Fundación e Instituto Torcuato Di Tella – International PtX Hub

# Assessing the risk of carbon lock-in of hydrogen and PtX policy options: a proposed framework

## *—With an application for the case of Argentina—*

October 2024

International PtX Hub

Supported by:
Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

IKI INTERNATIONAL CLIMATE INITIATIVE

Implemented by
giz Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

Developed by Fundación Torcuato Di Tella

**Authors:**
Hernan Carlino
Luciano Caratori
Micaela Carlino

The International PtX Hub is implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry of Economy and Climate Action (BMWK) and funded by the International Climate Initiative (Internationale Klimaschutzinitiative, IKI). The activities of the PtX Hub in Argentina are implemented by a consortium consisting of GIZ, the Argentine Energy Secretariat, Fundación Torcuato Di Tella, CEARE (Centro de Estudios de la Actividad Regulatoria Energética), Agora Energiewende and DECHEMA e.V.

International PtX Hub

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

IKI INTERNATIONAL CLIMATE INITIATIVE

Implemented by
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

# Table of Contents

EXECUTIVE SUMMARY 4

INTRODUCTION: THE ARGENTINE ENERGY CONTEXT 5

1 THE PROBLEM OF CARBON LOCK-IN 8

2 A PROPOSED FRAMEWORK TO ASSESS CARBON LOCK-IN RISKS IN HYDROGEN AND POWER-TO-X POLICY CHOICES 18

2.1 GENERAL PROCESS 18
2.2 FRAMING QUESTIONS 20
2.3 FINAL STEPS 21

3 CONCLUSIONS AND RECOMMENDATIONS 23

4 ANNEX 1: SYNTHETIC DESCRIPTION OF AN APPLICATION OF THE ANALYTIC HIERARCHY PROCESS 24

5 REFERENCES 28

# Executive Summary

This policy brief examines issues related to path dependency and the risks of carbon lock-in, with a specific focus on the case in which fossil fuel-based energy systems may delay or obstruct the shift to lower-carbon alternatives, such as hydrogen and Power-to-x technologies, and also its implications for the country's transition towards net-zero emissions, with an application for Argentina.

Based on the case study of Argentina, the introduction underscores the country's significant reliance on fossil fuels, especially natural gas, which is a key component of the nation's energy mix and a relevant source of income for several provinces[1]. This dependency results in considerable challenges in diminishing carbon lock-in, as existing infrastructure and institutional practices favour fossil fuels, while some policy options to incentivise emerging technologies may unintentionally exacerbate this phenomenon, and, hence, the need to develop an evaluation framework to steer the energy transition effectively.

The core section of the document explores the concept of path dependence, lock-in and carbon lock-in in the context of the energy sector, discussing choices and systemic factors that have resulted in increased fossil fuel reliance, assessing the interplay between economic, technological, and policy factors that sustain this dependency.  Additionally, it establishes the dual relationship between hydrogen development and carbon lock-in, acknowledging the consequent difficulties to increase the competitiveness of hydrogen and its derivatives as a commercially viable alternative to fossil fuels, and the risks posed by certain hydrogen production and consumption pathways that may inadvertently prolong the use of fossil fuels.

In the next section we propose a framework to assess carbon lock-in risks associated with policy options and projects, offering a structured methodology to evaluate carbon lock-in risks within hydrogen and PtX initiatives. The section introduces a set of evaluative questions arranged into four relevant dimensions: i) Infrastructure and Technological Lock-in, ii) Institutional Lock-in, iii) Behavioural Lock-in, and iv) Policy and Regulatory Lock-in. Then a scoring system to gauge

---

[1] See the Policy Note developed under the framework of the PtX Project "Fiscal Federalism and Environmental Governance: Implications for the Development of Green Hydrogen in Argentina" (2024).

the potential impact of energy policies and projects in overcoming, preserving, or exacerbating carbon lock in is then outlined.

Both a weighted and an unweighted option for the assessment are presented, with a preference for multi-stakeholder evaluations, for which the Analytic Hierarchy Process (AHP) is proposed to add stakeholder-informed weights to the evaluation, in order to ensure a more nuanced, contextually relevant, and multi-stakeholder perspective assessment.

