sum_{m} f_{mnt} - \sum_{m} f_{nmt}\right) - s_{nt} = 0,\ \forall t \in T,\ \forall n \in N, (n,m) \in F \tag{14}$$

$$D_{nm} = \sqrt{\frac{4F_{nmt}^{exp}}{\upsilon \pi \rho}} \tag{15}$$

$$S_{nt-1} + s_{nt} = S_{nt} \tag{16}$$

$$S_{nt} \le S_{n}^{max} \tag{17}$$

$$f_{nmt} \le F_{nmt}^{max} \tag{18}$$

$$F_{nmt-1}^{max} + F_{nmt}^{exp} \ge F_{nmt}^{max} \tag{19}$$

$$B_{nmt} + B_{mnt} \le 1 \tag{20}$$

$$\mathrm{H} * B_{nmt} \ge F_{nmt}^{exp} \tag{21}$$

Parameters:

E_{nt} CO_2 entering system at node n in *kilo*Tons of CO_2 at time period t

C constant cost factor for the cross section of pipeline per unit of diameter per unit of length $\$/m^2$

C_{fixed} fixed cost per unit of length, irrespective of the diameter, of building a new line $\$/m$

l_{nm} distance from node n to m in m

S_n^{max} Maximum storage capacity at node n *in kilo*Tons

M Big M

N set of nodes in the system

T set of timesteps, 2020–2050

Decision Variables:

f_{nmt} flow from node n to m in *kilo*Tons/hr at time period t

F_{nmt}^{exp} capacity increase to line n m at time period t in *kilo*Tons/hr

F_{nmt}^{max} maximum flow capacity in *kilo*Tons/hr from node n to m at time period t

$$B_{nmt} \begin{cases} 1, & if\ F_{nmt}^{exp} > 0 \\ 0, & otherwise \end{cases}$$

s_{nt} CO_2 injected at node n in kilotons at time t

S_{nt} Cumulative CO_2 stored at node n in kilotons and time period t

D_{nm} diameter of the pipeline (m)

The objective function (13) of the model minimizes the sum of variable and fixed costs for constructing a CCS network, which are driven by D_{nm}, over the planning period. To calculate the diameter in meters, we use Eq. (15). Here υ is the velocity of the flow within the pipeline in m/s and ρ is the density of the CO_2 in kg/m^3. We assume the velocity of the CO_2 through the pipeline to be 1.5 m/s, this is within the range of cost-effective velocities for dense phase CO_2 ($1.5 - 2\ m/s$) [38]. The density ρ of the CO_2 in the pipelines is assumed to be of 800 kg/m^3 [38]. As the relation between the diameter and the flow through the pipeline is nonlinear we use a piecewise function within our objective function, as shown in Fig. 9.

The fixed costs in the objective function are associated with purchasing land and building pipelines, whereas the variable costs are related to the capacity of each pipeline built. The variable cost component of the objective function is based on linear cost models such as those established in [39]. We are using a cost factor C for the pipelines of 1443 $\$_{2016}/\mathrm{m}^2$, this number is based on a linear regression of uncorrected Federal Energy Regulatory Commission (FERC) cost data [39].

Constraint (14) ensures conservation of mass within the system so that all the CO_2 entering the system has to be stored at a storage node. Constraints (16) and (17) keep track of the cumulative storage at each node and ensure that the total CO_2 stored at each node (S_{nt}) does not exceed the storage capacity (S_n^{max}) for that node. Constraints (18) and

