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Research Article

The multi-level economic impacts of deep decarbonization strategies for the energy system

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A R T I C L E I N F O

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A B S T R A C T

To cap global warming below 2$^{\circ}C$, countries are urged to upscale their climate commitments and develop national deep decarbonization (DD) strategies for the energy system. But, fast and deep transformations will have wide-ranging economic implications at the macroeconomic level, in energy industries, and also in other sectors. Such impacts need to be understood by policy-makers. This paper develops an original integrated approach based on loading consolidated energy pathways into a multi-sector economy-wide model to assess within a consistent framework the multi-level economic impacts of the DD strategies. The method is applied to Argentina and gives representative insights into the global challenge to move towards a low-carbon economy. Our results show key multi-level impacts of shifting from a 'reference' to a DD pathway by 2050. In energy industries, value-added and employment shift from fossil fuel to low-carbon power industries. Aggregated GDP and welfare impacts are limited but incremental investments are significant at the macroeconomic level, with indirect and induced impacts across the economy. It includes net job creations in upstream industries that supply low-carbon infrastructures, but also risks of job losses in exposed sectors. Eventually, our approach highlights enabling conditions and possible block points to lift to trigger the transition.

1. Introduction

The Paris Agreement objective to hold the increase of global average temperature 'to well below 2°' requires the fast decrease of CO_2 emissions towards net-zero by around 2050 (IPCC, 2018). However, Nationally Determined Contributions (NDCs) committed to the United Nations Framework Convention on Climate Change (UNFCCC) are far from aligned with these targets (United Nations Environment Programme, 2019) and countries are urged to change the scale of their commitments (The Global Commission on the Economy and Climate, 2018) and develop deep decarbonization (DD) strategies.

The strong reduction of energy-related emissions (two-thirds of total greenhouse gas (GHG) emissions) are central to these strategies and technical solutions are already available to develop low-carbon -and even net-zero- emissions energy systems by mid-century (Davis et al., 2018). Such pathways mean the fast expansion of low-carbon power generation (Zappa et al., 2019), the decline of fossil fuel supply and early retirement of fossil fuel power plants (Kefford et al., 2018), the electrification of energy uses (Zhang and Fujimori, 2020; Wang and Chen, 2019) and energy demand management through highly efficient processes and appliances in particular (Rogelj et al., 2018; Lovins et al., 2019). Many recent studies explore technically feasible decarbonization pathways for energy systems in different country contexts. These studies are based on energy models capturing the key techno-economic aspects of transformations in energy supply and demand sectors (electricity, transportation, buildings, industry, etc.) (Lallana et al., 2021; Godínez-Zamora et al., 2020; Burandt et al., 2019).

Beyond technical concerns, policy-makers need to understand the long-term economic impacts of DD strategies, not only in energy industries but also in other sectors and at the macroeconomic level. Computable general equilibrium (CGE) models are suitable tools for this purpose and have been widely used to explore the economy-wide impacts of environmental policies (Lin and Jia, 2018; Hannum et al., 2017; Bergman, 1988). To improve the technical realism of energy policy

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analysis and explore the economic implications of energy transition scenarios, they have been linked to either energy models or dual data-accounting frameworks (Hourcade et al., 2006). Such hybrid CGE models have first been used to study particular energy strategies, such as the development of renewable energy (Dai et al., 2016; Cai and Arora, 2015), and both their macroeconomic and sectoral economic impacts, including direct and indirect employment effects (Mu et al., 2018; Fragkos and Paroussos, 2018; Bulavskaya and Reynès, 2018). Other CGE-based studies have assessed the macroeconomic impacts of economy-wide climate policy based on carbon pricing (Gupta et al., 2019; Krook-Riekkola et al., 2017; Soummane et al., 2019; Landa Rivera et al., 2016) or a broader set of policies (Vrontisi et al., 2019) associated with energy transition pathways.

From a methodological perspective, integrating energy data and pathways to CGE models usually follows two approaches. In a first approach, energy information can be directly included in a standalone CGE model to simulate energy and climate policy scenarios with a standalone model (Dai et al., 2016; Wing, 2006). Because there are practical constraints to capture at the same time a full energy description with technological details, energy information is usually reduced to specific sectors, notably the electricity sector. A second widely used approach is to link energy and CGE models through key variables to capture more detailed feedbacks between the energy system and the economy (Drouet et al., 2005; Krook-Riekkola et al., 2017; Fujimori et al., 2019). Compared to the standalone CGE approach, it allows keeping the richness of both models although the linking can usually not cover all the relationships between the variables in the models. Such coupling is often based on iterative runs up to convergence to compute cost-optimal energy systems or to simulate endogenous energy system transformations triggered by carbon pricing.

The literature review highlights two research gaps that are addressed in this paper. First, most CGE-based studies either analyze a particular aspect of decarbonization (e.g. expansion of renewable energy) or full cost-optimal energy scenarios associated with carbon pricing. But in policy-making, decarbonization strategies cover all sectors and are based on a bottom-up process that consolidates sectoral roadmaps.[1] The resulting energy pathways reflect feasible strategic proposals that may deviate from cost-optimal energy scenarios. There is thus a need to adapt modeling methods to the specific objective of evaluating the economic impacts of such pre-defined decarbonization strategies. Second, there is a general lack of studies that consolidate the long-term macroeconomic and sectoral effects of full decarbonization strategies. This is however important to provide a multi-level perspective to policy-makers with direct, indirect, and induced sectoral impacts - including employment - consistent with the macroeconomic context.

This paper aims to bridge these gaps and develops a two-stage modeling approach based on developing full energy scenarios with the LEAP energy model and to load these scenarios into the IMACLIM multi-sector economy-wide model. A specific effort has been made to fully harmonize energy balances between the two models and to embark technical costs information in the economic model. The economic modeling also improves the intersectoral feedbacks by capturing the investment structure of supply activities into an original investment matrix. The model linking makes it possible to assess the multi-level economic impacts of DD strategies. We expect that the results will be sensitive to key technological choices as related technical costs and investment flows will have significant impacts on production costs and prices, but also on upstream economic activities through a knock-on stimulating effect. We apply the method to Argentina to evaluate the energy system from DD proposals up to 2050 that have partly been explored in previous work (Lallana et al., 2021). Land-use changes and afforestation are required to meet net-zero CO_2 emissions by compensating residual emissions from the energy system but such carbon sinks are out of the scope of this paper, and we only represent the energy-related emissions from the broader DD strategies. Argentina is interesting as representative of the global challenge for a low-carbon economy: it is still a fossil fuel (gas) orientated economy but quite independent from the worldwide energy context (IAE, 2019), growing with upper middle income, and with an emission intensity of GDP close to the global average (World Bank Database). Such application also contributes to the expansion of studies on the Latin America region as analyses of mitigation -and even more of deep decarbonization-strategies are still scarce for countries of this area compared to other regions.

The paper is structured as follows. Section 2 describes the modeling approach. Section 3 narrates the energy scenarios developed. Section 4 presents the results on the transformations of the energy system and the multi-level economic impacts. Section 5 discusses the results in the case of Argentina. Section 6 provides policy recommendations and draws general conclusions.

2. Modeling approach

The modeling approach developed in this paper must be tailored to its specific goal which is to assess the multi-level economic impacts of pre-defined strategies for the energy system. First, it involves an energy model to simulate comprehensive energy pathways and capture the peculiarities of energy supply and demand systems in detail. Second, it requires a multi-sector economy-wide model to assess multi-level economic impacts. Therefore the full model linking strategy is the most relevant. Iterative runs are not required and a one-way linking imposing energy variables as exogenous parameters in the economic model is sufficient to assess the economic impacts of a pre-defined energy strategy. The macroeconomic feedback which can be significant in practice does not affect the intended strategy itself by definition which also may not be optimal. The economic impact analysis can provide useful information to eventually revise the energy strategy afterward. We thus develop a two-stage modeling strategy comparable in spirit as in Lekavičius et al. (2019). First, the combined qualitative-quantitative Deep Decarbonization Pathways (DDP) method is applied to build full energy pathways that reflect the views of various stakeholders and realistic strategic proposals for future decarbonized energy systems at the country-scale (Waisman et al., 2019; Bataille et al., 2020). The LEAP energy model is used to quantify the narratives and provides consolidated energy balances and details about the dynamics of technologies, infrastructures, and equipment as well as the related technical costs and investment expenditures for both energy supply and demand. Second, consolidated characteristics of energy pathways are exogenously prescribed in the IMACLIM economy-wide model which simulates endogenous feedbacks such as the impacts of price variations or the impacts of economic activity on total energy demand from industries. However, economic feedbacks do not affect the dynamics of key technologies, infrastructures, and the supply and demand energy structure as pre-defined by the energy strategy. Additional details on the modeling approach are provided below.

2.1. Building energy pathways with the LEAP model

The LEAP model is an integrated energy planning and climate change mitigation assessment modeling tool (Heaps, 2016). Through a simulation approach, LEAP represents a detailed energy system of a country to formulate energy plans consistent with the national context. In particular, the model makes it possible to develop full backcasting scenarios that ensure consistency in the energy choices (available technologies, resources, transformation, demand, etc.) toward low-carbon transition. LEAP covers energy demand, transformation, and supply and can be used to account for both the energy and non-energy related GHG emissions and sinks. In our case, it is used to track only CO_2 emission

[1] For instance, the Net Zero plan for United-Kingdom, or the National low-carbon strategy (SNBC) from the French government.

from energy combustion.