The concluding section synthesizes the findings, emphasizing the critical nature of being able to escaping carbon lock-in within the energy sector transitions, including these considerations in the process of energy planning and decision-making as well as the  broader mitigation strategies, particularly in sectors where transitioning away from fossil fuels —as recently agreed at the international level in the context of the outcome of the Global Stocktake— presents extremely complex challenges.

## Introduction: The Argentine energy context

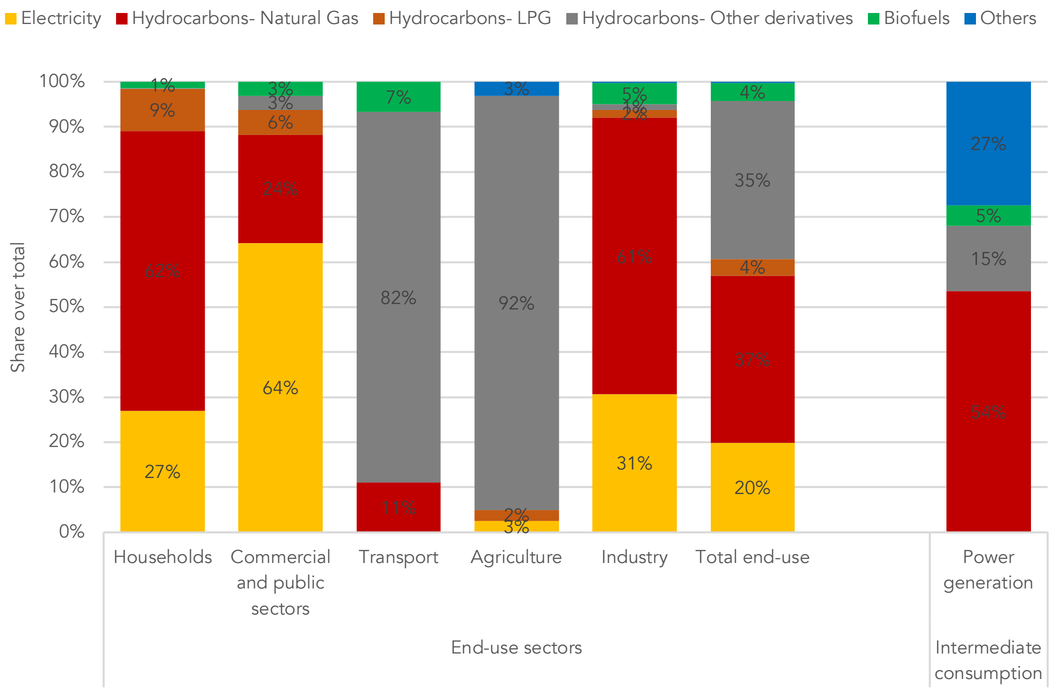
The energy sector of Argentina is characterised by a strong dependence on fossil fuels, which explain 76% of end use sectors' total final energy consumption, and 68% of the country's power generation (Secretaría de Energía, 2023). In this context, the phenomenon of carbon lock-in, wherein existing fossil fuel-based technologies and infrastructures hinder the adoption of low-carbon alternatives, poses a genuinely significant challenge.

This is particularly evident in the strong reliance on natural gas, a key component of the nation's total final energy consumption, which explains 62% of the countries' household's energy consumption and 61% of industrial energy consumption, along with 54% of power generation (Secretaría de Energía, 2023).

While natural gas plays a central role across various sectors—such as residential heating, industrial processes, and electricity generation—, enabled by vast resources, targeted policies and a historically widespread infrastructure, it may also turn into an implicit barrier to the country's transition to a net zero emissions energy future.

The following figure depicts the role of several energy sources in end-use sectors and power generation in Argentina.

*Figure 1: Share of energy sources in final and intermediate energy consumption by sector*



*Source: Own elaboration based on data from Argentina's National Energy Balance for 2022 (Secretaría de Energía, 2023)*

Argentina stands at a crossroads in its energy transition, trying to reconcile short-term challenges with strategic priorities, with several instruments, stated policies and regulation being put in place to guide the country's energy transition towards net zero emissions by 2050, including:

- Argentina's Revised Second National Determined Contribution (NDC, 2021)
- Long-Term Strategy for Low-Emission Development (LTS-LEDS, 2023), both NDC and LTS submitted to UNFCCC,
- Argentina's National Strategy of Carbon Markets (2023)
- National Energy Transition Plan towards 2030 (2023)
- Scenarios and Strategy towards 2050 (2023).