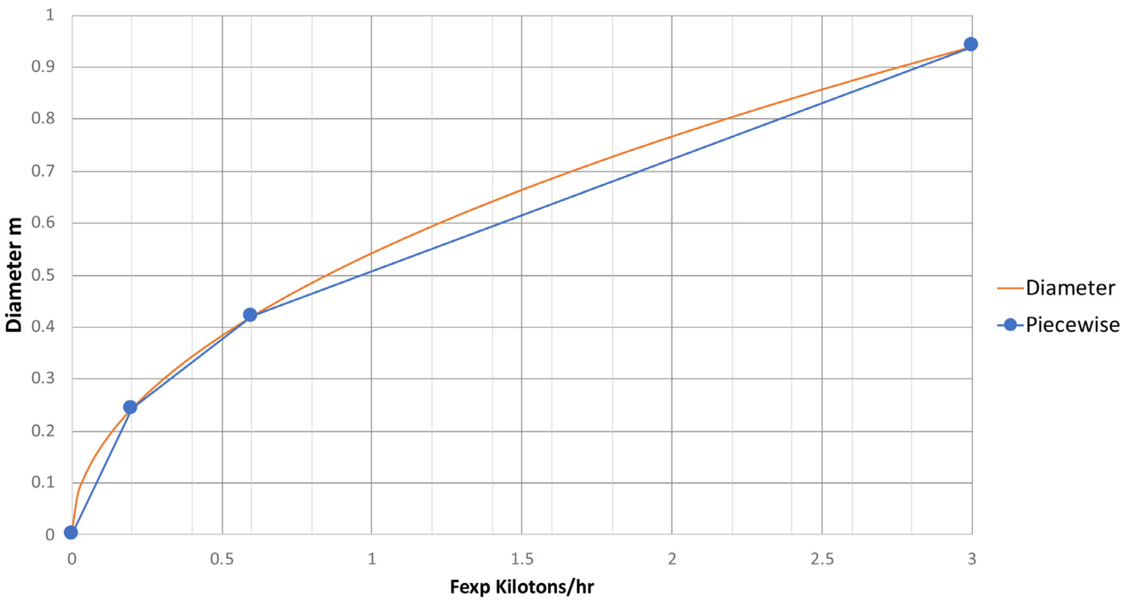

Fig. 9. Diameter of Pipeline m vs F^{exp}_{nmt} kilotons/hr.

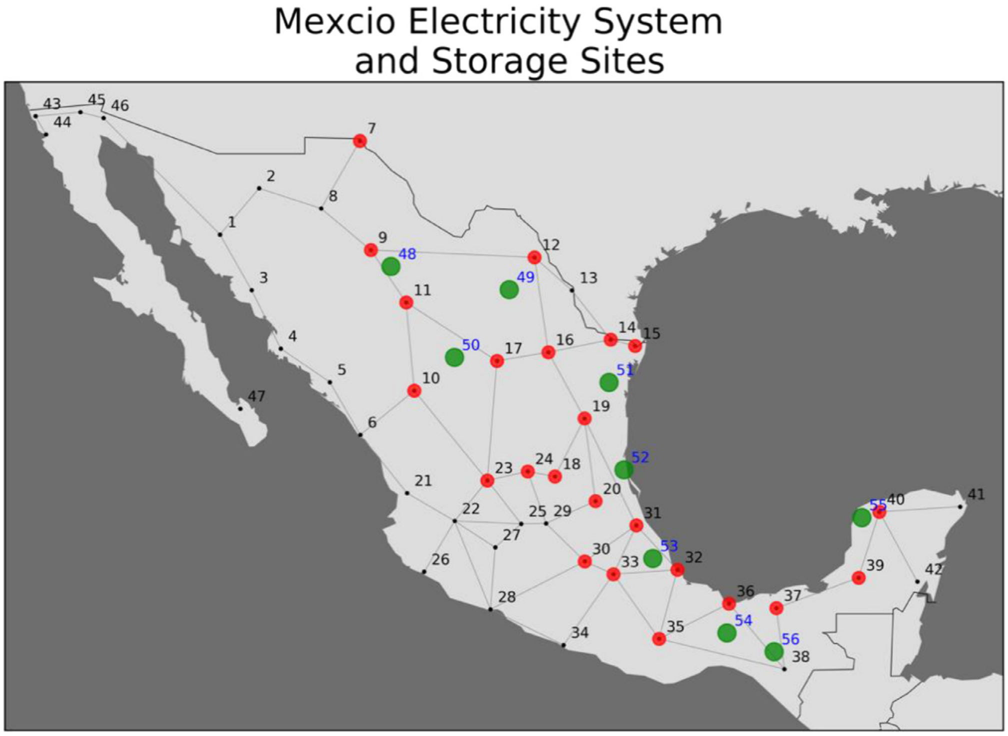

Fig. 10. Mexican electrical grid and storage sites. Black nodes indicate potential generation or demand nodes within the electricity grid. Red nodes indicate nodes within the electricity grid where CCS generation plants can be deployed. Green nodes indicate potential $\boldsymbol{CO_2}$ storage sites. gray lines indicate connections within the transmission system.

(19) set the maximum flow capacity for each line (F^{max}_{nmt}) within the system and required expansions for the capacity of a line (F^{exp}_{nmt}). Constraint (20) allows for only one line to be built between any two points n and m. Finally, constraint (21) uses a binary variable to indicate when the model expands the capacity of a line within the system.

Appendix D – MCDA Linear additive value function

We evaluate the overall sustainability of each expansion plan with linear additive value function (weighted sum method) with Eq. (22).

$$S_i = \sum w_j z_{ij} \tag{22}$$

Where S_i is the sustainability score of expansion plan i, w_j is the weight for the sustainability criteria j, z_{ij} is the normalized score for criteria j and expansion plan i. The normalized scores for each criteria will have values from 0 to 1, were we consider 1 to be the highest score, being the most favorable, out of the expansion plans and 0 the lowest score. The normalized scores for each criteria are obtained using Eqs. (23) and (24) with the raw sustainability scores x_j:

$$z_{ji} = \frac{x_{ji} - x_{jmin}}{x_{jmax} - x_{jmin}} \; where \; x_{jmax} \; is \; preferred \tag{23}$$

$$z_{ji} = \frac{x_{jmax} - x_{ji}}{x_{jmax} - x_{jmin}} \; where \; x_{jmin} \; is \; preferred \tag{24}$$