In this paper, we use the LEAP model version calibrated for the region of Argentina which has already been applied to mitigation studies (Di Sbroiavacca et al., 2014). Following the 'qualitative-quantitative' DD Pathway approach, the LEAP model is used to quantify full decarbonized energy systems that reflect realistic pathways with technical options adapted to the specific context of Argentina (Lallana et al., 2021). The pathways describe all the energy transformations, from the structure of supply to the demand composition, and explicit the dynamics of technologies, infrastructures construction, and equipment.

In practice, some policy incentives will be needed to ensure the fulfillment of energy pathways but have not been analyzed in this study which rather focuses on technical transformation pathways. Further work would be required to clarify the incentives needed to meet the goals.

The key quantitive information is synthesized as time series of consolidated energy balances, detailed technical costs (fixed and variable Operations & Maintenance (O&M) costs, capital expenditures, etc.) and also investment expenditure for power generation.

2.2. The IMACLIM economy-wide model

IMACLIM-Country is a multi-sector CGE model available in several national versions. Versions exist for France (Le Treut, 2017; Combet, 2013), Brazil (Lefèvre et al., 2018), South Africa (Schers, 2018), India (Gupta et al., 2019), Saudi Arabia (Soummane et al., 2019), and ultimately Argentina. For the sake of transparency, a platform in open-access has been released to support the development of national IMACLIM versions (Le Treut et al., 2019). The model simulates full pictures of the future economy at different time horizons under energy-GHG emissions-economy constraints. Used standalone, IMACLIM can assess the macroeconomic costs and multi-sectoral impacts of emission-oriented policies such as carbon-pricing instruments, or specific sectoral policies and regulations. The model departs from more standard neoclassical CGE models in several features. First, it computes Walrasian-type markets of goods and services characterized by possible underemployment of production factors (unemployment) and market imperfections (through mark-up pricing) constrained by other specific structural assumptions (e.g. demand-driven investment). Second, the description of the consumers' and producers' trade-offs, and the underlying technical systems, are specifically designed to facilitate a calibration on bottom-up (BU) expertise in the energy field, to ensure technical realism of the simulations (Hourcade et al., 2006).

IMACLIM is based on a national Input-Output table (IOT) coupled with a consistent economic account table.[2] A key characteristic of the IMACLIM IOT is that it includes a dual physical-economy accounting framework: physical flows (energy flows in *toe* physical units) *and* economic flows (energy payments) are both balanced and linked by a consistent price system. Such 'hybrid' accounting requires a careful combination of energy and economic data to build a realistic picture of energy-economy relationships (Combet et al., 2014). Also, it makes it possible to draw direct and consistent linkage with energy models without a 'translating' procedure as often used (Drouet et al., 2005). For a complete description of the IMACLIM-Country model, we refer the reader to its full formulary available in the model documentation (Le Treut, 2020).

Each country version of IMACLIM comes with its specificities. The IMACLIM Argentina model is calibrated at the year 2012, represents six hybrid energy sectors,[3] twelve productive activities[4] and, a 'composite' aggregate for the rest of the economy. All the data are available in a data publication (Le Treut et al., 2020). The model offers an innovation as part of this study by describing an *investment matrix* for the overall economy. Commonly, the gross fixed capital formation, represented by a vector in the IOT, informs about the amount each sector invests within the overall economy but does not describe which activities are driving the investment demand of a given sector. By gathering external information (Freitas, 2010), we decompose the vector of investment demand[5] into a matrix[6] to capture the sectoral effects embodied in investments. We address a particular interest in isolating the investment demand for the power sector. Its decarbonization can be achieved through a wide range of technologies relying on different upstream activities that may have contrasted feedbacks within the economy. For instance, the expansion of hydropower plants will mobilize the construction sector while the expansion of the Carbon Capture and Storage (CCS) technology will require a greater share of manufacturing goods. As a consequence, the industries that benefit from the low-carbon strategy differ. Such specific investment contents can be informed exogenously under deep decarbonization simulations.

2.3. Linking LEAP and IMACLIM models

Based on energy pathways from the LEAP model, the second stage of the modeling strategy consists of loading their key characteristics as exogenous parameters into the IMACLIM model. The inputs are domestic energy consumption structure and traded energy, technical costs and investment expenditures in the power sector, and equipment expenditures supported by households for transportation and residential energy services (Fig. 1).

First, energy balances from LEAP are transformed into a IOT format compatible with the IMACLIM model detailing the energy consumption from energy industries (energy conversion processes and self-consumption), other industries (end-use energy), households (transportation and residential energy), and energy trade volumes (imports and exports). The effort undertaken to describe the energy flows in physical units within the economic model takes its full meaning here. It makes it possible to directly use the energy balances to inform energy consumption in the economic model which is a significant advantage of the model linking developed in this paper. Household consumption, imports, and exports per energy type are set in absolute terms as exogenous parameters in IMACLIM while for economic sectors, we set energy intensities of production per energy type. It substitutes the results of production and consumption trade-off of the standalone IMACLIM model. By prescribing the only energy intensities of economic sectors, the feedbacks on economic production levels affect the total energy consumption and thus, total energy production is endogenously determined.

Second, a specific effort is made to set IMACLIM with detailed BU information on the power sector as it is key in the decarbonization strategy. We summarize below the main features of the linkage, and we refer the reader to Appendix A for more details on quantified information.

Beyond the energy balances that inform the demand and the variable fuel costs of the electricity, LEAP provides additional information on power generation and electricity supply costs, and investment

[2] Together, the IOT and the economic account table can be combined into a Social Accounting Matrix (SAM) format which synthesizes the full transactions between economic branches and between institutional sectors (firms, public administration, households groups, and the "rest of the world").

[3] Crude oil, gas, fossil fuels, biofuels, electricity, renewables.

[4] Agriculture, cattle, cement, iron& steel, rest of heavy industries, food & beverage, rest of manufacturing industries, transport road freight, transport road passenger, rest of transport, commerce & services, construction.

[5] dimension [*sectors*, 1].

[6] dimension [*sectors*, *sectors*].

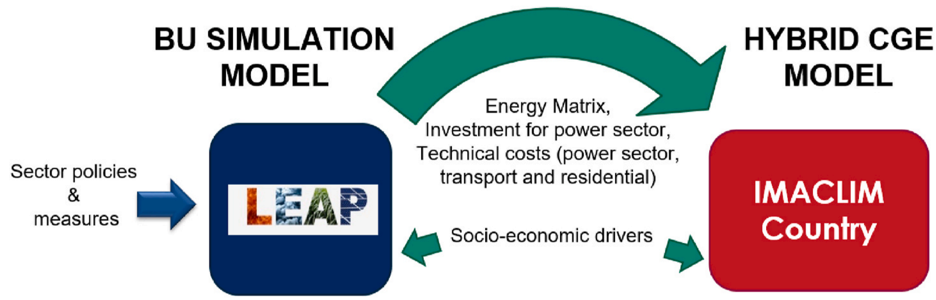


Fig. 1. Linking procedure from LEAP to IMACLIM-Country.

expenditures. LEAP details existing generation capacities, the time sequence of newly installed capacities, and the technology-specific capital expenditure (CAPEX) and operational expenditure (OPEX). This information is first used to calculate total annualized capital costs and fixed O&M costs for power generation (as the sum of costs across technologies of existing and newly installed capacities) which is assimilated to total power sector capital and labor costs both fixed exogenously in IMACLIM. LEAP also provides detailed information on investment expenses, their structure in terms of investment goods and services, and the specific time profile to build capacities for the different power technologies. This detailed information makes it possible to estimate with precision the total investment expenditures and their content in terms of investment goods and services at a given year, which are then loaded as an exogenous vector of the power sector in the IMACLIM investment matrix.

Third, based on BU calculations, we inform into IMACLIM an incremental expense supported by households related to energy efficiency gains and conversion into low-carbon equipment for residential energy (insulation, heat pumps, etc.) and transport (electric vehicles) in the DD scenarios (see Section A.2 of Appendix A). Outside households, energy efficiency gains and fuel switches in productive sectors lead to increased capital costs through an aggregate elasticity.

Eventually, the LEAP and IMACLIM models are calibrated with the same socio-economic assumptions to simulate consistent scenarios within the global framework. GDP assumptions are translated into labor productivity drivers in IMACLIM: actual GDP is endogenous in the model and can depart from reference GDP levels.

Some economic feedbacks on the energy pathway are endogenously modeled in IMACLIM. Technical costs and expenses from LEAP are exogenously set in real terms (*AR$*2012) and current costs and expenses in the economic model depend on price variations (goods, energy, labor, etc.). The economic feedback thus affects industrial production levels and in a row the total energy demand from industries, and the total energy production. But, it does not affect the predefined energy strategy. Fossil fuel industries only adapt their production level to the new demand. The slight variation in electricity demand has also no impact on the generation park and related total capital and labor costs as well as investment expenses. It only impacts the average utilization rate of capacities.

Eventually, the model linking focuses on the economy-wide effects induced by the technical and investment costs related to the energy developments, without including explicit incentives (subsidies, taxes, etc.) that could be needed in practice to trigger the technical transformations. This leaves open the discussion on incentives and their economic effects, and, it amounts to implicitly assuming economically neutral incentives - outside technical costs - such as with regulations or price incentives with neutral revenue recycling.

3. Scenarios

We develop three energy scenarios for Argentina from 2015 to 2050: (i) one ***NDC scenario*** consistent with Argentinian NDC until 2030 extended up to 2050, (ii) two ***deep decarbonization scenarios*** based on a shift towards a low-carbon energy system which differ by the technological strategy to decarbonize power generation.