The development of green (renewables-based) hydrogen and Power-to-X (PtX) technologies offer opportunities to leverage a sustainable path to promote economic growth and development, while contributing to Argentina's ambitions towards addressing climate change and fostering sustainable development in line with the country's circumstances, strategic priorities, resources and needs.

As it was addressed in previous policy briefs (Carlino et al, 2024)[2], Argentina's federal system presents additional layers of complexity, as provincial autonomy can lead to diverse and sometimes conflicting energy policies, posing challenges for the coordination of a unified national transition plan.

This federal fiscal architecture, marked by significant decentralisation and a high degree of vertical fiscal imbalance, influences the paths of energy sector development and the distribution of investment, also leading to a patchwork of energy policies that may not always be conducive to a coherent national strategy for decarbonisation and that may reinforce the risk of potential carbon lock-in, for example, though a vast array of incumbent stakeholder groups which are heavily dependent or benefitted by the hydrocarbons economy through direct and indirect revenues.

Path dependence, introduced by Brian Arthur (1989), describes how historical choices in energy systems incur sunk costs and coordination issues, creating a lock-in effect that impedes shifts to sustainable alternatives, particularly, in sectors like transportation and heavy industry (Geels, 2002; Grübler, 1998).

In this context, Argentina’s energy transition strategy needs to carefully balance leveraging existing natural resources for economic and energy security benefits while actively reducing dependence on fossil fuels to achieve long-term decarbonisation goals.

---

[2] “Fiscal Federalism and Environmental Governance: Implications for the Development of Green Hydrogen in Argentina” (2024).

# 1 The problem of Carbon Lock-in

Path dependence reinforces the need to consider the long-term implications of choices for energy policy, especially in hard-to-abate sectors. These sectors are often characterised by complex and costly transitions, where direct electrification is non-feasible, due to economic or technical constraints, such as transport, petrochemical, and heavy industries.

The prevalence of policies, regulations, and incumbent stakeholder groups that favour existing fossil fuel systems contribute to reinforce this path dependence, ultimately, leading towards the lock-in effect as countries face the difficulties of aligning multiple actors within the energy system toward new technologies.

In this line, hydrogen and its derivatives' relationship with carbon lock-in is dual: on one side, incumbent energy technologies can impede the development of green hydrogen by reinforcing institutional uncertainties (Bento, 2010), while on the other, certain hydrogen and derivatives' production pathways, especially those reliant on fossil fuels (such as "grey", "blue" or "turquoise" hydrogen), risk exacerbating carbon lock-in by prolonging the use of natural gas infrastructure and potentially increasing methane emissions, despite the possibility of green hydrogen serving as an alternative in the near future (Szabo, 2020; Rosenow, 2021; Oh, 2022; Griffiths et al., 2021; Kaya, 2021).

Additionally, the use of hydrogen for certain end-use sectors, while benefitting from the cost-efficiency of leveraging existing infrastructure and fleets end-use equipment, can contribute to lock-in for some sectors where electrification is already the best alternative for decarbonisation. For example, the use of hydrogen for heating in cases where electrification is already a competitive technology can contribute to delay the smart electrification of end-use sectors.

For example, the principles outlined in Argentina's official guidelines for the elaboration of environmental strategic assessments (SAyDS, 2019) are valuable in supporting these transitions while including tools for the assessment of strategic environmental and social issues beyond climate change, considering the full scope of environmental impacts, including effects on ecological systems, human communities, biodiversity, and water resources.

These can be complemented with additional tools in light of the particular challenges related to PtX development and carbon lock-in.

These broader risks of carbon lock-in in the energy sector demand a strategic and comprehensive framework that transcends short-term development considerations, addressing the underlying institutional and federalist dynamics.

Integrating environmental strategic assessment and the principles of the hydrogen and PtX development strategy is critical for enabling countries to harness their natural resources while avoiding becoming locked-into unsustainable technologies and practices, in the context of progressive global action against climate change.

