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ABSTRACT

To align near term action with a deep decarbonization objective by 2050, a long term low-greenhouse gas emissions development strategy is needed and involves drastic changes to the energy system and the AFOLU sectors. To help move forward the policy debate in this direction, this paper explores deep decarbonization pathways for the country until 2050 which break with existing more conservative national scenarios. It uses a combined qualitative-quantitative deep decarbonization pathway method based on the complementarity between exploratory storylines and the quantification of pathways based on linked energy-economy models. The built pathways show how deep decarbonization could be reached in Argentina along with other economic development goals and through contrasted possible routes all involving significant changes to the energy and AFOLU sectors. Remarkably, afforestation stands out as a key sectorial measure for reaching DDP. We contrast two alternative DDP Scenarios with a BAU one with specific focus on CO2 emissions, with emphasis on energy sector demand and supply alternatives. Many of the energy initiatives proposed for the BAU scenario were maintained but increased in ambition and many others were incorporated only in these deep decarbonization scenarios. While the HardPath proposes and requires natural gas use - with CO2 capture and storage - the Enlighten scenario proposes replacing it by hydro-nuclear energy. Finally, in none of the DDP scenarios is the export of natural gas proposed as an explicit energy policy objective, since little space is considered in external markets for fossil fuels, within the framework of a global action aimed at decarbonization.

1. Introduction

The Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) aims at holding the increase in the global average temperature well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C. In all scenarios from the last report of the Intergovernmental Panel on Climate Change (IPCC), both 2 °C and 1.5 °C targets will require reaching net zero emissions of CO_2eq around mid-century [1].

Although the absolute level of greenhouse gas emissions in Argentina does not rank it among the top-emitting countries, its level of per capita emissions (8.35 CO_2eq/per capita by 2016, following 3rd BUR Argentina Government (2019)) places it in a medium to high rank at the global scale. Similarly, emissions per unit of Gross Domestic Product (GDP) are close to the world mean with respectively 0.24 and 0.32 kg CO_2eq/$ PPP GDP for the year 2014 [2].

Energy combustion is the largest sector of greenhouse gas (GHG) emissions and counted for 53% of the net (GHG) emissions in 2016. Indeed, Argentina is an intensive fossil fuel-orientated, gas-based economy. In 2010, the discovery in the south of the country of recoverable hydrocarbons (oil and natural gas) in the *Vaca Muerta* formation has boosted the country's fossil fuel independence while providing great potential for additional incomes. It explains why fossil resources contribute significantly to both primary energy supply (88% of the total in 2015) and final consumption (77% of the total in 2015) according to the national energy balance from the Energy Secretariat. Even if there are some hydroelectric power plants, most electricity is produced through gas and oil thermal power plants, while the final energy demand of the residential sector is mainly met by natural gas (NG) supply. The Agriculture, Forestry and Other Land Use (AFOLU) sector is the second source of Argentinian emissions and represents 37% of total GHG emissions in 2016, unlike the energy sector, agriculture production goes

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to a large extent to external markets. The remaining emissions (10%) are equally due to industrial processes and waste.

In its Nationally Determined Contributions (NDC) under the Paris Agreement, Argentina has unconditionally committed not to exceed 483 $MtCO_2eq$ of net emissions in 2030. It represents a net reduction of 18% in comparison with a business-as-usual scenario for the same year of 2030 (a reduction of 109$MtCO_2eq$) but an increase of 33% compared to the 2016 level. The government has planned a heterogeneous reduction effort among activities. Furthermore, NDC proposals have to be distinguished from sectorial plans within a comprehensive National Mitigation Strategy and the imminent Long-Term Strategy.

The objective is supposed to be reached through the implementation of a series of measures focusing first on the energy and forestry sectors, and, on a secondary basis, on agriculture, transport, industry, and waste sectors. Decarbonizing power supply and the electrification of uses are thus key players for a low carbon transition which have already been pointed out. According to the Ministry of Environment and Sustainable Development, about 70% of the 109 $MtCO_2eq$ unconditional reduction effort in the NDC scenario has to be subtracted from the energy production sector and final energy demand (buildings). Despite its weight on emissions, the agriculture sector has received much less attention for developing mitigation measures possibly due to its atomization, difficulties of implementation, and scarcity of validated actions. Together with the food industry, it represented only 8% of the GDP in 2015, but 37% (authors' calculations[1]) and 61% [3] of the exports for respectively the years 2015 and 2018. Export of grains (oilseeds and cereals) counts for 36% of the domestic production without adding further value, while 18% of total beef production goes to external markets [7]. Exports, mainly from natural resources in both energy and agriculture sectors, played an important role in the country's growth and helped it to recover from the 2001 crisis. A brief mention of conditional measures is found in the National Action Plan for the Agro Sector and Climate Change, recently launched by the Environmental Secretariat (2019). Reforestation stands out as the key lever in terms of carbon absorption and mitigation.

However, these NDCs imply increasing absolute emissions in Argentina until 2030 – if compared with 2016 emissions. Therefore, they are not aligned with the Paris Agreement goals which require deeper decarbonization in a long-term scenario and the absolute decrease of emissions towards at least their current level by 2050 [8]. That means much more challenging targets for the country by 2030, and, a significant shift in both energy and economic systems. In that sense, recently in February 2020, Argentina's Environment and Sustainable Development Ministry stated that reducing carbon emissions (decarbonizing energy supply) and stopping deforestation are two key action areas of his mandate. It has further stated that it will present at COP26 a long-term plan to achieve carbon neutrality in 2050, but so far, nothing has been said about a possible revision of the presented NDC's [9].

Aside from the two pillars already mentioned (energy and agriculture), transport is also a major player in reducing emissions from energy combustion to reach deep decarbonization in the long run. It accounted for 14% of the emissions from fossil fuel combustion in 2016 [7,10] and it is expected to double by 2030 compared to 2015 level in a business-as-usual scenario [11]. A few actions aimed mainly at improving efficiency in road transport of loads, prioritizing railroads and public transport, among other unconditional measures are proposed, but they will not revert the increasing trends [11].

A key long-term challenge for Argentina is to achieve the Sustainable Development Goals (SDGs) of the United Nations while deeply mitigating its GHG emissions. Since the economic crisis in 2001, the country has experienced strong GDP and GDP per capita growth with an average of respectively +3.3% and +2.2% per year for the 2001–2015 period. It has recovered slowly from a high unemployment rate during the economic crisis, which reached 20% in 2002 [12], but figures from recent years have shown that unemployment is increasing once again.

However, there is no other strategy beyond the commitments to 2030 in Argentina. To align more ambitious near-term action with a deep decarbonization objective by 2050, a long-term low-greenhouse gas emissions development strategy is needed. The goal of this paper is to help the policy debate to move forward by exploring two deep decarbonization pathways (DDP) for the country until 2050, which break with less ambitious objectives for Argentina, including the one set by its NDCs. Such 'backcasting' pathways allow identifying the sequence of the technical and socio-economic transformations required to reach a deep decarbonization long-term objective as well as the underlying drivers, enabling conditions, and required policy measures in the context of inertia, lock-ins, and innovation. To build such pathways, we use a combined qualitative-quantitative Deep Decarbonization Pathways (DDP) method [13] based on the complementarity between exploratory storylines and the quantification of pathways through a set of numerical models. The specific tools employed are the LEAP-Arg [14] energy model, IMACLIM-ARG computable general equilibrium (CGE) model, and FABLE (Food, Agriculture, Biodiversity, Land-use, and Energy) model. By combining such tools, it makes it possible to quantify the energy, land use, and socio-economic dimensions of the pathways. We explore two contrasted deep decarbonization scenarios for Argentina up to 2050. Both pathways involve significant changes to the energy sector and the whole economic system and are built under constraints to meet other economic development goals. The baseline scenario is built to be consistent with the NDCs objective and thus does not reach net-zero emissions in 2050.

The reader should keep in mind that this piece of writing is framed into a broad research and modeling capacity-building project, DDP-LAC.[2] More published documents are available for complementing and providing additional information [15,16].

The paper is organized into five sections as follows. Section 2 describes the DDP method and the modeling tools used to quantify our scenarios for Argentina. Section 3 describes the storylines of the NDC baseline scenario extended to 2050, and the two Deep Decarbonization (DD) scenarios. Section 4 presents and discusses the quantitative pathways. Section 5 presents the conclusions and recommendations.