These scenarios are mainly drawn from a previous work of the authors (Lallana et al., 2021). All energy scenarios, based on common socio-economic assumptions, reflect a steady evolution of the economy in Argentina with little structural change (Table 1). In particular, it is assumed that Argentina neither significantly change its structure of production nor its trade relationships. Gross Domestic Product (GDP) and GDP per capita is projected to evolve at a slightly higher pace than during the last 30 years: + 2.2% resp. + 1.3% for the 2015–2030 period and +2.7% resp. + 2.1% for the 2030–2050 period (GDP has been growing at + 1.3% on average since 1992).

We detail the narrative of the scenarios analyzed in the following. Fig. 2 gives an overview of their main characteristics.

3.1. The NDC scenario

In the NDC scenario, Argentina's primary energy system continues to mainly depend on natural gas and oil, although the latter will slightly decrease in the long run due to the substitution of liquid fuels for electricity in the transport sector. The scenario includes the climate mitigation measures already committed under the Paris Agreement through the NDCs detailed in an official report (Argentine Government Secretariat of Environment and Sustainable Development, 2019) for the United Nations (UN). On the energy supply side, the boost to renewable power generation - mainly wind and solar - leads to generation percentages where deployment is economically competitive. The scenario also includes a program of development of nuclear power until 2030. On the demand side, the NDC scenario details a series of measures in transport and residential sectors mainly (with modest goals) such as modal changes and the renovation of the vehicle fleet for freight transport, the introduction of electric buses, incentives for hybrid and electric vehicles (EVs) in private passenger transport, regulatory standards linked to the thermal envelope of buildings (insulation), heat pumps for heating (replacing natural gas stoves for electricity appliances), improvements in residential hot water systems using natural gas, etc. These measures committed until 2030 were maintained until 2050 without increasing the mitigation ambition to reflect a NDC tendency

Table 1
Key socio-economic assumptions.

Reference Year	**2012**	**2015**	**2025**	**2030**	**2035**	**2040**	**2045**
Year of Resolution	**2015**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP	0.8%	1.7%	3.2%	2.7%	2.7%	2.7%	2.7%
Population	1.1%	1.0%	0.8%	0.7%	0.6%	0.5%	0.5%
Retired	2.1%	2.0%	1.8%	1.9%	2.2%	2.1%	1.9%
Labour force	0.0%	1.4%	1.0%	1.0%	1.0%	1.0%	1.0%
GDP world	2.5%	3.0%	2.5%	2.5%	2.5%	2.2%	2.0%
in mean growth annual rate							

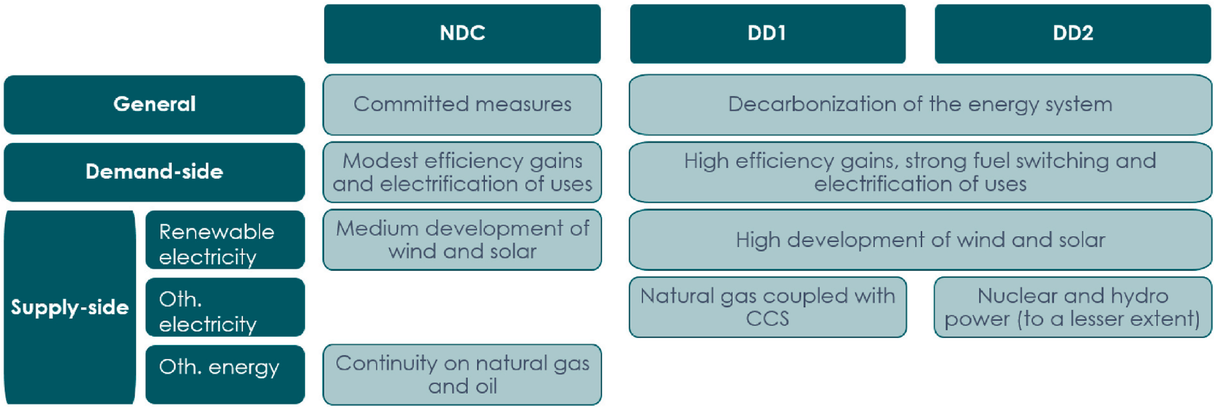


Fig. 2. Main characteristics of the scenarios.

scenario.

3.2. Deep decarbonization scenarios

The two deep decarbonization scenarios, named DD1 and DD2, reflect a major upscale of climate ambition compared the NDC scenario and realistic energy proposals in the context of Argentina. They share the same assumptions about demand-side mitigation measures with the same strong energy efficiency gains and fuel switching but are based on different visions of decarbonized power generation systems.

On the energy demand-side, deep energy efficiency gains and fuel switching towards low-carbon fuels are achieved in all energy end-use sectors. In residential and commercial sectors, highly energy-efficient electric systems replace current natural gas equipment for water, space heating, and cooking services with heat pumps especially for space heating together with better thermal insulation. In the transport sector, strong penetration of efficient hybrid and EVs happens for all fleet types (cars, buses, trucks) replacing thermic vehicles, and also some modal shifts towards metros and rail systems. In the industrial sector, high energy efficiency gains are reached, for direct heat generation especially, together with the electrification of many processes that were originally based on natural gas.

On the energy supply side, DD scenarios include same sizeable development of renewable electricity - wind power and solar PV - compared to the NDC scenario. However, the DD1 scenario assumes that the exploitation of the *Vaca Muerta* hydrocarbons basin, with an abundance of gas resources, remains a priority with the same production objectives as in the NDC scenario. The additional gas exploration makes it possible to feed a growing power generation system in the context of an increase of final electricity demand due to the electrification of usages. Gas combined-cycle (CC) power plants are further coupled with CCS technologies to build a low-carbon power generation system. In practice, significant investments are carried out to equip most gas CC power plants with CCS feature by 2050. Conversely, in the DD2 scenario, another strategy of power generation is adopted with the strong development of nuclear-based power generation and hydropower to a lesser extent. We assume for both deep decarbonization scenarios that the external trade of fossil fuels remains at the level of the NDC scenario. Thus, Argentina does not take advantage of its resources in the international market. Consequently, the bulk of additional natural gas resource is not exported in the DD2 scenario which stays under the ground.

All three energy scenarios are fully quantified with the LEAP model and further simulated in the IMACLIM-ARG model. Comparing economic outputs of DD scenarios to that of NDC scenario makes it possible to highlight the economic impacts of decarbonization strategies.

4. Results

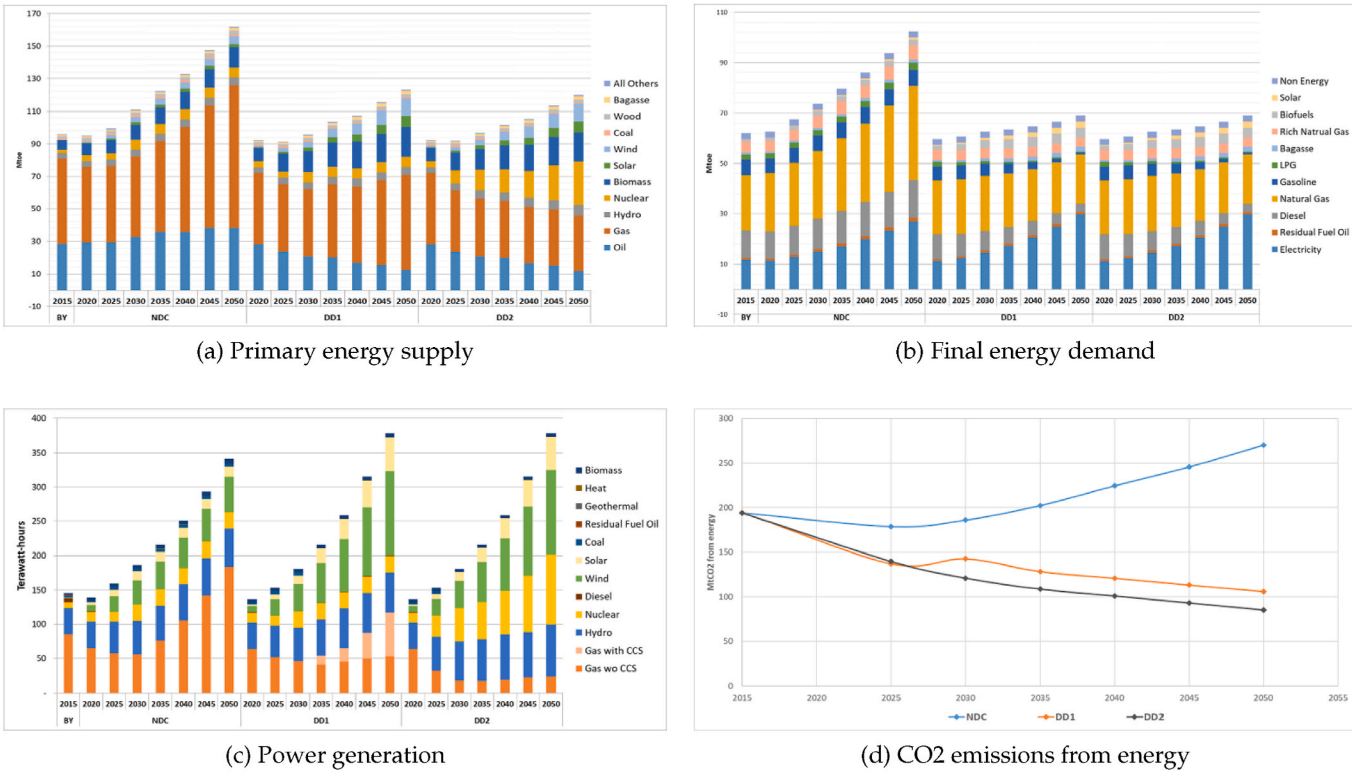
4.1. Energy system transformations and resulting CO2 emissions

The type of transformations of the energy system is qualitatively different between the NDC and DD scenarios (Fig. 3).