The purpose of this policy brief is hence to evaluate the different dimensions of carbon lock-in, specifically in the context of the development of a hydrogen and PtX economy and to propose a framework for assessing how different policy choices and projects can avoid or, alternatively, at least, minimise carbon lock-in, or in the contrary, exacerbate these challenges.

Path dependence, was first introduced as a concept by Brian Arthur (1989) as mentioned, refers to the idea that the choices taken and the actions implemented in the past can shape and constrain future options and outcomes for a given system (Geels, 2002) and partially explains the difficulty of transitioning away from established technologies and systems (Grübler, 1998), involving at times large sunk costs and huge coordination challenges, increased financial costs, and ultimately resulting in a lock-in effect (Arthur, 1989).

This concept reinforces the importance of considering the long-term implications of past and current choices and actions, and in the context of this policy brief, particularly for those commonly known as hard to abate sectors[3], where the transition to more sustainable alternatives can be both complex and costly, such as the energy industry and sectors where direct electrification is either non feasible, due to economic or technical matters, or, in other cases, such as the transport sectors, petrochemical and heavy industries, with particularly challenging complex industrial processes.

For example, in the energy sector, the continued dependence on fossil fuels, and the associated infrastructure, such as pipelines and refineries and the nature of the revenues, as well as the prevalent policies, regulations and multiple

---

[3] These usually include Steel, Cement, Aluminium, certain petrochemical industries, Aviation, and Maritime transport, among others.

incumbent stakeholder groups from the private and public sectors, contribute to create or reinforce this path dependence.

Liebowithz et al (1995) categorise path dependence in three forms:

i. a weak form, in which initial actions result in a path that cannot be left without incurring in costs, but with no clear inefficiencies (first degree path dependence);
ii. a second form, where the inferiority of the path chosen by a series of decisions was not knowable at the time a choice was made (second degree path dependence);
iii. and a third form, in which not only intertemporal effects propagate error and that path cannot be avoided without incurring in costs, but also results in clear inefficiencies and that series of error were "avoidable" or the negative consequences of taking the path were known at the time were decisions were made (third degree path dependence).

For the purpose of this policy brief and associated methodology, the interest of the authors is focused on the first and second forms for the sole purpose of understanding current constraints, but the proposed assessment framework will be focused on the third form, given that the final objective is to propose an entire forward-looking analysis, intending to avoid or mitigate the lock-in effect, or, as a minimum, to avoid exacerbating it.

The lock-in effect, an extreme case of path dependence, refers to the difficulty of transitioning away from established and prevalent technologies and systems (Arthur, 1989; Seto et al., 2019). This can be due to the financial costs of transitioning to new technologies, as well as the difficulties of coordinating and aligning the actions of multiple actors within the energy system. Grübler (1998) differentiates the lock-in effect from path dependence, by reserving the term "lock-in" to describe a particular historical choice that becomes almost irreversible while using "path dependency" for describing apparent stabilities in macro-patterns of technological change resulting from the accumulation of many decisions moving in a persistent direction.

According to Grübler, the cases of path dependence are not the result of a discrete historical event or "accident". They result from persistent "signals" driving technological change in one particular direction and thereby creating irreversibilities, or at least substantial inertia.

Particularly, carbon lock-in refers to the long-term dependence on fossil fuel-based infrastructure and technologies, which makes it difficult to transition to low-carbon alternatives. This phenomenon can occur at various levels, including individual behaviours, as well as the level of firms and entire systems. This type of lock-in is driven by a combination of several factors (as explored in this document), which can make it more difficult to transition to low-carbon alternatives.

For example, consumers may be hesitant to switch to more energy-efficient appliances if they have already invested in less efficient ones at the residential, commercial, and industrial level, for reasons that include the existence of available equipment stocks (Seto et al., 2016), well-established and known standards (Haoqi, 2017; Janipour et al., 2020), compatibility or integration issues (Janipour et al., 2020), strongly developed supply chains (Narasimhan et al., 2009), and service providers, or higher upfront costs of the challenging alternatives, for example, in capital intensive alternatives, such as wind or solar PV power vs. thermoelectric power plants.

In the transportation sector, carbon lock-in can occur, for example, through the use of fossil fuel-based vehicles, such as gasoline-powered cars. The (so far, but decreasing) higher upfront cost of electric vehicles and the lack or insufficiency of charging infrastructure can make it difficult for consumers to switch from gasoline-powered vehicles to EVs. Additionally, the infrastructure that has been built to support fossil fuel-based transportation, such as roads and gas stations, can also create barriers or concrete obstacles to the adoption of other low-carbon alternatives.