2. Methods

A "storyline and quantification" approach is followed [13,17]. First, desirable futures for Argentina are designed, by proposing key drivers and policies. Thus, backcasting scenarios are built as qualitative or semi-quantitative storylines to explore under which circumstances Argentina can upscale and substantially improve its current climate pledges to align with the Paris Agreement, assuming a 2tCO_2 per capita emission target for 2050 and a trajectory towards zero in2070.[3] Second, the drivers of the storylines are 'loaded' into modeling tools to allow for detailed quantification of the proposed storylines to build full quantified pathways. This section describes the modeling framework used for quantifying the storylines described in Section 3.

2.1. LEAP model

LEAP is a modeling tool for analyzing strategic integrated energy-environment scenarios for policy [14]. The LEAP modeling software's strength is based on the comparison of a set of different narratives of

[1] The calculation is based on the following sources: Dirección Nacional de Cuentas Nacionales - INDEC [3]; Mastronardi [4]; Coremberg [5]; INDEC [6]; Argentina energy balance, SE, (2018).

[2] IDDRI Initiative. Deep Decarbonization Pathways. https://www.iddri.org/en/initiative/deep-decarbonization-pathways.

[3] The per capita emission target for 2050 used within the project is assumed as consistent with Paris agreement.

possible futures. It can be used as an integrated resource planning system for the energy sector by modeling both the demand (with subsector disaggregation) and the supply side (including power generation and capacity expansion). The model can be applied at different scales, from regional to global. In the case of our analysis, it is used at the country scale, which involves adjustments of the main data tree structure. In LEAP-Arg model, energy consumption and production systems are modeled by including the feedbacks between energy supply and demand actions, and their effects on total GHG emissions are tracked. First, LEAP-Arg is calibrated based on official historical data for the country, both in the energy and environmental dimensions. Expected evolutions of a set of key variables are informed as well. Second, since national energy balances do not offer enough detail on energy end-uses, energy sector consumption has been disaggregated based on the author's prior experience [18]. A detailed framework is actually needed for the main energy services (residential, transport, agriculture, industry, and commercial, sectors), to better model and inform targeted mitigation measures (e.g. energy efficiency labeling on fridges and air conditioning devices) and thus to give in the end robust insights at the level of the end-user.

As a key example, the transport sector, central to a low-carbon transition, has been disaggregated both by modes and means to allow identification of the impacts of eco-driving measures, electric and hybrid car introduction, and substitution of freight truck transport for rail transport. The model has been calibrated to 2015.

2.2. IMACLIM-ARG model

The IMACLIM-ARG model is a hybrid Computable General Equilibrium (CGE) model [19,20]. Articulating LEAP and IMACLIM allows bridging the gap between bottom-up and top-down approaches to assess low-carbon pathways for Argentina. IMACLIM-ARG departs from a more standard neoclassical CGE approach in several features. First, like standard CGE models, it is based on the representation of Walrasian markets of goods and services with a global income balance. However, it has a dual quantity-economy accounting framework: economic flows and physical flows are balanced and linked by a consistent price system. The description of the consumers' and producers' trade-offs, and the underlying technical systems, are thus specifically designed to facilitate articulation with LEAP, and as a consequence, our method lends better technical realism to the simulations [21]. Second, IMACLIM-ARG outputs are not necessarily located on an equilibrated growth pathway. It computes possible underemployment of production factors (labor) and imperfect markets (goods and factors). To do so, the model relies on a specific representation of capital, and, on other structural assumptions. At last, we develop an *investment matrix* that allows sectoral specification for investment demand generated by the power system developments. IMACLIM-ARG is calibrated to 2012 on an original dataset constructed by the authors and representing fifteen sectors.

An iterative coupling between LEAP and IMACLIM can be achieved at each step of simulation (see Fig. 1). Concretely, key variables, such as energy content of the economy, investments, and costs of the power sectors resulting from LEAP-Argentina are used to inform IMACLIM-ARG to get a consistent picture of the economy-wide implications. Then IMACLIM informs LEAP on GDP growth and sectoral production growth.

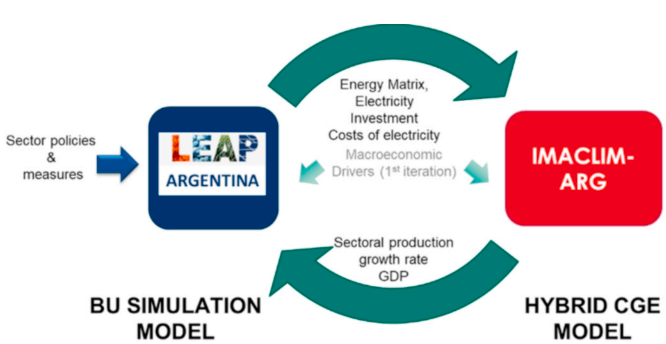


Fig. 1. LEAP-IMACLIM coupling framework.

2.3. FABLE model

To assess the impacts of deep changes in food and land use in Argentina, we benefit from the FABLE consortium's work [22]. We rely on the FABLE tool[4] for Argentina to get alternative projections on the distribution of land among the following uses: agriculture, pasture, forest, urban areas, and other uses. These projections are used as guidelines for building scenarios on land use that are needed to estimate AFOLU emissions. Using compatible socio-economic drivers for LEAP and FABLE models helps to provide consistency to the results.

The main drivers of FABLE land use allocations are GDP, population growth, diet structure, imports and exports of food products, crop and livestock productivity, livestock density, potential land available for agricultural expansion, and afforestation target. Different scenarios can be simulated setting up the values of these main drivers from a predefined range of options.

The model is calibrated for the period 2000–2015 using historical data.

3. Storylines toward deep decarbonization pathways for Argentina

Decarbonization pathways and the underlying energy scenarios are built upon socio-economic scenarios. We propose two socio-economic scenarios that are stylized stories of how the future might look like. Instead of describing a most probable or a desired future, we explore contrasted development paths to identify a different set of economic policies which could lead to each one. A single demographic scenario for the two socio-economic scenarios is considered. We detail in the following the two socio-economic storylines whose macroeconomic drivers are summarized in Table 1.

In the socio-economic **Tendency scenario**, the following three economic tensions and challenges are not solved:

- The false dichotomy between agricultural primary production and manufacturing industry as leading sector for economic growth
- The age-old dilemma between trade openness and protectionism
- The need for employment generation corresponding with the needed technological change, meaning modernization and actualization of productive technologies, while providing employment opportunities.

The productive structure does not change significantly and unemployment and equality, although slight improvements, do not change as fast as it would be desirable.

In addition, the Argentina economy does not achieve a high level of modernization, which limits its role within the global context. The country rather relies on the same type of products for trading with other regions, which reduces its future GDP and its real fiscal resources for covering social needs with public policies.

Activities show also low productivity, freezing Argentina in its

[4] Fable tool is an Excel based accounting tool. It focuses on agriculture and livestock as the main drivers of land-use change and includes land demand for the production of diverse crops and livestock products. These, in turn, are mainly driven by population grow scenarios, dietary requirements and exports targets, among other variables. This model relies on INTA and FAOSTAT databases for input data. Source: IIASA/SDSN, Documentation FABLE Calculator, September 2019.

Table 1
Main socio-economic indicators by Scenario, expressed in annual growth rates, percentage of unemployment and US$ 2014 for GDP p/c.

		Socio-Economic Scenario I "Tendency"		Socio-Economic Scenario II "Structural Change"	
	2015–2019	2019–2030	2030–2050	2019–2030	2030–2050
GDP	−0.51%	3.22%	2,70%	4.65%	4,53%
Population	1.03%	0.87%	0.58%	0.87%	0.58%
GDP p/c	−1.53%	2.34%	2.11%	3.76%	3.93%
GDP p/c (us$ 2014) last year of period	12,748	16,439	24,965	19,122	41,342
unemployment rate	8.3%	9.1%	7.4%	7.9%	5.1%

Note: calculations and modelization were done previous to COVID-19, thus reaching somehow former conservative levels of growth by 2030, became more ambitious.
Source: own estimations from INDEC official source.

position of low value-added commodity exporters (agro-commodity, minerals and unconventional natural gas) with evident difficulties for achieving the UN's Sustainable Development Goals.

The reduced job creation, due to scarce productive diversification, has a moderate effect on unemployment, poverty, and income distribution. The low growth rate of per capita consumption is explained by a lower dynamism of economic activity, instead of increasing domestic savings.