In the NDC scenario, the 32% decrease in the energy intensity of GDP between 2015 and 2050 (1.1%/*yr*, slightly below the world average of the past 20 years) hardly impacts the continuous rise of total primary energy consumption (Fig. 3a) which is multiplied by 1.7 driven by economic growth (GDP is multiplied by 2.5), despite a short term plateau (2015–2025) due to the NDC energy efficiency measures. The share of non-fossil primary energy (biomass, solar, wind power, nuclear, hydropower, etc.) increases to 25% due to early period mitigation measures but keeps this level beyond 2030. Overall, the non-fossil energy only piles up on top of fossil energy (oil and natural gas almost exclusively) which also keeps increasing (+55% by 2050) to supply the growing energy demand. The NDC scenario thus does not embody a genuine energy transition process but only a limited diversification of the energy supply -still dominated by fossil energies (more than 75% of the primary mix). Conversely, DD scenarios embody more radical transformations of the energy system. First, the total primary energy supply is only multiplied by around 1.2 by 2050 in both scenarios (corresponding to an average 1.9%/*yr* decrease of the energy intensity of GDP) due to stronger energy efficiency measures. Second, the composition of energy sources changes more radically. In the DD1 scenario, total fossil energy supply remains almost constant after 2015 and the climb of natural gas - especially used in conjunction with CCS in power generation after 2030 - is offset by the drop of oil. The additional energy demand is supplied by the strong development of renewable energy (biomass, solar, and wind power increases 3.7-fold in total). Finally, only the DD2 scenario embodies an energy transition *per se*. Total fossil energy supply falls by 43% by 2050 which strongly breaks with the past continued growth of fossil energy consumption in Argentina. Non-fossil low-carbon energy expands strongly to replace fossil energy (a 5.3-fold increase of total non-fossil energy including the additional strong expansion of nuclear and hydropower on top of the fast development of biomass, solar, and wind compared to the DD1 scenario) and reaches 61% of total primary energy in 2050.

The contrasted energy system transformations across scenarios are first linked to different energy demand patterns (Fig. 3b). The NDC scenario shows a sustained increase of total final energy demand (+63% by 2050) and limited electrification of end-uses. Conversely, in DD scenarios final energy demand increases slowly (+10% by 2050 only) with strong electrification of end-uses (from 18% in 2015 to 40% of final energy demand in 2050) and the use of biofuels.

Scenarios also differ dramatically regarding the future of power generation (Fig. 3c). In the NDC scenario, total power generation grows



(a) Primary energy supply

(b) Final energy demand

(c) Power generation

(d) CO2 emissions from energy

Fig. 3. Energy structure in NDC and DD scenarios (2015–2050).

significantly (a 2.4-fold increase) and the mitigation measures based on the development of renewable power (solar and windpower mainly) make it possible to reduce the need for gas-fired power until 2030 only. Non-fossil low-carbon power technologies finally represent ‘only’ 48% of total power generation in 2050 (comparable to 2015 but with a higher share of solar and wind power). Conversely, DD scenarios develop almost fully decarbonized power generation systems by 2050 (except for electricity auto production still relying on gas-fired technologies), but with alternative technological strategies. The strong electrification of end-uses first implies 11% higher electricity demand than in NDC by 2050. Second, both DD scenarios seek much faster penetration of solar and wind power than in NDC (with 2.4 and 3.2-fold increases for wind power and solar respectively -together, almost 50% of the power mix in 2050). Beyond 2030, the DD1 scenario builds on the strong development of gas-fired power plants with CCS (95 TWh, 27% of the power mix in 2050), whereas in the DD2 scenario nuclear and hydropower expand strongly until 2050 (76 TWh of hydropower - 22%, 102 TWh of nuclear - 29%). The remaining production by gas in the DD2 scenario (21 TWh in 2050) corresponds to self-consumption by power plants and is accounted for at the same level in the DD1 scenario (21 TWh out of a total of 51 TWh of electricity generated by gas without CCS).

Eventually, the contrasted evolutions of energy systems across scenarios have direct implications for the qualitative shape of the implied CO_2 emissions pathways (Fig. 3d). The NDC scenario which embodies limited structural change of the energy system does not allow to mitigate absolute CO_2 emissions in the medium run and, emissions increase by 53% by 2050. Conversely, DD scenarios imply a sharp bifurcation that breaks with the fast historical rise of energy-related CO_2 emissions in Argentina. In the DD2 scenario, future emissions decrease in absolute terms by 2.3%/*yr* on average to reach the deep decarbonization of the Argentinian economy (−56% CO_2 emissions in 2050 compared to 2015). The gap between DD1 and DD2 scenarios correspond to the additional emissions from electricity generation in the DD1 scenario. In broader DD strategies targeting same ambition of GHG emissions outside energy combustion, the gap is offset by additional efforts on the non-energy related emissions (agriculture and livestock), which is not taken into account in the present analysis.

4.2. *Multi-level economic impacts of deep decarbonization scenarios*

4.2.1. *Upscaling investment in low-carbon power generation*

The LEAP model also provides details on the sequence of power generation capacities installation through time for the different technologies and associated investment costs and thus a first-level of economic implications. The results show that to sustain the increase of power supply in the NDC scenario, 69 GW of power generation capacity are built from 2015 to 2050 (2 GW/yr on average) including 24.3 GW of windpower plus solar PV but also 35.8 GW of gas-fired power plants (cf. Table 2). In the DD scenarios, much more capacities are required to sustain a higher power supply which is furthermore based on a much higher share of intermittent renewable technologies. In both DD scenarios, around 100 GW of new capacity are built from 2015 to 2050 (3 GW/*year* on average) including 64.5 GW of windpower plus solar PV but with negligible new gas-fired power plants without CCS after 2020, a precondition for the deep decarbonization objective. On top of the same

Table 2
Total built capacity per power technology from 2015 to 2050 in NDC and DD scenarios.

Installed GW	NDC	DD1	DD2
Diesel motors	1.1	1.1	1.1
Coal steam turbine	0.2	0.2	0.2
Gas turbine	9.5	5.1	4.4
Biomass steam turbine	0.2	0.2	0.2
Combined Cycle Gas	26.2	3.8	3.8
NGCC with CCS	0.00	18.4	0.00
Nuclear	1.9	1.9	17.3
Solar	7.8	24.7	24.7
Wind power	16.5	39.8	39.8
Hydro	5.1	5.7	11.0
Total	**68.6**	**101.0**	**102.5**

development of wind power and solar capacity, 18.4 GW of gas-fired power plants with CCS are built from 2030 on in the DD1 scenario and only 1.9 and 5.7 GW of nuclear and hydropower, whereas 17.3 and 11.0 GW of nuclear and hydropower are installed in the DD2 scenario.

Considering the higher average capacity cost of nuclear and renewable technologies compared to gas-fired technology - even when future technological progress is taken into account (see Appendix A for further details), total investment costs for power generation are all the higher in DD scenarios than in NDC scenario (Fig. 4).

Therefore, in the DD scenarios, the mean annual investment in power generation from 2015 to 2050 amounts to 6-7*USb$/yr* including 3.5*USb$/yr* for windpower plus solar PV in both DD scenarios, 2.4*USb$/yr* for gas-fired power with CCS in the DD1 scenario and 3.7*USb$/yr* for nuclear plus hydropower in the DD2 scenario. This compares to less than 3*USb$/yr* mean total annual investment in power generation in the NDC scenario (including 1.5*USb$* for gas-fired power plants). The 3.5–4.5*USb$/yr* additional investment is a significant amount that represents around 1.5–2% of total investment and around 0.3% of GDP on average between 2015 and 2050.

4.2.2. Deep structural change in energy industries

Linking energy scenarios into the economic model first lights on the economic impacts on energy industries. The contrasted transformations of the energy system across scenarios have deep implications for the economic structural change happening in energy supply sectors (Figs. 5 and 6).

First of all, the NDC scenario only implies limited structural change with a steady contribution of fossil energy industries (oil and gas extraction, refining and distribution) to the valued-added (45%) and employment (more than 30%) of the overall energy sector. Conversely, DD scenarios embody a fast and deep structural change with declining fossil fuel industries and the strong climb of non-fossil power industries that generate significant additional value-added and new direct jobs. The share of fossil industries out of total energy sector value-added drops to 20% in 2050 in the DD1 scenario with 21 thousand fewer jobs than today (1.6% mean annual decrease). The sustained need for gas distribution for gas-fired power generation with CCS limits the decline of the natural gas industry in the DD1 scenario. The decline of fossil industries is thus even more pronounced in the DD2 scenario and these industries only stand for 15% of the value-added of the energy sector in 2050 with 27 thousand fewer jobs than today (2.2% mean annual decrease).

Conversely, the power industry (power generation, distribution, and transmission) reaches 75%–80% of total energy sector value-added in DD scenarios. In total, the low-carbon power industry represents 2.7–3.1% of total GDP in 2050 which is comparable to other main economic sectors such as agriculture or freight transportation. Besides, the power industry generates significant additional jobs compared to today in the DD scenarios: 120–150 thousand direct additional jobs are created by 2050 (more than + 3%/*yr*). Overall, accounting for both job losses in fossil industries and job creations in the power and other non-fossil industries, 100–130 thousand net jobs are created in the energy sector in DD scenarios by 2050, which is twice more than in the NDC scenario, despite the smaller total energy supply. Net job creations in an overall smaller energy supply system are allowed by the development of labor-intensive low-carbon power industries replacing part of fossil fuel industries. The expansion of the power industry is most pronounced in the DD2 scenario with the fast upscale of labor-intensive nuclear and hydropower industries on top of the fast development of other renewable industries.