Carbon lock-in may also occur at the system level, as entire societies become reliant on fossil fuel-based infrastructure, revenues, and technologies, particularly in the case of interdependent technological systems when these are a result of the coevolution of technological systems with private and public institutions (Unruh, 2000).

For example, the World Energy Outlook 2022 (IEA, 2022) shows that the consumption of fossil fuels in the global energy system has increased over time, despite the availability and increasing penetration of low-carbon alternatives such as renewables, which now represent the majority of capacity additions in the power sector (IEA, 2024). This is related to a combination of economic, technological, and policy factors that have supported the continued expansion of fossil fuel-based energy sources.

Hydrogen, the focus of this brief, has a dual relationship with the lock-in effect: on one hand, according to Bento (2010) the dominance of incumbent technologies hinders the possibilities of development of green hydrogen through several of the mechanisms identified in this document, particularly through the reinforcement of institutional uncertainties, while other authors have tried to comprehensively characterise the relationship of hydrogen with socio-technical systems, which may become sources of lock-in restraining the development of hydrogen in specific sectors (Griffiths et al. 2021; Kaya, 2021), as further characterized in this section.

Conversely, certain hydrogen pathways, particularly those based on fossil fuels (such as "grey", "blue" or "turquoise" hydrogen), may further contribute to carbon lock-in (Szabo, 2020; Rosenow, 2021; Oh, 2022), along with certain use cases by delaying the phase out of existing natural gas plays, failing to address, or even increasing fugitive methane emissions or increasing reliance on long-lived carbon capture assets where "green" hydrogen can replace fossil-based hydrogen in the short- to medium terms or where direct electrification can substitute the use of fossil fuels.

A third aspect of lock-in that is important for the purpose of this document is related to carbon sources for hydrogen derivatives (particularly for RFNBO, renewable fuels of non-biological origin). In this case, which may impact the accounting of emissions savings from renewable fuels based on hydrogen (GIZ, 2023), currently eligible carbon sources (emissions from inputs' existing use or fate, those that are avoided when carbon is used as input for fuel production) face increased risks to become less desirable or ineligible in the future, and may have, in turn, consequences on pricing, taxes or on the acceptability of their GHG intensity thresholds.

For example, carbon sources associated with industries or activities not aligned with 1.5°C compatible pathways, such as refining or point-source $CO_2$ from industrial processes, including for instance cement, face increased risks to become ineligible in the future when compared to biogenic carbon sources when these are non-associated with land use change or deforestation, particularly in scenarios where more stringent rules may apply for sustainability certification and procurement standards.

One key driver of carbon lock-in is the existence of sunk costs, which are investments that have already been made and cannot be recovered (Sutton, 1989). For example, a power plant that has been built to use fossil fuels may have a long lifespan, and the cost of replacing it with renewable energy sources and technologies may be high.

Similarly, consumers may be hesitant to switch to more energy-efficient appliances if they have already invested in less efficient ones, as in the case of gas-fired heating equipment vs. heat pumps, or regular air conditioning equipment vs inverter technologies, which is accentuated in the case of the existence of energy subsidies.

Another driver of carbon lock-in is the existence of network externalities, which occur when the value of a product or service increases as more people use it, with incentives for firms and consumers to maximise compatibility through standardisation (Katz & Shapiro, 1985). For instance, the more people who use a particular transportation system, the more convenient and useful it may become for everyone (except, for example, in the case of increased congestion as a result of the massive adoption of individual cars). This can create a positive feedback loop, as more people are encouraged to use the system, further increasing its value. However, this can also make it difficult for alternative technologies to gain a significant share of the market, as these may not have yet developed such level of network spill over effects.

Additionally, regulatory and policy frameworks, as well as information can also contribute to carbon lock-in. For example, subsidies or other financial incentives for fossil fuel industries as well as yet non-internalised environmental externalities may make low-carbon alternatives less competitive (Jaffe et al., 1995), suggesting that uninternalized environmental externalities associated with particular sources of energy clearly calls for those externalities to be internalized, such as through pollution taxes, tradeable permit systems, or other economic instruments, or through conventional command-and-control regulations. In the case of Argentina, this is exacerbated by consumer subsidies, lowering the cost of natural gas and LPG for households. Similarly, the lack of regulatory frameworks or incentives for low-carbon technologies can also discourage their adoption.