Therefore, many of the policies aligned with the decarbonization objectives are financed with external savings - foreign debt - imposing an additional factor of macroeconomic vulnerability arising from the weakened balance of payments sustainability. All in all, a lower economic growth rate trend will set a limit on real fiscal resources (revenues). Not only will decarbonization-oriented policies need to be financed by foreign debt, but also compensating social transfers. Sectoral GDP structure by 2050 remains very similar to the baseline year 2015, with a slightly higher weight of Agriculture and a diminished role for industries.

In the socio-economic **Structural Change scenario**, we propose a deep economic shift in the country. The three above-mentioned tensions are successfully addressed, and, at the time horizon, the trajectory not only exhibits a lower structural unemployment level and a more desirable income distribution, but also an enhanced and more modern productive structure.

This alternative scenario promotes a virtuous productive transformation where all sectors act as drivers for GDP growth that achieves significantly higher values than in the Tendency scenario.[5]

The narrative of the development strategy relies on the transformation of the productive apparatus towards a more "intensive" specialization pattern promoting highly-skilled formal work, domestic technological efforts, greater value-added and differentiated goods allowing broader social inclusion, employment creation, and sustainable economic development in the long term. Box 1 provides more details on action/policies/strategies that such a scenario may require.

Besides the difficulties discussed above, the country faces the challenge of decarbonizing its agriculture sector, whose demand becomes uncertain and is sensitive to domestic and global changes toward a low-emissions diet.

In the next section, three energy-policy pathways (NDC, Hard Path and Enlighten) are explored for reaching DD scenarios, that are either link to the Tendency socio-economic scenario or the Structural Change socio-economic scenario (see Table 2). To fully model Argentina CO_2 eq. GHG emissions, non-energy-related emissions sources are also included in the three pathways. From the emissions point of view, the NDC scenario represents the official unconditional NDCs compromises until 2030 extrapolated to 2050, while the two other energy scenarios do reach a DD objective.

3.1. Energy sector mitigation measures

Based on the above narratives, a set of mitigation options is considered to reduce the energy demand, decarbonize the energy supply, and thus trigger a shift in the GHG emissions trend. In this section, we set out the key levers used for the three different energy storylines that we explore by 2050.

We point out that for the short-term quantitative targets (2015–2030) mitigation options of each energy pathway have been mainly defined using government action plans [7,29,30], and as complementary material, we have also used previous simulation exercises [18,31,32]. However, since most of the national works do not present detailed mitigation options information for the long-term (2030–2050), we have thus relied on our expertise and have benefited from key international references for selecting and quantifying this time range. The DDP-LAC consortium also provided guidelines for constructing the long-term pathways.

3.1.1. NDC pathway

The NDC guidelines are the reference energy pathway of our study. It takes into account the energy policies implemented shortly before the year 2015 and committed in the Paris Agreement. The modeled measures consist of fifteen initiatives presented as part of the NDC, with varying degrees of commitment and penetration. In a nutshell, such a scenario implies realistic objectives without deep shifts:

1. Household sector: decrease of energy intensity in lighting, improvement of the thermal envelope (insulation), penetration of electric heat pumps for heating, replacement with efficient refrigerators, replacement with efficient air conditioning, and penetration of solar collectors for domestic hot water.
2. Transport sector: modal change in freight transport (increase in rail freight), technical training to reduce fuel consumption by driving behavior (EcoDriving), penetration of hybrid and electric light vehicles, incorporation of electric buses, increase in the share of biofuel.
3. Public sector: substitution in public lighting of old lamps for LEDs.
4. Electricity generation sector: compliance with the National target to reach 20% (2025) and 30% (2030) of renewables sources.[6]

3.1.2. Deep decarbonization pathways

We explore two deep decarbonization pathways at the horizon 2050: the Hard Path and the Enlighten (ENL) scenarios. For both pathways, the typology of energy measures used for the final demand sectors are equivalent, but different objectives have been set in terms of specific

[5] Some inputs for this narrative were taken from a Government-Society broad discussion forum, called Programa Argentina 2030 within the Chief of Cabinet of Ministers, Presidency of the Nation [23], and from other different publications: Albrieu, Ramiro, et al. [24] and Ajmechet, Sabrina et al. [25].

[6] National Law N° 27191/2015, Development Scheme for Electricity Production from renewable sources (including hydro plants smaller than 50 MW and other).

Box 1
Features of a possible Structural Change socio-economic Scenario for Argentina 2050

Driven by a strong change in the productive matrix as well as a significant improvement in the distribution of income (Gini coefficient of 0.29 at 2050, from 0.42 at 2018), per capita income grows strongly: 3.2% average 2017–2050, breaking with the historical trends. Towards the year 2050, there is a high energy consumption per capita, in terms of square meters of household per family, vehicles per 1000 inhabitants, and generalized access to durable goods.

Both primary and manufacturing sectors manage to upgrade up to the global value chains and require more labor, absorbing the labor force growth. In this sense, lower unemployment rates are achieved faster (7.3% by 2025, and 3.2% in 2050) compared to in the tendency socio-economic scenario (7.3% by 2050). Similar trajectories can be shown by poverty and income distribution metrics: 15% share of population below the poverty level by 2030 and 4.2% by 2050. An improved labor market is the main player for such goals.

The industry sector significantly grows – as shown in Figure A-in particular energy-intensive and food products, while cattle growing diminishes as well as light industry and other primary activities. Nevertheless, the added value in absolute terms (Table A) still grows significantly for all sub-sectors. The industrialization features of the Structural Change Scenario are reflected in the differential growth of the food industry and sectors linked with infrastructure: energy-intensive industries, electricity.

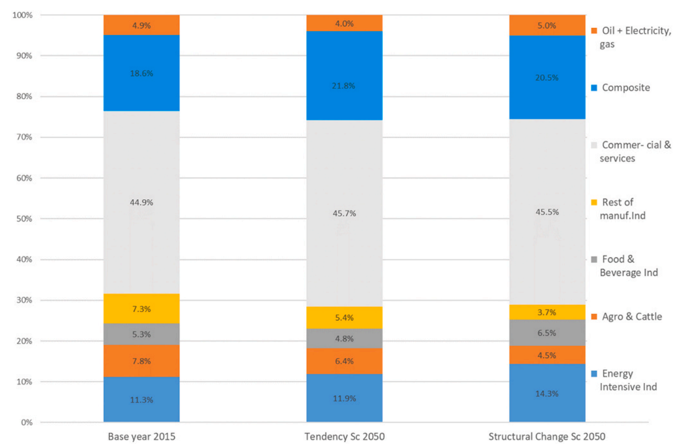


Figure A. GDP structure Base year (2015) and Scenarios (2050) in %

Table A
GDP structure in 2004 million pesos, base year (2015) and Scenarios (2050)

(in 2004 million pesos)	2015	Scen. Tendency 2050	Scen. Structural Change 2050	Sectoral grouping
Agriculture	37,380	76,091	88,995	Agro and Cattle
Cattle	9641	14,344	15,895	
Food & Beverage Industries	31,935	67,886	152,236	Food & Beverage Industries
Rest of manuf.Industries	43,790	76,348	85,822	Rest of manuf.Industries
Rest of heavy Industries	31,513	76,371	160,311	Energy Intensive Industries
Cement	2558	7076	19,731	
Iron and Steel	11,216	32,548	69,057	
Construction	22,554	52,359	86,321	
Commercial and services	244,814	582,685	971,971	Commercial and services
Transport	25,812	63,643	93,684	
Composite	112,409	308,362	480,971	Composite
Oil + Electricity, Gas	29,317	56,571	117,105	Oil + Electricity, Gas
Total Added Value	**602,940**	**1,414,283**	**2,342,098**	

To make the scenario of structural change viable, an integrated and accepted national development strategy is needed, covering issues such as agro-industrial production, integrated into nodes or clusters, bio-industry, sustainable industrialization of biomass, logistics, and investments in basic infrastructure, human resources training and related technological development. The central idea is to add capacities to available capabilities: improving access to technology, having the tools needed to make complex products, building strong institutions to plan ambitious projects with longer time horizons, developing connectivity at the country level so that inputs from different regions extend the range of opportunities (Huertas, G in Ref. [25].

Regarding labor issues, as of 2015, job generation is driven by self-employment and accompanied by a reduction in formal private employment, leading to a worsening of the living conditions of Argentina workers. The low labor participation and the gender gap (marginalization of the poorest women, with the low level of education and no or little labor training) provides immediate availability to raise the necessary workforce and accelerate growth per capita (Sartorio, L. in Ref. [25].