4.2.3. Macroeconomic impacts

The DD scenarios have important economic implications beyond the energy sector. The significant investment effort to be sustained for several decades not only to decarbonize the power sector but also in end-use sectors (industry, buildings, transportation), the sizable variations of energy and capital costs induced, and, the productivity effect of energy efficiency are expected to have significant impacts at the macroeconomic level over the long run. Our results first show that the aggregated GDP implications of shifting a pathway from NDC to DDPs are small on average over the period (Fig. 7). The net present value (NPV) of cumulated GDP is only 0.1% and 0.8% lower in the DD1 and DD2 scenarios respectively than in the NDC scenario. These results are robust to key uncertain parameters such as the investment needs and related capital costs in non-energy sectors (see Appendix B). However, the limited GDP implications in aggregated terms hide sizable structural change on the demand-side GDP composition in DD scenarios compared to NDC (Fig. 7). First of all, the mean annual incremental investment in DD scenarios is +0.6–0.8% of GDP compared to NDC. It means + 4–5% net additional annual investment on average (8-10*USb$/yr*). Around one third is net additional investment needed in energy supply sectors (+0.4*%GDP* for the power sector including generation, distribution and transmission half offset by 0.2*%GDP* lower annual investment in declining fossil fuel industries) and two third is net additional investment in other economic sectors including investment in more energy-efficient and low-carbon capital and infrastructures for transportation, buildings, and industrial production. These results are in line with existing estimates of the mean global incremental GDP share of annual

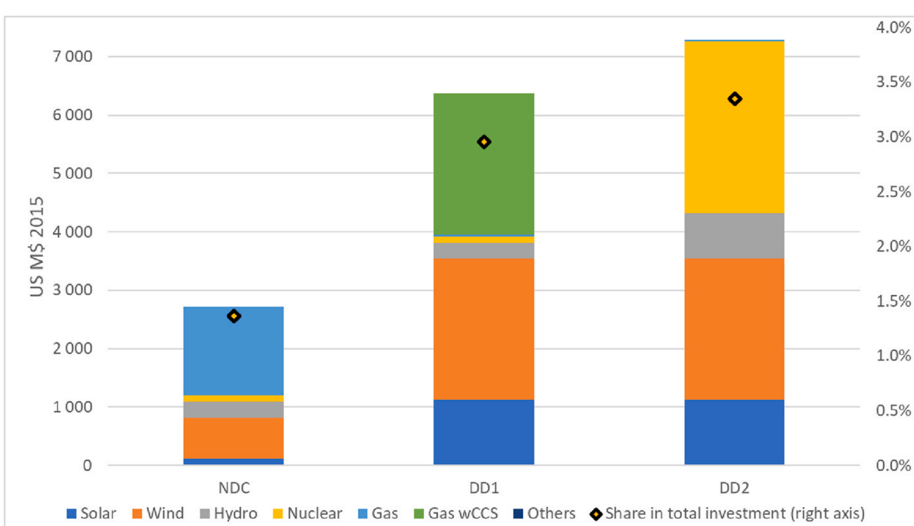


Fig. 4. Mean annual investment in power generation and its mean share out of total investment (2015–2050).

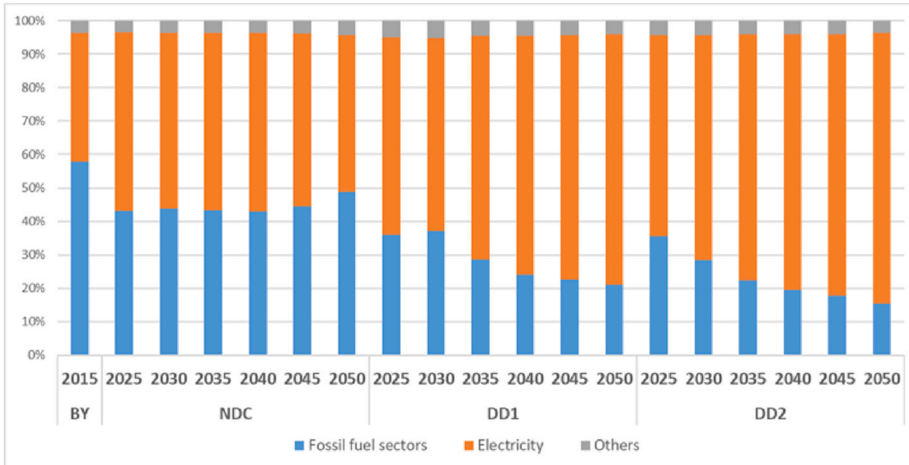


Fig. 5. Shares of the different energy industries out of the total value-added of the energy sector.

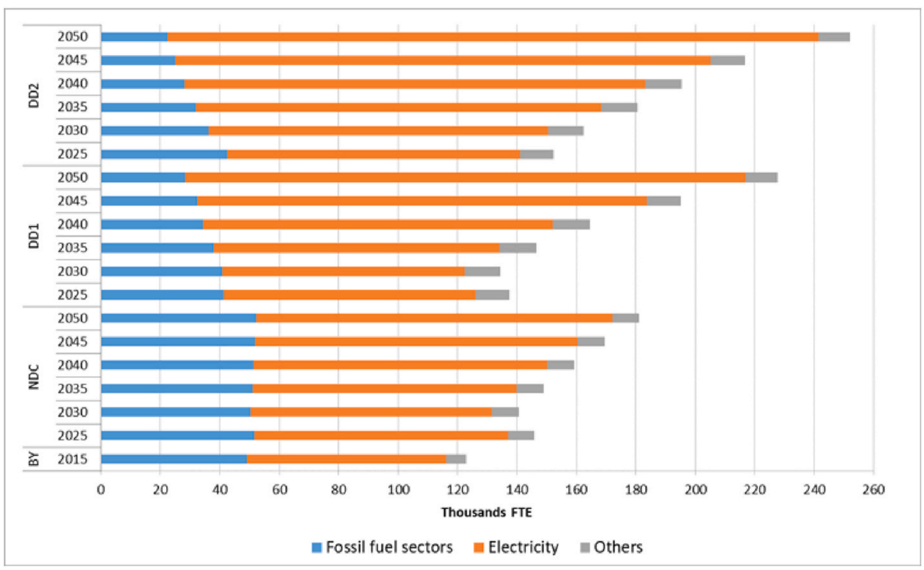


Fig. 6. Total employment in energy industries.

mitigation investments needed to shift from baselines to below 2°C scenarios (IPCC, 2018). At the macroeconomic level, the incremental net additional investment in DD scenarios has a demand-side stimulus effect compared to NDC that tends to drive GDP up. This stimulus effect is the highest in the DD2 scenario with the investment push in hydropower and nuclear industries.

Conversely, both final consumption and trade balance have mean negative contributions to GDP in the long run: − 0.5% and −0.6% respectively in the DD1 scenario and −0.9% for both in the DD2 scenario. However, the relative impact on final consumption remains limited as final consumption represents 75% of GDP (only − 0.6/− 1.3% difference of the NPV of cumulated consumption between DD scenarios and the NDC). All the more so as roughly half of the macroeconomic consumption 'losses' correspond to the drop of household energy consumption but without a drop of related energy services (transportation, housing) thanks to more efficient equipment, which has no real negative welfare implications overall. Besides, it could even be interpreted as a kind of welfare improvement, considering energy efficiency implies better satisfaction to reach the same energy basic needs. The remainder of consumption losses is due to the slightly lower purchasing power in DD scenarios due to higher consumer prices. These higher prices reflect higher production costs (+3–4%) due to higher average capital costs (4–5%) and higher energy prices (+20–27% including 26–41% higher electricity prices) despite 10–12% lower mean energy intensity of production. Furthermore, the higher production costs of domestic industries have more pronounced relative impacts on the trade balance as a result of competitiveness losses: mean annual net exports are 7–10% lower in the DD scenarios than in the NDC scenario. Finally, the mean annual negative impacts on final consumption and trade are slightly more pronounced in DD2 than DD1 scenario mainly because of higher domestic prices due to higher electricity prices.

Eventually, the national debt slightly increases in DD scenarios: it reaches +0.6*ptsGDP* and +1.6*ptsGDP* in 2050 in DD1 and DD2 scenarios respectively compared to NDC.

4.2.4. *Indirect and induced sectoral impacts*

Beyond the energy sector and overall macroeconomic effects, deep energy transitions have indirect and induced economic impacts across economic sectors.