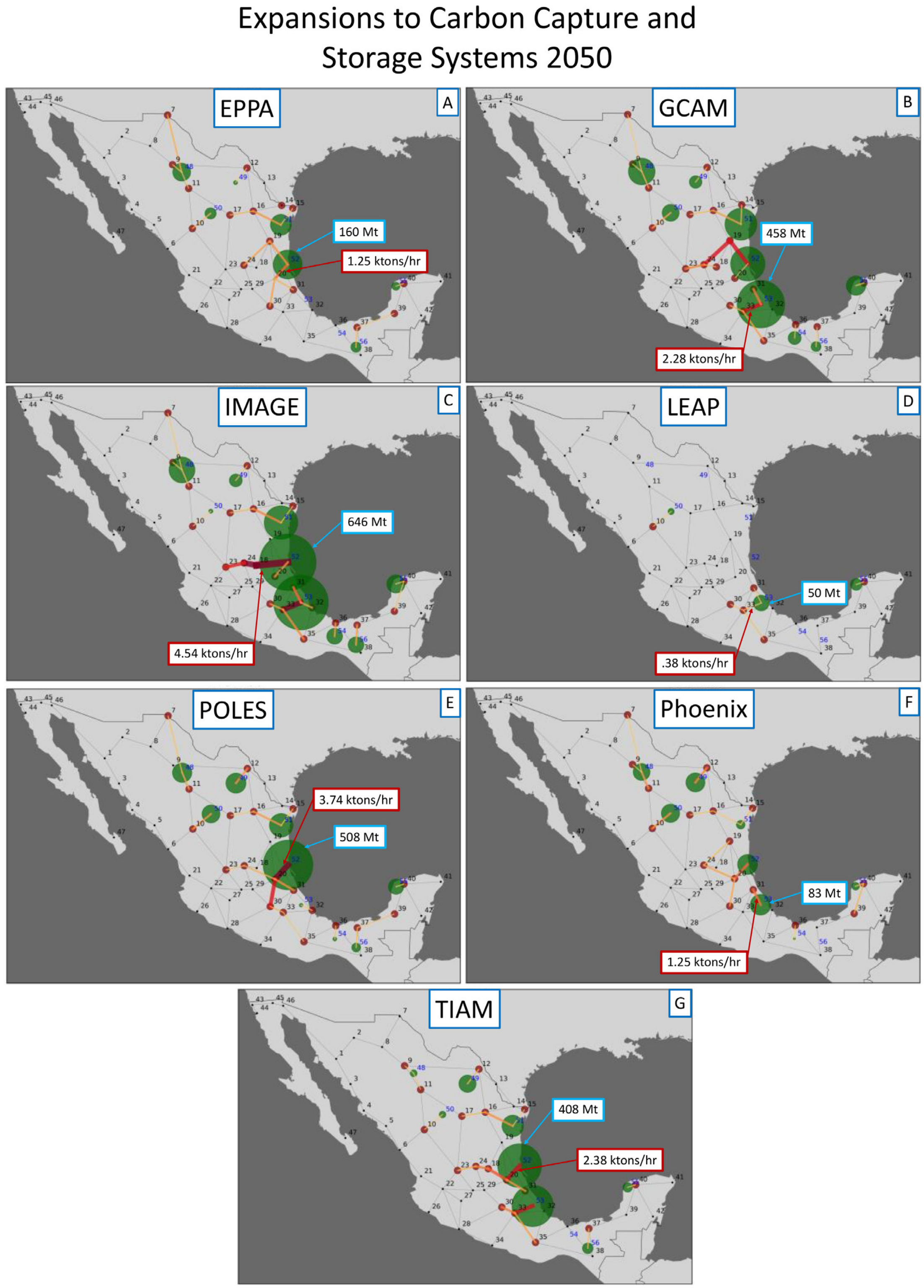

Fig. 11. Expansions to CCS Network 2016–2050. Black nodes indicate potential generation or demand nodes within the electricity grid. Red nodes indicate nodes with CCS generation plants. Green nodes indicate CO_2 storage sites and the size represents the amount of CO_2 stored there. gray lines indicate connections within the transmission system and red lines indicate connections within the CCS pipeline network.

Where x_{ji} is the raw sustainability score for metric j and expansion plan i, x_{jmax} is the highest raw score for criteria j obtained from all the possible expansion plans and $x_{jmin}$is the lowest raw score for criteria j obtained from all the possible expansion plans. Eq. (23) is used when a higher value is preferred such as energy diversity while Eq. (24) is used when a lower value is preferred such as emissions and water use.

Using a similar approach to [13] we use the weighting method from [30] but apply it to expansion plans to the Mexican electrical grid from

2016 to 2050 rather than to individual generation technologies or portfolios.

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