Interestingly, a labor market information system is proposed, aimed at identifying who is being hired, the required skills and knowledge, including competency certification [26,27]. This can be implemented jointly with a protective mechanism for unemployment in the informal sector and with a clear identification of committed fiscal resources with a reduction of labor taxes (Maurizio, Roxana p. 111 in Ref. [23].

From an operative point of view, the strategy for structural change must be coordinated by the State, based on some boost to national production, productive diversification, and greater added value [28]. and Bisang, R. p. 253 in Ref. [23].

Some institutional improvements are also proposed, including the development of an effective National Agency for Scientific and Technological

Promotion, an Industrial Development Bank, a ministerial role for science and technology, and a better underpinning of key existing institutions. In terms of possible financial resources, the establishment of a national stabilization fund, depending on world exported commodities prices to mitigate volatility and to finance infrastructure investments is suggested (Tenreyro, S. Pag 227 in Ref. [23].

Finally, from a global perspective, regional integration is identified as a priority for reaching the Structural Change scenario. The chances of improving international commerce and trade rely on building a regional homogeneous trading block; South America represents 400 million inhabitants with enormous diversity and richness in terms of natural resources and food supply.
Source: own estimations from official sources, INDEC, Dirección Nacional de Cuentas Nacionales.

targets and/or shares. As an example, while in the NDC pathway penetration of electric vehicles is assumed to be only 0.5% for the horizon year, it is assumed to reach respectively 85% and 100% in the Hard Path scenario and the Enlighten scenario. Some energy initiatives proposed in the NDC scenario are maintained but are deployed with higher ambition, and some new options are incorporated in the DDP. They incorporate a total of twenty-six specific emission reduction actions in the energy sector.

We summarize the measures on the energy demand side in Table 3.

Energy efficiency measures incorporated into DDPs refer to two main areas, changes in the way energy is consumed and the efficiency of transformation of net energy into useful energy. The first area has to do with cultural patterns of energy use and rational energy use, for example, avoiding opening windows when heating is too high instead of lowering the heating. The second area involves using better energy technology choices for satisfying the same energy requirement, for example, using heat pumps for heating instead of resistive heating appliances. There is a third area, that even when it cannot be considered to be directly related to efficiency measures can lead to carbon emissions reductions. This involves the substitution of fossil energy sources by energy sources with low or zero lifecycle carbon emissions.[7]

On the supply side:

- Both DDPs comfortably meet the legal goal of renewable electricity generation, reaching wind and solar generation values close to 50% by 2030.
- The development of hydroelectric power plants, using the vast unused potential that exists in Argentina, is promoted mostly in the Enlighten pathway. It is proposed to reach 60% of the existing technical and economic potential, reaching 24 GW of installed power.
- The significantly different narrative among the DDPs analyzed is associated with the use of existing natural gas reserves in the country. While the Hard Path pathway proposes and requires its use, the Enlighten pathway proposes the scarce use of natural gas being replaced by nuclear energy.
- To achieve the objectives of decarbonizing the energy system, the Hard Path DDP, which does make use of the abundant reserves of non-conventional natural gas, requires electricity generation with CO_2 capture and storage.
- In both DDPs, there is no energy policy to support natural gas exports, since little space is considered in external markets for fossil fuels, within the framework of a global climate mitigation action. However, all the pathways have some volumes of exported natural gas, but much lower than expected/desired ones in a baseline scenario.

3.2. Non-energy sector mitigation measures

Non-Energy sector measures are identified and the estimation of the associated GHG emission saving potential is based on the Third National Communication (3CN) [33], and on specific non-energy sector studies (National Agro and Climate Change Action Plan, Argentine SESD, [7]; Third Biennial Report, Argentine SESD [29],.[8] The storyline takes into account the following sectors: livestock, agriculture, industrial processes, waste, and the rest of land-uses. Emissions at the base year are calibrated on national information [33].

Table 2
Scenario panel for assessing impacts of contrasted pathways.

Socio-Economic storyline	Energy storyline
Tendency	NDC
Tendency	Hard Path
Structural Change	Enlighten

Emissions savings for each sector under a specific scenario are estimated using emissions indicators per unit driver multiplied by driver projections. The main drivers are cropland, livestock heads, agricultural and livestock productivity, and forest land. These estimations are exogenous assessments that are then included in our energy-related modeling results to quantify total national GHG emissions.

There is a lack of information on the non-energy sector drivers and their emissions at the national level for the long term. We assume the same drivers of the FABLE model for Argentina and reference studies.

Emissions for the NDC scenario are based on the 3NC [33] data until 2030 and follow the same trend for the period 2030–2050. Projection assumptions by sector for each scenario are presented below.

3.2.1. Livestock

We assume no emission savings in livestock for the NDC scenario. This is consistent with an indicator of emissions per head of bovine cattle close to 1.1 tons of CO_2eq/head per year for the entire projection period [35].

The total hectares devoted to pasture and agriculture, remain the same in all scenarios, without any displacement from forest/silviculture/silvopasture lands to the main agriculture and cattle growing activities. Although land-use projections are equal for all scenarios, the number of cattle heads in the NDC and the Hard Path scenarios follows the 3CN [33] while the projection for the Enlighten scenario considers the increase in livestock sector added value.[9]

In the Hard Path scenario, a reduction in emissions per head of livestock of 30% by 2050 is assumed compared to the NDC scenario. This reduction potential could be achieved through diet modification and other measures (tannins, lipids, pasture management, food

[7] Three ways of reducing carbon emissions are modeled, rationality in energy use affecting the energy intensity, conversion efficiency measures by substituting or improving the appliances and fuel switch due to substitution or conversion of devices.

[8] Without further mention, the assumptions of our storylines are drawn from these studies. Argentina's Government is making progress in the identification of mitigation measures and their avoided emissions within the SPIPA project and the elaboration of its Long-Term Strategies [34], once these actions are developed, the mitigation measures can be updated.

[9] In 2050 an increase of the sector added value of +49% is expected for the tendency socioeconomic scenario (which provides drivers for both NDC and Hard Path) and +65% for the structural change socioeconomic scenario (related with the Enlighten). These figures rely on both a relative increase in values (commodity sales prices) and quantities (cattle heads) with increased efficiency and intensification.

Table 3
Demand-side proposed measures by DD scenarios.

Energy consumers & measures:	Deep Decarbonization Pathway:	
	Hard Path 2050	Enlighten 2050
Households		
LEDs incorporation	100%	100% [a]
Thermal efficiency in buildings, useful energy savings for heating in 2050 [b]	28%	44%
Equipment Replacement: natural gas heating devices by electric heat pumps for space heating:	80% of households	86% of households
Equipment Replacement: natural gas hot water heating by electricity devices [c]	50% of households	60% of households
Equipment incorporation: solar water heaters	35% of households	40% of households
Refrigerators efficiency		50% less useful energy required (class A+)
Air conditioning, for space cooling		50% less useful energy required [d]
Equipment Replacement: natural gas devices by electric induction stoves technology	80% of households	95% of households
Transport Sector		
Rail Transport promotion (road trucks replacement) [e]	25% by rail	30% increase in rail alternatives
Eco-driving in freight and public transport	100% of drivers trained by 2050	
Deep electrification of private cars, reaching:	84%	100%
Urban buses switched to electricity	100%	100%
Urban Taxis:	50% electricity 50% compressed nat. gas	100% electric
Road freight transport: electricity, compressed and liquefied natural gas, respectively:	30%, 25%, and 5%	75%, 10%, and 15%
Biodiesel penetration in **transport** and **agriculture:**	B35	B40
Electrification and promotion of railway passenger transport [f], Passenger/km is multiplied by:	3	4

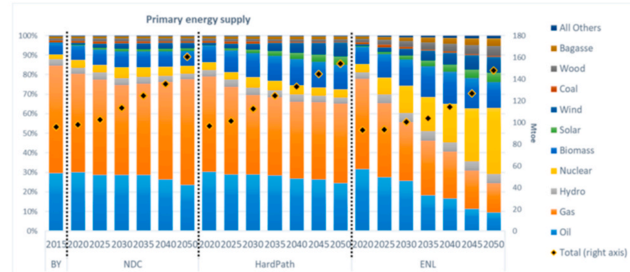
[a] Energy intensity per household, further reduction of 50% in useful requirements is proposed.
[b] Reductions in useful energy requirements per household due to isolation.
[c] A 10% decrease in projected useful energy intensity in 2050 as a result of water economizers is also assumed [1].
[d] Due to home isolation improvements, together with energy-saving promotion and a higher target temperature for the air conditioning of the rooms.
[e] Rail took 5% of freight transport in 2015, 25% is proposed by 2050. In 2015, 71% of train transport consumed diesel and the remaining 29% consumed electricity. Increases compared to NDC scenario.
[f] 3 and 4 times total Passenger/km of the NDC baseline scenario for 2050. 80% subtracted from bus transport and the rest from private cars.

processing), but there is still high uncertainty on the levels of enteric methane reduction and their permanence in time.