Fig. 8 shows that sectoral impacts are very heterogeneous and can be very different from the economy average. First of all, the total output (Fig. 8a) of the energy sector is sizably lower in the DD scenarios (−20/−28%) in compliance with the lower energy demand - but with a higher absolute value-added thanks to the development of high value-added

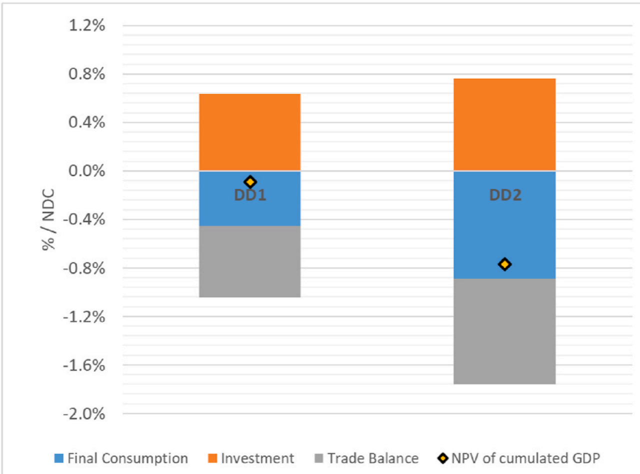


Fig. 7. Net present value of cumulated GDP losses (2015–2050) in DD scenarios compared to NDC discounted at a 5% discount rate and mean annual incremental difference of GDP components (total investment, final consumption and trade balance) as shares of GDP compared to NDC.

low-carbon power production. Second, significant additional investment and purchase of low-carbon equipment for power generation and end-use sectors have an indirect stimulation effect on the upstream industries that provide the corresponding goods and services. The domestic construction sector is the most stimulated (+5–7% mean output) as it is needed to build the power plants, the low-carbon transport, and industrial infrastructures, and to retrofit commercial and residential buildings. The manufacturing industry is the second sector indirectly stimulated with mean losses lower than the economy average. However, contrary to the construction sector, the domestic manufacturing industry competes with foreign industries to supply the needs of investment goods and low-carbon equipment (wind turbines, silicon plates, CCS equipment, electric cars, etc.). The overall indirect impact of the decarbonization strategy on the domestic manufacturing industry is thus highly dependent on the industrial strategies and the resulting market shares of domestic productions in the different supply chains. Interestingly, the results also show that the alternative decarbonization strategies for the power sector between DD1 and DD2 scenarios can lead to contrasted indirect impacts on upstream sectors. The construction sector (resp. the manufacturing industry) is relatively more (resp. less) stimulated in the DD2 than in the DD1 scenario because the investments related to building nuclear and hydropower capacities are relatively more intensive in construction and less intensive in manufactured goods than for gas-fired power with CCS. Finally, the decarbonization pathways have broader induced impacts on other sectors through macroeconomic feedbacks and sectoral changes in production costs, and related responses of domestic and foreign demand. Therefore, the sectors producing tradable goods and services and/or incurring higher cost increases than average (agriculture, heavy industry, transport services, etc.) are the most impacted (around 2–4% lower output).

Ultimately, sectoral impacts have employment implications (Fig. 8b) which constitute the key markers of the socio-economic transformations implied by the deep decarbonization strategies. We first confirm that deep decarbonization induces net job creations in the energy sector (+10-36kFTE on average) compared to the NDC scenario despite the significant reduction of total output, thanks to the development of labor-intensive low-carbon power industries. For other sectors, the difference in mean net employment arises from the difference of sectoral output. The construction sector concentrates the bulk of net job creations in the DD scenarios with a mean additional +90-144kFTE of non-relocatable jobs. The manufacturing industry creates several thousands of jobs depending on the DD scenario but the net balance is highly dependent on what happens for the different manufacturing branches. Overall, the net job creations in the energy, construction, and manufacturing sectors are more than offset by job destructions in other sectors (agriculture, transport, and services). However, the net negative balance is small in light of total employment (−0.5-0.7% only) and is mainly driven by the net job losses in service sectors directly correlated to GDP.

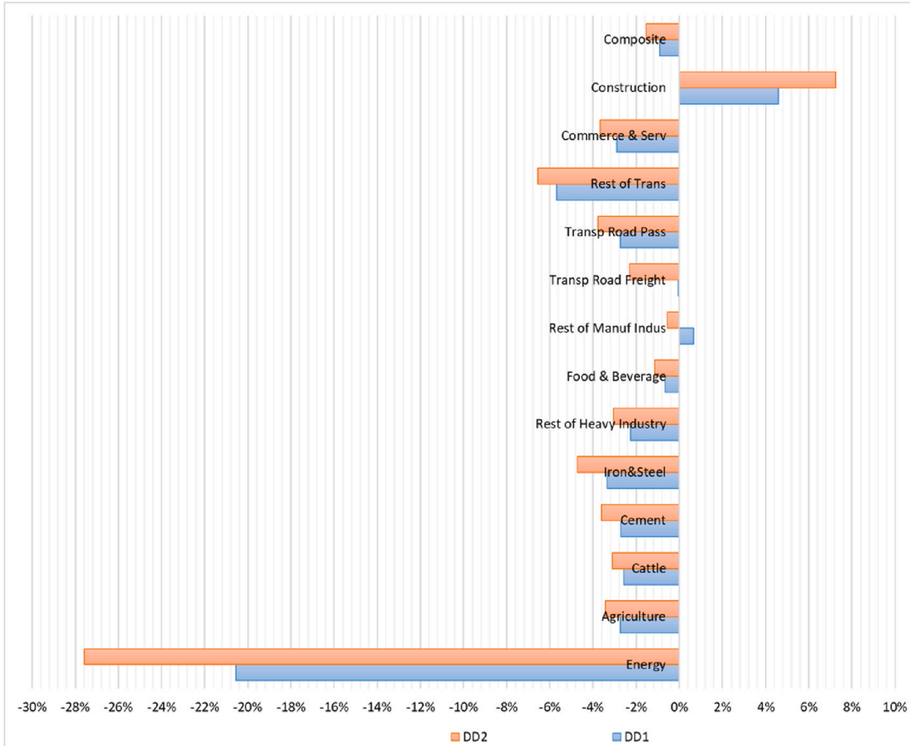
5. Discussion

Overall, our results show that feasible DD pathways for the energy system based on deep transformations on both supply and demand sides could have limited GDP and aggregate welfare implications in Argentina. However, DD strategies induce sizable structural change in the economy, on top of additional investment efforts. Significant structural transformations are implied in different industries, in the energy sector in particular.

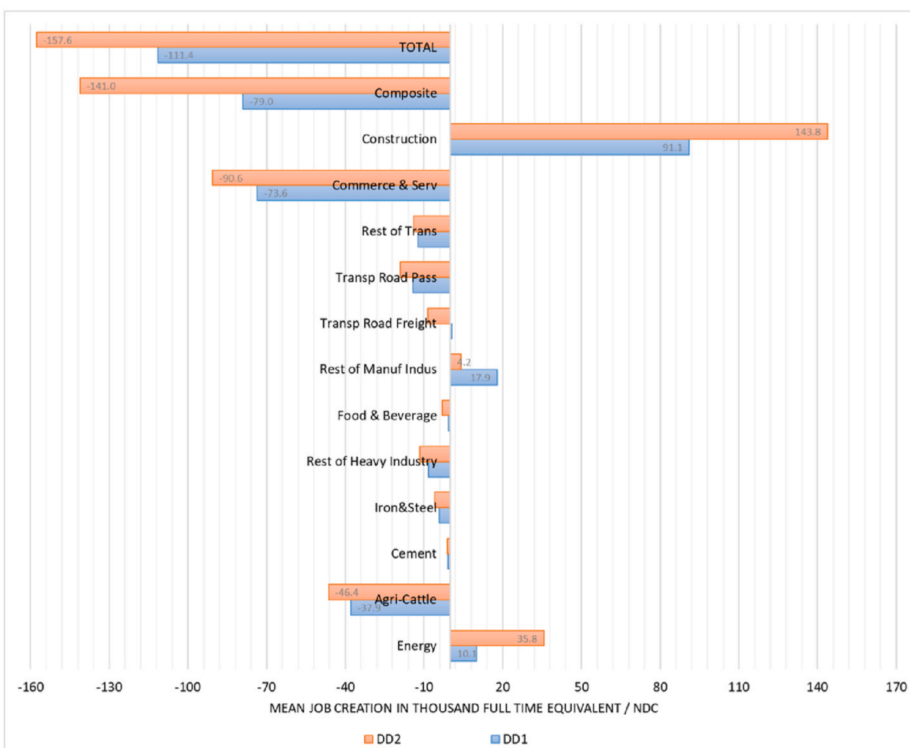
On the one hand, the steep decline of fossil fuel industries (around −2% per year) results in the shut-down of about one refinery per year until 2050 and the direct loss of about one thousand jobs. In addition, significant economic value is lost and part of economic assets become stranded which implies financial risks. On the other hand, the fast expansion of low-carbon power capacities in the DD2 scenario (around 3% per year production increase) results in the annual commissioning of about one new nuclear plant, 500 additional wind turbines, and 500ha of additional solar panels with the creation of 4–5 thousand new direct jobs. On the whole, redirections and upscale of investments, and also both displacements and creation of jobs are significant at the scale of the energy sector but remain small relative to the whole economy.

The energy transition also brings substantial impacts on upstream sectors that supply low-carbon equipment and infrastructures for energy supply and demand (power generation, transportation, industry, buildings). The non-relocatable construction sector records a significant additional activity during the transition (+5–7% annual production compared to the NDC scenario) and creates the bulk of jobs - 5 to 10 times more than net energy jobs. The manufacturing industry also benefits from the transition but to a lesser extent than the construction sector due to international competition. It should be noted that we haven't state particular market conditions or industrial strategies for these sectors in Argentina. We assume that the domestic market shares for the supply of key low-carbon equipment (solar panels, wind turbines, CCS technology, EVs, etc.) follow the average of the manufacturing industry in Argentina. Alternative assumptions (e.g. higher import market shares for equipment) would have key implications in domestic manufacturing activities, and thus in the economic outcomes of the energy transition.