The drivers of carbon lock-in have been categorised in several groups of factors by recent literature.

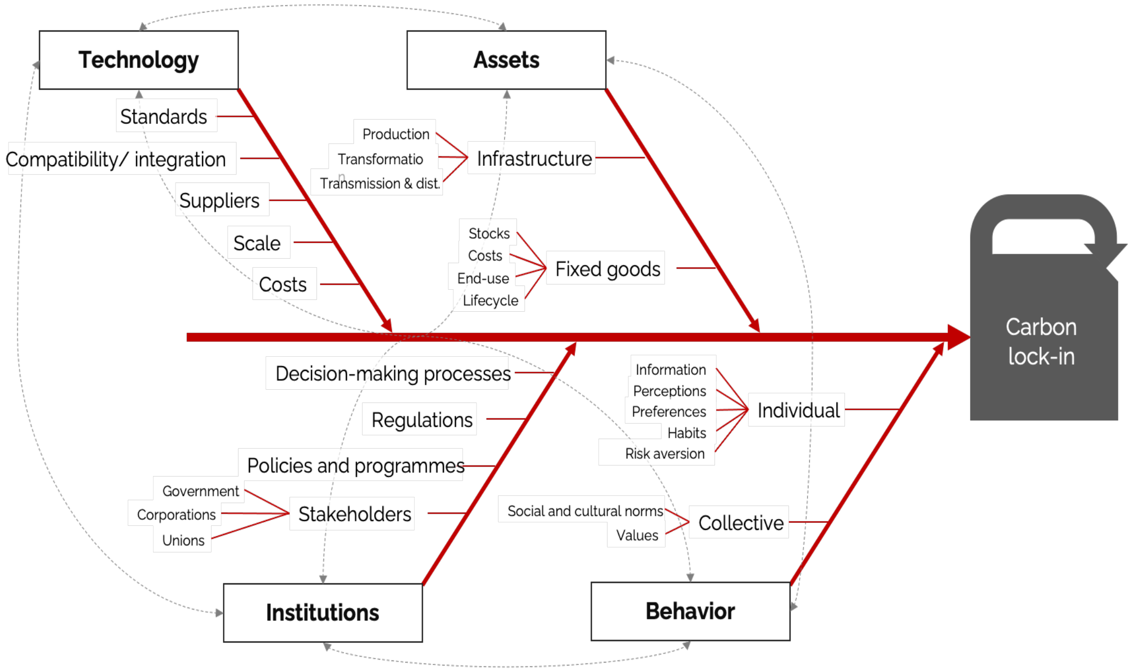
Seto et al. (2016) categorised carbon lock-in in three types: Infrastructure and technological, corresponding to technological and economic forces leading to inertia, long lead times, large investments and sunk costs, among others; Institutional, including powerful economic, social, and political actors ("incumbents") seeking to reinforce status quo that favours their interests, institutional designs aiming to enhance stability and ultimately locking in technologies and practices; and Behavioural Lock-in through individual decision making where single, calculated choices become a long string of non-calculated and self-reinforcing individual and collective habits.

Janipour et al. (2019) identified five key lock-in themes via semi-structured interviews when assessing sources of carbon lock-in in energy intensive industries in the Netherlands, including:

- Technological incompatibility, raising issues related to economies of scale, learning effects and adaptive expectations which could affect business continuity or produce additional fixed costs;
- System integration matters, particularly regarding those changes which could reduce the stakeholder's flexibility to switch feedstock and technologies in the future or issues related to Balance of Plant equipment;
- Sunk costs, resulting from the high capital costs of existing long-lived installations, including a dilemma related to energy efficiency optimisation of the existing installations, particularly when payback times are long;
- Policy inconsistency, particularly regarding the potential lock-in resulting from short-term emission reduction measures in existing fossil-based technologies, and the learning effects for knowledge set to become obsolete if a currently inconsistent policy is eventually made consistent; and, finally,
- Safety routines, where the authors highlight that the delay in the development of new safety standards conditions learning effects, adaptive expectation and network effects in the safety routines serving the existing system, when not built upon existing standards, risking a reduction of confidence in the safety performance of the new technologies.