In the Enlighten scenario, we assume a 40% reduction in emissions per head of livestock compared to the NDC scenario at the time horizon. The measures are similar but slightly deeper, to those considered for the Hard Path Scenario (nitrates, tannins, lipids, pasture management, food processing).

3.2.2. *Agriculture*

The projection assumption of the cropland area is similar for all



Note: ENL: Enlighten Pathway

Fig. 2. Breakdown of primary energy supply by resources .

scenarios with an annual increase of 0.6% at the year 2030, ending to 0.35% at the time horizon, relying on hectares from former livestock activities[10]

In the Hard Path scenario, agriculture reduces its emissions by 20% emissions compared to the NDC scenario [36]. These savings are based on: crop rotation, the incorporation of crop residues into the soil, efficient nitrogen use (e.g. N release inhibitors, biological N fixers), and proportion changes between oilseeds and cereals production (from 70/30 to a 50/50 ratio).

In the Enlighten Scenario, emissions reduction reaches 30% compared to the NDC scenario. The measures are similar to the Hard Path scenario, but on top of these measures, fertilizer application technologies are implemented to minimize its use [37]. It is assumed that the latter measure provides an additional reduction of 10% compared to Hard Path Scenario.

3.2.3. *Industrial processes*

We adopt emissions savings estimations based on carbon capture technologies for certain industrial processes for both Hard Path and Enlighten scenarios [32].

3.2.4. *Waste*

We assume the conversion of 90% of methane emitted in the NDC scenario into CO_2 by flaring for both the Hard Path and Enlighten scenarios.

3.2.5. *Other land uses*

To lower land-use change emissions, we have considered afforestation as a net carbon sink. Following the 3CN guidelines [33], we assume the possibility to implant additional 2 million hectares of forest, at a rate of 61 kHa/year. This target has been included in the NDC scenario, and the hectares of the forest increase until 2050 at a similar rate to the period 2012–2030 totalizing 2 million added in 2050.

The DD scenarios aim at complying with a per capita emissions target close to 2 tCO_2eq per capita for the GHG emissions. To reach this target, we assume 5 million additional hectares available of the 20 MHa suitable for afforestation mentioned in 3CN. Emissions savings per hectare are the same as for the NDC scenario, close to an average of 28 kt CO_2 eq/ha.year [38].

We assume the availability of land for implementing these measures without displacing agriculture activities or pastures. However, we should note that this hypothesis is not based on a technical assessment and their feasibility evaluation are out of the scope of this paper. An in-depth study that includes an assessment of the suitability of soils and climate, water requirements, environmental impacts, competition with other land uses, and long-term capture rates per hectare and species

[10] We assume a yield increase per hectare equal to the agricultural added value ratio affected by the elasticity of 0.5 Thus, the yield increase in the Enlighten scenario is higher to the one in the NDC and Hard Path scenarios as it relies on a contrasted socio-economic storyline.

would be required.

4. Quantitative results

By using the modeling tools introduced in Section 2, we simulate the implications of the key drivers and climate policy packages of the storylines described in the previous section. We depict results on the GHG emission pathways and the underlying energy systems for Argentina. Eventually, we assess key changes in land uses and forestry.

The LEAP-IMACLIM coupled framework provides a high level of consistency between the energy projections and their macroeconomic context. It especially provides relevant insights on the multi-level economic implications of the deep decarbonization strategies that we explore further in a companion paper [20]. In this paper, we focus on the detailed results about energy and emission pathways.

4.1. Energy pathways

4.1.1. Primary energy supply

The final energy demand sector includes several mitigation actions, with different penetration rates for each scenario. To be consistent with the resulting demand, measures have also been considered for the primary energy supply and transformation (i.e. electricity and fossil fuel processing/refining).

Fig. 2 shows the structure of the primary energy supply by fuels. The first important finding is that the absolute level of primary energy supply is similar in all scenarios. In the first place, such a situation seems unexpected but it is the result of two tendencies that are counterbalanced. On the one hand, in the Enlighten scenario, there is a strong increase in consumption of useful energy per capita (driven by an increase in income per capita and a drastic decrease in poverty with the consequent increase in final demand), together with a much higher economic output. On the other hand, there is a strong increase in average efficiency in uses, due to the adoption of more efficient technologies and the electrification of uses. Both factors are neutralized resulting in a similar primary energy requirement. The main difference between the NDC and Hard Path scenarios and the Enlighten one is the decrease in the use of natural gas as the main primary source of energy. For the NDC and the Hard Path scenario, there is no break with the historical trend. The existence of productive "surface" infrastructure, ducts and the important reserves of natural gas suggest its use as the main resource in the energy mix. Only in a scenario with strong structural change, such as in the Enlighten scenario, a fast substitution to nuclear and hydroelectric energy is conceivable. However, as it could be perceived as unrealistic, the country's nuclear history, its technical capabilities, and the existence of vast untapped hydroelectric resources give meaning to this alternative. Large investments, but low unit costs, are involved resulting in lower total cost assuming small discount rates with a long-term logic, instead of just market finance analysis with a higher rate. The key issue is not only to include risk reduction measures, which make long-term projects possible but to have a systemic view that weighs up large projects that are usually undertaken with public or development funding. This is also only compatible with an economic scenario of structural change where labor-intensive and local expertise activities could motorize the transformation.

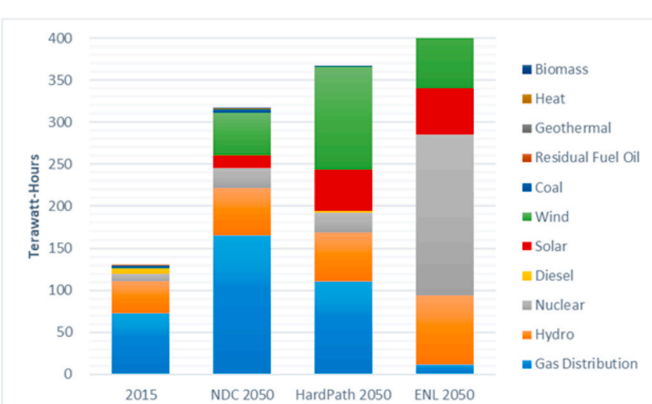


Fig. 3. Electricity production by fuels at the year 2050 for all scenarios.

However, the Enlighten scenario, based on economic structural change, implies significant industrial productive growth, and as a result, there is a growing industrial demand for natural gas that maintains its requirement in the year 2050. An equivalent situation occurs with the requirements for liquid fuels from the agricultural sector, and the maritime and river transport.

4.1.2. Power generation

Electricity generation is one of the main pillars for decarbonizing the energy sector [15]. As mentioned, the NDC and the Hard Path scenarios yet require the use of a natural gas generation option with carbon capture and sequestration. Such a technology, combine cycles w/CCS, emerges as the lowest cost per unit of electricity generated in the context of high-interest rates (12%). Thus, in these scenarios, the base-load of electricity generation is covered by them (see Fig. 3). The addition of wind and solar power is substantial, reaching almost 50% of the total electricity production at the time horizon.

Conversely, the Enlighten scenario promotes a rapid substitution towards nuclear energy with a strong local technological component, thus feeding the narrative of productive structural change and industrial dynamics. Nuclear energy provides the base-load of the electricity demand, complemented with strong participation of variable renewables and storage hydro-energy. The existing thermal plants are not retired to cover the backup power requirements for a generation system made up of 65% of the power installed by non-dispatchable plants. The underlying complexities and implications in terms of industrial inputs (cement, iron & steel, and labor) are addressed in the companion paper [20], with the full use of the IMACLIM-ARG model.