Eventually, we find a risk of competitiveness losses for energy-intensive and trade-exposed industries due to higher energy and production costs that could hamper 3–5% annual production in these sectors compared to the reference scenario. However, we assume unilateral climate action, and only industries in Argentina support the costs increase. The study thus features a worst-case scenario and alternative assumptions about global climate action would partly offset these negative competitiveness effects. We can identify several limitations of our study. First of all, we do not capture real-world transition costs in labor and capital markets. In the modeling, structural changes in energy industries are supposed to happen with a perfect adaptation of the labor force without any friction related to skill shifts and industrial restructuring. We also assume no friction to shift investment from one sector to another, and optimal general financing conditions with no crowding-out of low-carbon investments on other investments in the economy. More pessimistic assumptions on less flexible labor markets and less favorable financing conditions with some crowding-out (Antosiewicz et al., 2020) could lead to a less optimistic economic outlook. Second, we set aside several dynamic aspects of the economic implications. The temporality of the investments and the phasing-out process may both hide disparate implications over time and have effects on the results at the time horizon of the study. Such aspects could also be explored in further works.



(a) Mean annual difference of sectoral output (%)



(b) Employment (kFTE)

Fig. 8. Mean annual sectoral impacts in DD scenarios compared to NDC.

6. Conclusion and policy implications

In this paper, we develop an original two-stage method based on linking an energy model to a macroeconomic model to evaluate the multi-level (sectoral and macroeconomic) impacts of DD roadmaps for the energy system at the country-scale. Based on the study case of Argentina, we can draw more general conclusions. First, deep decarbonization is feasible but requires genuine energy transitions with significant structural transformations of energy supply and demand systems, including upscaled energy efficiency, fast electrification of uses, and full decarbonization of power generation. Second, DD strategies may have limited macroeconomic implications in aggregate terms (total GDP, welfare, employment, debt, etc.) and consequently may neither be considered as a significant impediment nor a booster to future economic growth. However, such strategies imply significant structural effects on specific industries and the economy. Beyond investment redirections across sectors, the low-carbon transition requires a higher net investment effort in the economy (around + 1% of GDP) and reflects a more capital-intensive growth path. It also involves a deep restructuring of the energy sector, with the fast decline of fossil fuel industries and the fast development of clean power generation, and thus leads to important jobs and economic value displacements at the scale of the energy sector. However, the bulk of net job creations may come from upstream sectors that supply the low carbon equipment and infrastructure, in particular from the construction sector but also from the manufacturing industry according to the domestic industrial strategy. Eventually, depending on both the international context and the domestic policies, competitiveness losses in energy-intensive and trade-exposed sectors (agroindustry, heavy industry, transportation) could happen. These key results have important policy implications. Deep decarbonization should not be perceived as a major obstacle to dynamic development for growing economies based on fossil fuels like Argentina. However, the unavoidable structural transformations already mentioned need consistent planning, strong management, and accompanying policies. The transformations in energy and upstream sectors (construction, manufacturing) require specific policies that anticipate underlying social implications. Such policies need to organize the job transition by training workers toward new skills and by managing regional disparities to secure enough skilled labor fore at pace and scale. Socio-economic compensation for non-transferable workers must also be planned. To mobilize and redirect the amounts of investments needed, complex policy packages with a range of financial intermediaries have to be discussed with stakeholders. The investment effort also must come with industrial strategies to deploy national economic activity in key sectors, to benefit from the significant need for low-carbon equipment and infrastructure. These accompanying policies are as important as usual energy and climate policies but are generally overlooked. Overall, successful DD strategies require clear joint enabling conditions, actions, and policies to compensate the losers, allow job and social transitions, tackle specific induced economic risks, and tap industrial opportunities for upstream sectors to maximize the socio-economic benefits of the energy transition.

CRediT authorship contribution statement

Gaëlle Le Treut: Conceptualization, Data curation, Methodology, Writing – original draft, Software. **Julien Lefèvre:** Conceptualization, Methodology, Writing – original draft, Software. **Francisco Lallana:** Conceptualization, Data curation, Methodology, Writing – review & editing, Software. **Gonzalo Bravo:** Conceptualization, Data curation, Writing – review & editing.

Declaration of competing interest

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

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Appendix A Investments and costs for the transition

The integrated approach not only relies on consistent energy balances but also describes the main increasing costs and investments to shift from the NDC scenarios to the deep decarbonization scenarios. The resulting costs are then implemented into the IMACLIM Argentina model.

The two DD strategies evaluated differ in two key sectors for which we aim to assess the incremental costs. In that sense, the economic quantification carried out includes a cost assessment of the diversification of electricity generation towards a low-carbon generation system and additionally, the massive electrification of residential energy uses (including the almost global electrification of private transport). We conduct the assessment of the cost structures based on bottom-up accounting of the energy system shifts embodied in the storylines of the scenarios. On the one hand, the electricity sector is commonly characterized by accounting for existing capital costs (and its depreciation), expansion investment, O&M costs, and fuel costs. On the other hand, the costs faced by the households (that will endogenously impact the intermediate consumption through the IOT in the IMACLIM-ARG model) arise from a bottom-up accounting of the energy transformation required (in terms of technologies replacements and energy efficiency gains) to depict the evolution of the decarbonization scenarios. The following sections explain the resulting cost estimations.

A.1 Power generation costs

Capital cost

The capital costs of the electrical infrastructure of the three scenarios are estimated based on three components. First, we assign a unit cost of capital and a remaining useful life (to calculate an amortization or annual capital quota) to the existing electrical infrastructures (according to their typology) at the base year of our modeling exercise (see Table 3). Second, we estimate the unit cost of capital of the entering electrical infrastructures (see Table 4) which differ between scenarios. Finally, an additional term is included to reflect the incidence of the costs of transportation and distribution of electricity, which at the base year represents approximately 50% of the final value of electricity, which is embedded in the cost of the capital. We maintain this share constant until 2050.

Table 3
Capital cost of the existing power plants and transport and distribution infrastructure at BY

2015 MUS$	2015	2025	2030	2035	2040	2045	2050
Diesel Engine	260	130	65	0	0	0	0
GT	187	144	72	0	0	0	0
NG/Fuel ST	1121	1121	0	0	0	0	0
Coal ST	91	45	23	0	0	0	0
NG CCGT	213	164	82	0	0	0	0
NG/Fuel CCGT	904	696	348	0	0	0	0
NGCC wCCS	0	0	0	0	0	0	0
Nuclear	172	114	86	57	29	0	0
PV Solar	2	1	0	0	0	0	0
Onshore Wind	57	28	14	0	0	0	0
Comahue region Hydro	704	563	493	422	352	282	211
Rest Hydro	450	360	315	270	225	180	135
Bio	0	0	0	0	0	0	0
Total	4161	3367	1497	749	605	461	346

Table 4
Annual capital cost of the new power plants and transmission

2015 MUS$	NDC						DD1						DD2					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Diesel Engine	226	226	226	226	226	0	226	226	226	226	226	0	226	226	226	226	226	0
GT	365	403	570	662	774	520	365	365	421	430	444	107	365	365	365	365	375	46
NG/Fuel ST	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal ST	56	56	56	56	56	56	56	56	56	56	56	56	56	56	56	56	56	56
NG CCGT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NG/Fuel CCGT	588	834	1819	2434	3172	3445	588	588	588	588	588	0	588	588	588	588	588	0
NGCC wCCS	0	0	0	0	0	0	0	0	3189	3709	4454	5901	0	0	0	0	0	0
Nuclear	434	1080	1080	1080	1080	1080	434	1080	1080	1080	1080	1080	1573	4382	6910	6910	7472	9719
PV Solar	795	1068	1130	1162	887	432	605	1040	1737	2350	2841	2996	605	1040	1737	2350	2841	2996
Onshore Wind	1942	3004	3403	3592	3006	2072	2143	3394	4728	5862	6383	6355	2143	3394	4728	5862	6383	6355
Comahue region Hydro	374	546	546	546	546	546	374	546	546	546	546	546	644	1222	1222	1222	1222	1546
Rest Hydro	268	334	540	655	792	929	268	334	670	1109	1109	1109	268	334	670	1109	1109	1597
Bio	60	60	60	60	60	0	60	60	60	60	60	0	60	60	60	60	60	0
Total	5108	7612	9430	10 474	10 599	9082	5120	7690	13 301	16 017	17 788	18 151	6529	11 667	16 562	18 749	20 332	22 317

Table 5 compares the total electricity capital costs of the DD scenarios to the NDC as it finally stands in IMACLIM-ARG model.

Table 5
Differences between DD scenarios and the NDC scenario of the electricity capital cost

Electricity capital cost/NDC (%)	2025	2030	2035	2040	2045	2050
DD1	0%	1%	38%	50%	65%	96%
DD2	17%	45%	70%	75%	88%	140%

Investment

To evaluate the investment expenses for the newly installed electrical infrastructure, we first gather information from different sources on the unitary investment values of the plants (see Table 6). In particular, we rely on both local (CAMMSA[7]) and international references (International Energy Agency et al., 2015; IRENA, 2015, 2018).

Table 6
Overnight investment cost by type of plant and scenario year

Invesment cost [USD/kW]	Lifetime	2015	2025	2030	2035	2040	2045	2050

(*continued on next page*)

[7] Compañía Administradora del Mercado Mayorista Eléctrico Sociedad Anónima: administrator of the interconnected wholesale electricity system of Argentina.

Table 6 (*continued*)

Invesment cost [USD/kW]	Lifetime	2015	2025	2030	2035	2040	2045	2050
Diesel Engine	30	2000	2000	2000	2000	2000	2000	2000
GT	30	875	875	875	875	875	875	875
Biomass ST	30	2700	2700	2700	2700	2700	2700	2700
NG CCGT New	30	1450	1450	1450	1450	1450	1450	1450
NGCC wCCS	30	3500	3300	3200	3100	3000	2900	2800
Nuclear	60	5600	5600	5600	5600	5600	5600	5600
PV Solar	25	1950	1446	1333	1219	1105	991	878
PV Solar wBatery	20	3500	2307	1700	1475	1250	1250	1250
Onshore Wind	25	2750	2375	2200	1898	1595	1595	1595
Comahue region Hydro	80	2700	2700	2700	2700	2700	2700	2700
Rest Hydro	80	3050	3050	3050	3050	3050	3050	3050

Second, we establish an outlay profile for each power technology during the construction of the plant according to typical construction duration and standard S-type shape for the expenditures (see Table 7).