In terms of carbon sequestration, the Hard Path scenario is expected to capture an average amount of 21.5 Mt per year (Mtpa) which means having more plants in operation by 2035 than the total existing plants in the world today.[11]

A preliminary estimation of electricity generation costs has been made including investment, operation and maintenance components (fixed and variable), and fuel cost. Fig. 4 shows the comparative cost results of the DD scenarios compared to the NDC scenario. Positive values mean cost overruns compared to the NDC scenario while negatives reflect savings. It can be seen that both DD scenarios imply cost overruns in terms of capacity (capital costs), correlated with higher electricity generation requirements, due to the electrification of the end uses, as well as with the higher cost of non-GHG emitting technologies. Both scenarios also show significant fuel savings which are not enough to compensate for capacity overruns but partially mitigate them.

For the Enlighten scenario, both the components of capital and fixed operating cost stand out because of the significant nuclear incorporation proposed. In the Hard Path scenario, the variable operating cost is significant in relative terms, because it includes the cost of CO_2 transport and capture. It reaches 1.5 Billion USD in 2050 to capture 11 $MtCO_2$ that same year. In terms of total net incremental costs, it is estimated that the ENL scenario would imply a total cost overrun, at a discounted rate of 12%, of 10.2 Billion 2015USD, in present value, while the Hard Path scenario would imply a total cost overrun of only 3.5 Billion USD.

Although it is both obvious and expected that the decarbonization scenarios imply a higher cost for the electricity generation subsystem, the higher volume of electricity requirement for electrification suggests that the comparison is not straightforward. A comparison of the

[11] As could be seen in the Global CCS Institute statistics.

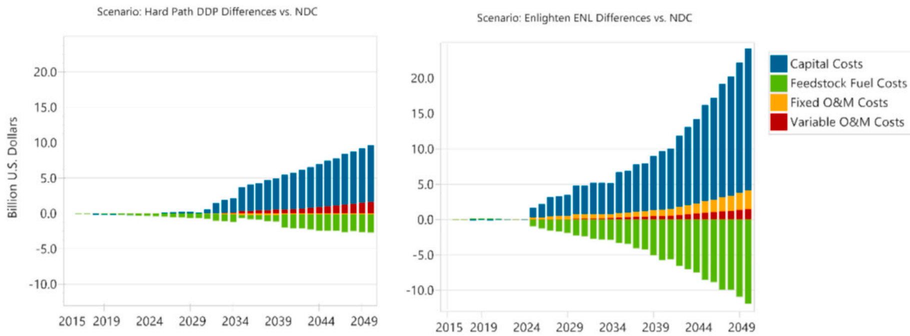


Fig. 4. Projection of electricity generation incremental costs and savings relative to the NDC scenario.

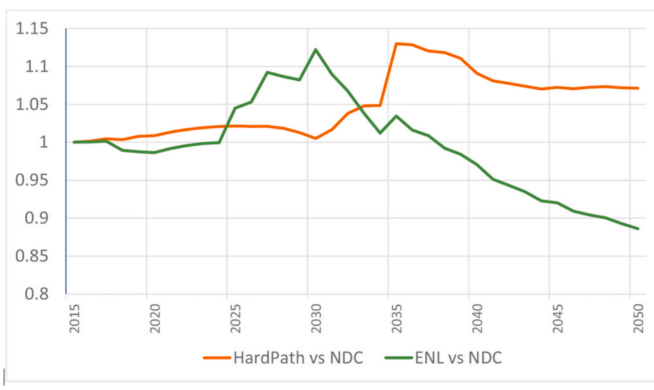


Fig. 5. Projection of the incremental cost per unit of electricity relative to the NDC scenario. Base year = 1.

incremental costs per unit of energy, taking the base year as a reference, allows visualizing the real evolution of the DD scenarios in terms of electricity costs (Fig. 5). We show that although the ENL scenario requires a significant initial effort, in the long term the electricity cost will be about 10% lower than the NDC scenario. The opposite trend occurs in the Hard Path scenario, and at the horizon time, its incremental costs are almost 20% higher than those expected for ENL.

Towards the horizon year, the significant increase of electricity generation requirements more than compensates the total incremental costs. This is a result of joint factors that would require further various sensitivity analyses, outside the scope of the paper but that yet raises an important conclusion. The relatively low investment cost of remaining hydropower potential in Argentina is a major component of the decline in costs. Deep decarbonization is much more a challenge of financing than cost overruns when it comes to electricity generation, the incremental costs overruns projections would almost vanish with discount rate values around 5%. Certainly, the devices required in the final demand that would allow substitution towards electricity could imply an incremental cost and should be considered and it wasn't done. Although it is also possible that efficiency savings could mitigate part of this effect. In the present cost overruns estimations, official fuel price scenarios are assumed, as well as the technological projected costs for Argentina. For new technology's costs, not present nor forecasted within the country, references from the International Energy Agency are used [39].

4.1.3. Energy demand

The projected final demand in the DD scenarios is substantially lower than in the NDC scenario (see Fig. 6). To a large extent, efficiency measures and end-use substitution towards electricity explain this outcome. The Enlighten scenario has higher specific requirements because the envisioned economic growth is higher. However, its higher electrification allows keeping the energy requirements at the same level as in the Hard Path scenario.

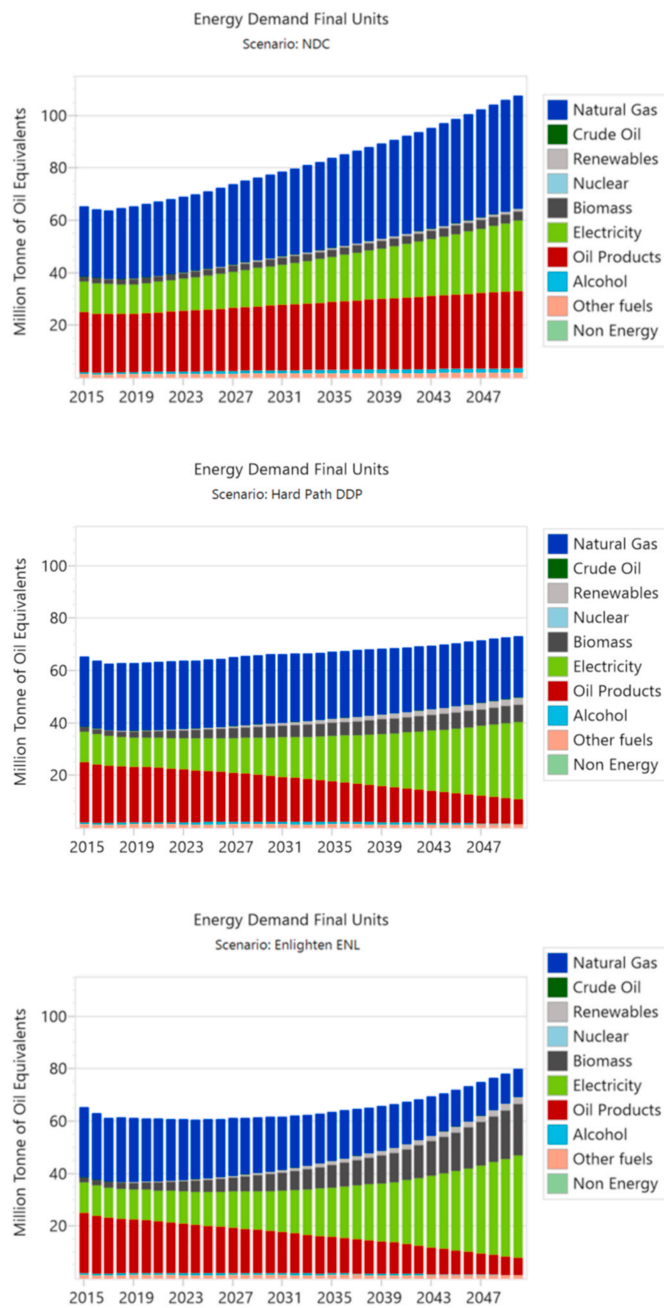


Fig. 6. Final energy demand by scenario and fuels.

Fig. 6 pictures the fuel distribution of the final energy demand.

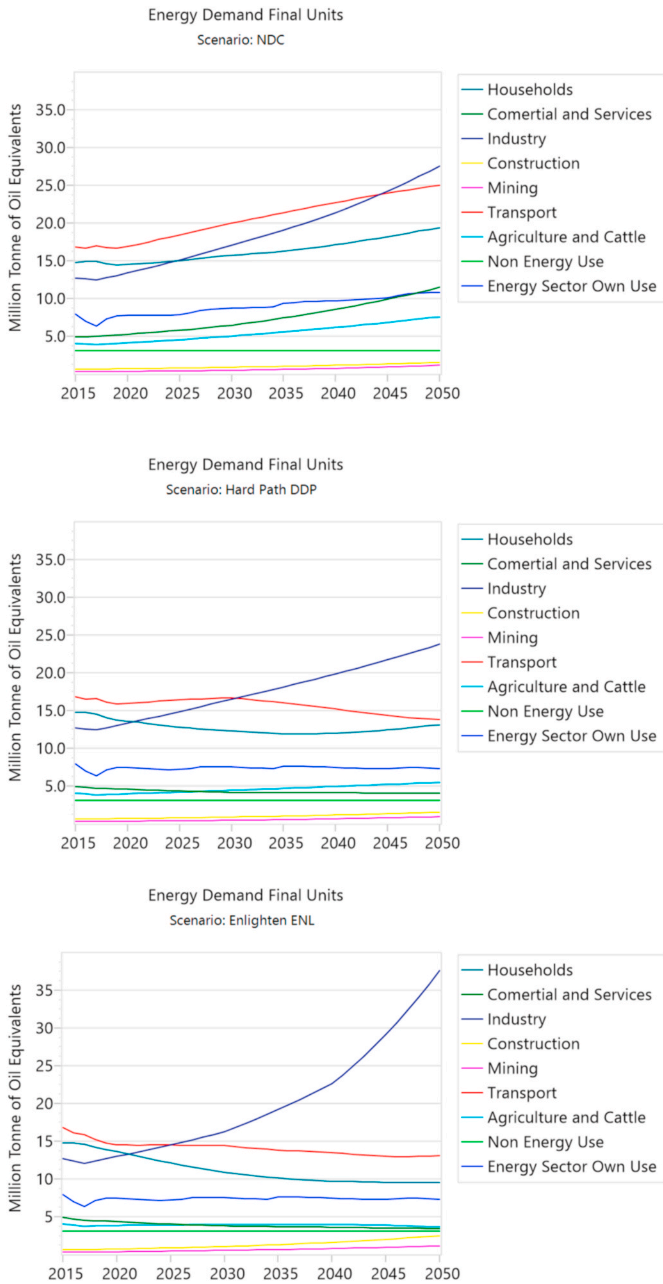


Fig. 7. Final energy demand by scenario and sector.

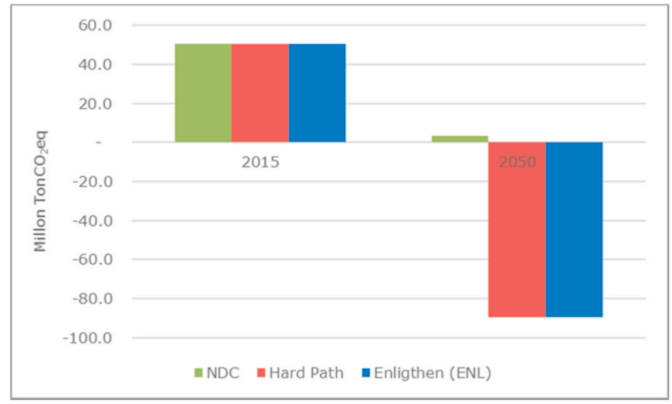


Fig. 9. AFOLU emissions by Scenario.

Electricity (in light green) takes an important share in both DD scenarios but the substitution of natural gas (in blue) is most appreciated in the Enlighten scenario. In both DD scenarios, the lower weight of liquid fuels (in red) compared to the NDC scenario, depicts a deep substitution of the vehicle fleet from thermal to electrical. The higher share of biomass uses (in dark grey) for thermal purposes in the industry is also highlighted in the Enlighten scenario.

Fig. 7 pictures the energy demand by sectors for the three scenarios. In all cases, industrial demand (blue line) accounts for the largest amount in absolute terms at the horizon year, and the Enlighten scenario records the strongest increase trend due to higher industrialization of the economy. The transport sector (red line) is the second-largest consumer of energy. In the DD scenarios, the increase in the vehicle fleet (reaching current Europe's number of per-capita vehicles) is mostly compensated by the efficiency gains of electric vehicles. Finally, the deep electrification of the residential and commercial sectors strongly decreases its demands compared to the base year in the DD scenarios.

4.2. Emissions pathways

The baseline emissions in the NDC scenario show a constant trendline up to 2050 to reach 544 $MtCO_2eq$. This projection is pictured by the upper line of the envelope (red line) of the DD wedge plots in Fig. 8. The lower edge of the wedge plots shows the evolution of the emissions expected for the DD scenarios. The total GHG emissions are reaching in 2050 194$MtCO_2eq$ and 118 $MtCO_2eq$, in respectively the Hard Path and the Enlighten scenarios. In both DD cases, a significant decrease in emissions is observed, tending towards carbon neutrality by years 2060–2070. The different color stripes represent the differential impact of key sectors, which are analyzed subsequently. Compared to the NDC scenario, the amount of emissions reduction is close to 65% and 80% in

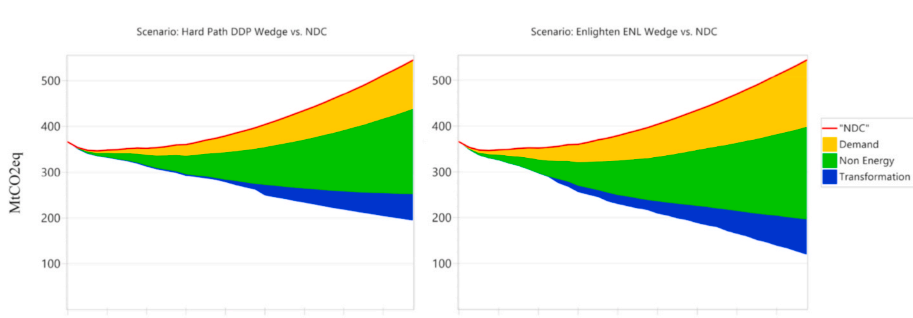


Fig. 8. GHG Emission reduction by sector for the Hard Path scenario (left) and the Enlighten scenario (right).

Table 4
Avoided emissions of ENL and Hard Path scenario vs NDC scenario for each sub-sector/measure considered.

Total NDC Scenario GHE Emissions in 2050 [MtCO$_2$ eq.]	544.4	
Avoided emissions by subsector/measure vs NDC in 2050	**Hard Path**	**ENL**
Land Use change emissions (afforestation)	−92.9	−92.9
Transport sector energy demand emissions	−47.6	−60.3
Electricity Generation emissions	−57.5	−58.4
Industrial Processes Non energy emissions	−32.5	−32.5
Cattle Non Energy emissions	−22.2	−29.6
Industry energy demand emissions	−8.3	−27.6
Agriculture Non energy emissions	−17.6	−26.4
Residues emissions	−20.3	−20.3
Natural Gas production emissions	–	−15.8
Households Space Heating energy demand emissions	−14.1	−15.0
Agriculture Sector energy demand emissions	−10.0	−14.2
Commercial and Services energy demand emissions	−10.8	−10.9
Electricity and Oil Products production own consumption emissions	−6.2	−6.2
Households Water Heating energy demand emissions	−4.9	−5.5
Households Cooking energy demand emissions	−3.7	−4.5
Cattle Sector energy demand emissions	−1.8	−2.7
Oil production emissions	–	−2.3
Mining energy demand emissions	−0.5	−0.4
Total avoided	**−350.7**	**−425.5**
Total DDP Scenario emissions [MtCO2 eq.]	**193.6**	**118.3**

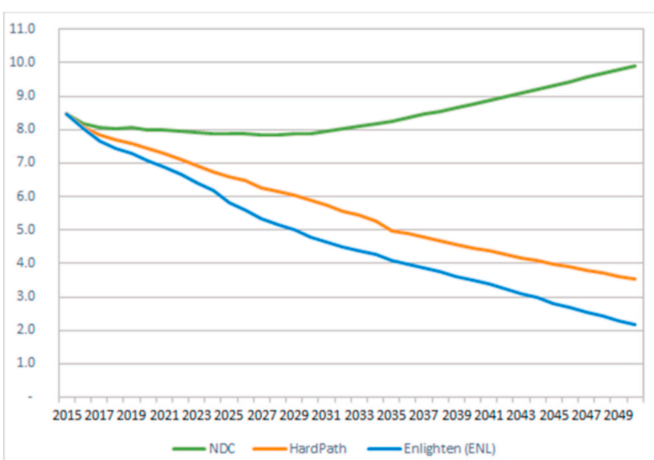


Fig. 10. Evolution of GHG emissions per capita for all scenarios.