Table 7
Years for construction and associated outlay of the total investment

Power generation	Construction	Annual payment quotas (% of the total invesment)							
Technology	in years	1	2	3	4	5	6	7	8
Diesel Engine	1	100%	–	–	–	–	–	–	–
GT	2	30%	70%	–	–	–	–	–	–
Biomass ST	3	25%	50%	25%	–	–	–	–	–
NG CCGT New	3	25%	50%	25%	–	–	–	–	–
NGCC wCCS	3	25%	50%	25%	–	–	–	–	–
Nuclear	7	2%	3%	15%	40%	25%	10%	5%	–
PV Solar	1	100%	–	–	–	–	–	–	–
PV Solar wBatery	1	100%	–	–	–	–	–	–	–
Onshore Wind	1	100%	–	–	–	–	–	–	–
Comahue region Hydro	8	1%	2%	8%	22%	40%	20%	5%	2%
Rest Hydro	8	1%	2%	8%	22%	40%	20%	5%	2%

The total capacities (see Table 2 in the text) are incorporated over time to meet the electrical requirements. The typology of the incorporations corresponds to the energy narrative and relies on policy guidelines pursued, consistent with envisioned scenarios. By crossing the unitary investment cost with the incorporation profile and the schedule of expenditures, we assess the total investment of the electricity sector (see Fig. 4) by time steps. Our innovation stands in the investment matrix that we have implemented into the IMACLIM-ARG model. Based on different references (IRENA, 2018; National Energy Technology Laboratory, 2010; National Renewable Energy Laboratory, 2012), we have assumed a breakdown of consumption goods required by type of generation technology (see Table 8). As each scenario differs in the investment profile (types of technologies) so the demand for upstream activities, which is thus captured by the investment matrix.

Table 8
Breakdown of activities required by investments for power generation

Breakdown of investment in IMACLIM sectors	**Rest of manufacturing industries**	**Construction**	**Composite**
Diesel Engine	0%	0%	100%
GT	63%	13%	24%
Biomass ST	47%	39%	14%
NG CCGT New	50%	21%	29%
NGCC wCCS	50%	21%	29%
Nuclear	20%	55%	25%
PV Solar	80%	10%	10%
PV Solar wBatery	80%	10%	10%
Onshore Wind	68%	17%	15%
Comahue region Hydro	32%	50%	18%
Rest Hydro	32%	50%	18%

Labor cost

The unitary fixed O&M costs by type of technology are constant over time (see Table 9). By crossing them with the expansion of the capacities, we assess the fixed costs of O&M of the power generation plants over time. The resulting evolution rates of costs are then applied to the quantity of labor from IMACLIM (in FTE) at the base year to assess the quantity of labor required under each low-carbon strategy. These quantities are exogenously implemented into the IMACLIM-ARG model.

Table 9
Unitary fixed O&M costs per kW installed

Labor cost by plant	2015US$/kW
Diesel Engine	40
GT	12
GT New	12
NG/Fuel ST	70
Coal ST	70
Biomass ST	70
NG CCGT	25
NG/Fuel CCGT	28
NG CCGT New	25
NGCC wCCS	30
Nuclear	100
SolarFV	50
Comahue region Hydro	20
Rest Hydro	30

For each technology, we assume that the share of non-labor related costs in the fixed O&M costs is marginal (U.S. Energy Information Administration (EIA), 2020). Table 10 compares the labor required in the electricity sector for the DD scenarios compared to the NDC as it finally stands.

Table 10
Differences between DD scenarios and the NDC scenario of labor in the electricity sector

Electricity labour/NDC (%)	2025	2030	2035	2040	2045	2050
DD1	−1%	−1%	8%	19%	37%	55%
DD2	15%	40%	55%	57%	64%	81%

A.2 Equipment's cost for households

Deep Decarbonization scenarios imply significant structural modifications of energy consumption devices and infrastructures with an increase in household expenditures for efficient appliances. We have assessed such over costs compared to the NDC scenario by focusing on three main levers of energy efficiency gains: efficiency in home constructions and renovations to reduce heating and cooling requirements, the transformation (or replacement) of the residential heating systems (substitution from natural gas to electricity) and, massive adoption of the electric private car (mainly in the early years of the projection). The bottom-upmethodology followed estimates the incremental replacement costs, postulating a useful life for the replacement devices, and calculating an annuity payment of the incremental cost (compared to the NDC scenario) compared to a "standard" device as if the acquisitions were financed at the system discount rate. Regarding technological convergence, it is postulated that the incremental cost present in the base year will become zero towards the final year of the modeled horizon, assuming a linear evolution.

Table 11 shows the annual incremental cost and its evolution over time that a home faces to become a "compatible" home with the proposed DD energy efficiency and fuel switching.

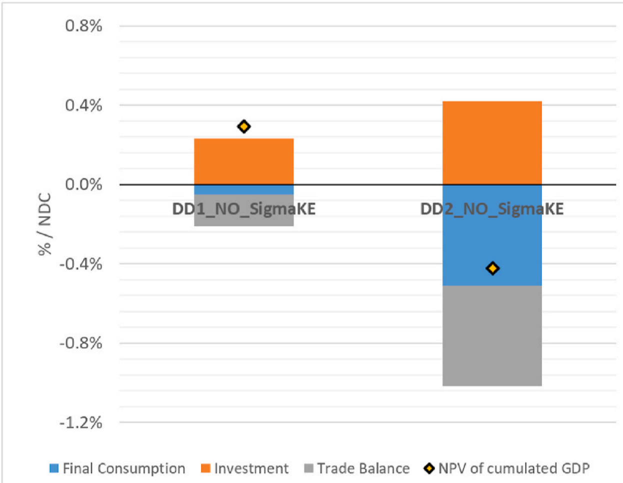
Table 11
Incremental unit cost per household to reach DD energy requirement standard

Equipments for house energy efficiency in US$	2025	2030	2040	2050
Electric vehicle	2018.0	1614.0	807.0	–
Heating + Hot water: heat pump	425.0	340.0	170.0	–
House insolation	1109.0	1009.0	807.0	605.0
Electric cooking	80.0	64.0	32.0	–
A+++ air condition	21.0	17.0	8.0	–
A+++ refrigerators	82.0	65.0	33.0	–
Incremental average conversion costs (%NDC costs)	99%	83%	33%	16%

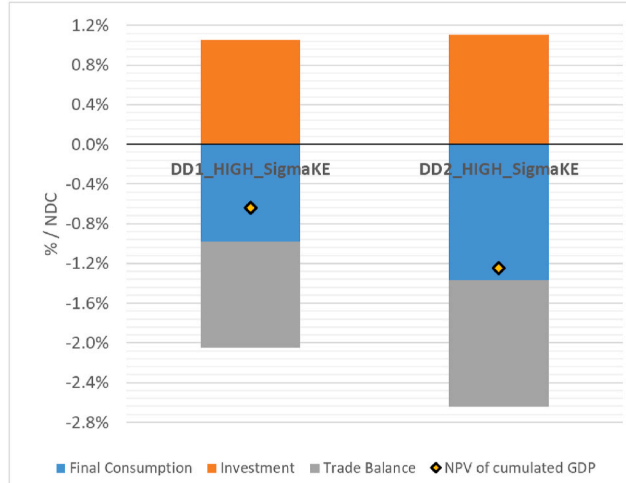
Finally, the total incremental cost is the incremental cost per household times the number of homes that are being efficiently transformed for each time step of the resolution. Both DD scenarios have the same narrative for efficiency and thus, the incremental costs are the same. The incremental cost gives an additional expense compared to the NDC scenario for the 'Rest of manufacturing industries' that households cannot spend elsewhere and which is exogenously informed into the IMACLIM-ARG model.

Appendix B Sensitivity analysis

In the IMACLIM-ARG model, we adapt the trade-off production function to capture the capital cost increases induced by energy efficiency gains in the non-energy sectors, which are significant in the DD. Energy efficiency gains in the non-energy sectors are compensated by an extra-cost on capital through an energy-capital elasticity. We assume that the capital intensity follows the evolution of the average energy intensity of each sector with an elasticity of −0.15 for the central simulations. We run a sensitivity analysis to get a range of macroeconomic results around this uncertain parameter. We first cut the adjustment by setting a nil value. Second, we double the value of the elasticity: each energy efficiency gain cost twice as much in capital compared to our central case. Fig. 9 shows the macroeconomic results. We see that the results are robust to this parameter. By not informing any increase of capital, there is a small gain of GDP in the DD1 scenarios (Fig. 9a). Otherwise, the total GDP cost remains limited. By doubling the value of the elasticity, the capital intensity increases which as a knock-on effect on investments for both DD scenarios. However, it is offset by higher prices that induce competitiveness losses.



(a) No substitution between capital and energy



(b) Multiplication by 2 of the elasticity of substitution

Fig. 9. Sensitivity analysis for substitution between capital and energy in non-energy sectors - NPV of cumulated GDP losses (2015–2050) in DD scenarios compared to NDC discounted at a 5% discount rate and mean annual incremental difference of GDP components as shares of GDP compared to NDC.

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