2050 for the Hard Path and the Enlighten scenarios respectively. The energy-related emissions reductions correspond to the yellow and blue stripes. The yellow stripe integrates the effect of all the measures proposed for mitigating final energy demand, which accounts for around −150 MtCO$_2$eq in the Enlighten scenario compared to the NDC scenario. The blue stripe represents the emission reduction from energy transformation (electricity generation, natural gas, and oil production own consumption) which avoids the emissions of around 70 MtCO$_2$eq in the DD scenarios compared to the NDC scenarios.

The green stripe in Fig. 9 pictures the non-energy-related emissions reductions. These emissions reduction not only represent a significant amount but they also represent a bigger share than the mitigation of energy-related emissions. Table 4 details by sector these avoided emissions.

Although transport and electricity generation are key sectors to avoid GHG emissions and reach a DD target, we identify that the highest lever is on the land-use sector. Avoided emissions thanks to afforestation are the same order of magnitude as the mitigation of transport and electricity generation accounted together. Fig. 9 shows the AFOLU total emissions both at base year and the horizon year 2050 for each scenario.

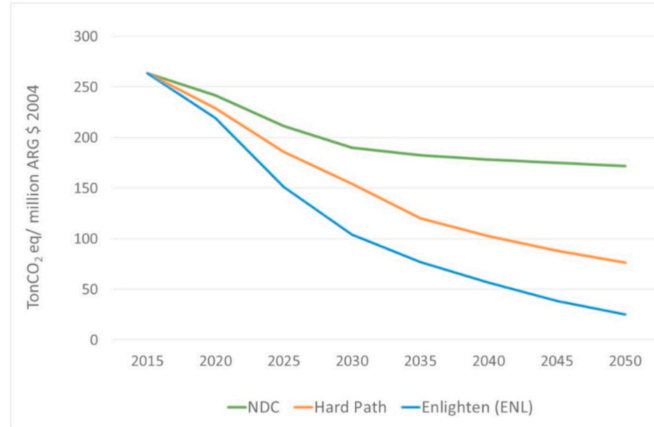


Fig. 11. Evolution of GHG Emissions per unit GDP for all scenarios.

In terms of net results, the AFOLU sector totalizes +50.6 MtCO$_2$eq in 2015, and +3.5 MtCO$_2$eq at the time horizon in the NDC scenario. In both DD scenarios, the net emissions are negative and amount for −89.4 MtCO$_2$eq in 2050, and thus 92.9 MtCO$_2$eq are avoided compared to the NDC situation.

In the short term, the per capita emissions projected for the NDC scenario (see Fig. 10) show a plateau resulting from ongoing mitigation policies combined with projected low economic performance. In the long term, without additional mitigation measures and with sustained economic growth, per capita emissions increase up to slightly below 10 tCO$_2$/cap at the time horizon.

The explored deep decarbonization scenarios, thanks to strong energy efficiency gains and early substitution initiatives, break with the NDC scenario from the first year of the period to record, at the time horizon, a strong decrease in emissions compatible with the Paris Agreement target. We emphasize again that the drastic mitigation actions of the energy sector would not allow such a shifted trajectory and final objective to be reached on its own. The backcast-type analysis allows identifying the necessity of incorporating 5 million hectares of land into forestry activity to trigger a deeper shift and make the emissions pathway finally consistent with a carbon budget of 2 tCO$_2$/cap in 2050.

By picturing the emission intensity of GDP in Fig. 11, we can see clearly that the Enlighten scenario -among the scenarios explored- involves an economy the most aligned with a deep decarbonization objective. Compared to the NDC scenario, the carbon intensity is reduced about seven times in the year 2050. The Hard Path scenario is less ambitious as its carbon intensity of GDP becomes 2.3 times lower compared to the NDC scenario.

5. Discussion and conclusions

The importance and urgency of exploring national long-term GHG emissions scenarios, that achieve both zero emissions and the pending development objectives, is evident. In this paper, we have designed such pathways and we have also identified the main impacts that a set of measures has on the productive system of Argentina.

Explored deep decarbonization scenarios allow the identification of the impact of quantified measures on energy and emissions. The contribution of this work consists in proposing a set of clearly identifiable policies, framed in economic strategies with potential structural changes. These changes are based on Argentina's specific context (availability of natural resources, scientific and technical capabilities, basic infrastructure, demographic bonus), key socio-economic aspects (employment, education, tax structure), the promotion of new activities (food with greater added value), the deployment of innovative sectors (knowledge-based services), the economic planning, and the stakeholder engagement.

Both the Hard Path and the Enlighten scenarios that we have built lead the country towards a deep decarbonization pathway. One of the key results of our backcasting approach is that the contribution of afforestation as an emissions sink is a prerequisite to a net-zero emission goal, and tackling the only energy-related emissions, even with aggressive mitigation measures, is not enough. This is mainly due to the significant weight of agriculture and bovine livestock activities in Argentina's productive system. However, the implementation of an afforestation measure of this magnitude (5 million hectares) faces twofold issues that we should address. First, there is a high degree of uncertainty associated with the emissions reduction potential of afforestation. Second, a technical study is required to evaluate the feasibility of such a measure and to assess its impact. However, under adequate circumstances and a State-led integrated land-use planning framework, this could result in the preservation and increase of forest stocks (both natural and planted), with potential benefits from ecosystems services provision (e.g. soil erosion prevention, and water basin and ecosystems protection), which in turn can have tangible economic and health benefits for the society. These potential positive outcomes align also with several National SDGs.

If Argentina were to set long-term GHG emission reduction targets compatible with a $+2\ ^{\circ}C$ temperature increase, an exhaustive set of mitigation measures would not be sufficient, and deep changes in the economic structure would be needed. Such changes should be explicit and integrated into a comprehensive national development plan. The strategy to be adopted must give priority to making the productive system more dynamic and to creating industrial jobs promoted by local manufacturing. Since Argentina is a country with both a high poverty rate and a relatively low development stage, all activities, particularly the energy sector, must be organized according to these priorities. Moreover, the integrated development strategy must be framed by coherent and compatible global changes, since it will be extremely difficult to achieve the Paris Agreement objectives under current patterns of distribution, production, trade, and consumption. As one example, far more substantial and efficient global cooperation funding is a requirement.

Indeed, such DD pathways come with significant needs of funding -that the virtuous Enlighten path drafted as Structural Change socio-economic scenario. Even if Argentina reaches an internal consensus on such a strategy, substantive external finance would be required. The conditions of the credits, including the time-span, interest rates, risk treatments, grace periods -among other financial aspects-are challenging given the current global financial system. And there is yet no success in helping Argentina getting out of its external debts, and overcoming the over-costs due to sovereign risk. Green or Climate funding ought to provide efficient and timely instruments to help a country like Argentina to trigger a shift toward net-zero emissions by 2050 while reaching its pending national development.

Finally, the viability of the two proposed scenarios for achieving deep decarbonization in Argentina requires further discussion at the global level. The developments of big hydroelectric and nuclear plants in the Enlighten scenario are commonly outside the mainstream discussion of mitigation actions. The Hard Path scenario is based on a mature technology of carbon capture and sequestration, which is not yet cost-effective. In addition, the increase of the material intensity to electrify production and final energy consumption in the DD scenarios requires further life cycle analyses to assess the viability in terms of resource pressures for key primary inputs such as cement, copper, plastics, or aluminum.

Author statement

Lallana, Francisco: Conceptualization, Data curation, Methodology, Writing – original draft preparation, Software, Bravo, Gonzalo: Conceptualization, Data curation, Methodology, Writing – original draft preparation LeTreut, Gaëlle: Conceptualization, Data curation, Methodology, Writing – original draft preparation, Software Lefèvre, Julien: Conceptualization, Methodology, Writing – review & editing Nadal, Gustavo: Conceptualization, Data curation, Methodology, Writing – original draft preparation, Di Sbroiavacca, Nicolas: Conceptualization, Methodology, Writing – review & editing

Declaration of competing interest

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

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