The following figure summarises these lock-in factors or clusters based on Seto et al. (2016), Janipour et al. (2019), Unruh (2000 and 2006) and Erickson et al. (2015).

*Figure 2: an Ishikawa diagram for Carbon Lock-in*



*Source: Elementos para una Estrategia Climática de Largo Plazo (FTDT/Decarboost, 2022)*

Erickson et al. (2015) also developed a practical approach to assess several factors related to carbon lock-in risks for major energy-consuming assets in the power, buildings, industry, and transport sectors, based on four dimensions:

- **Technical equipment lifetime**, relating the lifetime of a given technology or asset to how long it may continue to emit;
- **Scale of increase in $CO_2$ emissions**, based on the use of $CO_2$ accounting for the future emissions of the assets under full normal operation, which can be contrasted to the carbon budget resulting from the analysis of a given emissions scenario;
- **Financial barriers** to subsequent replacement of an asset with low-carbon alternatives, defined as the breakeven carbon price needed for early retirement and replacement of a technology with its predominant low-carbon alternative for a given carbon pathway; and, finally,
- System-wide **Techno-institutional mechanisms** that further strengthen high-carbon technologies at the expense of low-carbon alternatives, similarly to those identified by Seto et al. (2016), including a broad range of mechanisms linked to the economic, political and social advantages that incumbent technologies take advantage of, using for practical

purposes a normalised technology market share, cumulative production and cumulative investments as a quantitative proxy.

A recent report by New Climate Institute in the context of the project DECARBOOST (New Climate Institute, 2023) briefly analysed lock-in risks for different hydrogen end-use cases and technologies. The temporality criteria used in that document utilises four indicators for the risk assessment of carbon lock-in for the analysis of investment opportunities, based on the latter classification: equipment lifetime, financial barriers to subsequent replacement with low-carbon alternatives, over-committed emissions (i.e. the scale of increase of GHG emissions), and techno-institutional effects, based on Erickson et al. (2015), and makes use of the detailed results by technology elaborated by that research and published as supplementary information. The proposed analysis includes an assessment of how different investment opportunities contribute to move away from BAU activities that have carbon lock-in risks, or if, in the contrary, these continue to perpetuate fossil assets, increasing the risk of carbon lock-in.

Some technologies and pathways can contribute to "jump-over" carbon lock in through *leapfrogging*. This concept is often used in the context of technological development, and refers to the ability of countries, regions or sectors to bypass intermediate stages of development from traditional development paths and directly adopt more advanced technologies or systems (Brezis et al., 1993), thus circumventing some of the negative consequence of path dependence or aiming to create alternative paths, often though major external shocks (Simmie, 2011). This can be particularly relevant in the energy sector, where the infrastructure and technologies that have been developed and implemented over time can create barriers or constraints to the adoption of new and potentially more sustainable low-carbon alternatives.

In the context of energy, leapfrogging can refer to the adoption of cleaner and more sustainable energy sources, such as renewable energy or hydrogen and its derivatives, by bypassing the intermediate stage of reliance on fossil fuels (e.g. "blue" hydrogen obtained through steam methane reforming and carbon capture and storage technologies). This modality can be especially beneficial in developing countries where the energy infrastructure is not yet fully developed, allowing them to avoid the costs and challenges of transitioning away from fossil fuels in the future.

Hydrogen has been identified as a potential means of leapfrogging, as it presents an opportunity for developing countries to bypass the traditional fossil fuel-based energy systems and directly adopt a cleaner and more sustainable energy source.

There are several examples of developing countries considering hydrogen as a means of leapfrogging, such as the current plans under development in Africa and Latin America and the Caribbean.

Several authors have begun to explore the feasibility and implications of leapfrogging to hydrogen in large economies, such as China (Zhu, 2003) and Russia (Potashnikov et al. 2022), concluding respectively that this potential development in China will be both determined by resource availability, existing infrastructure (past energy expenditures) and political decisions, and that Russia can potentially transfer green energy to other energy-intensive goods to be traded on the global market, substituting losses from resource rent revenues through a flexible approach for using hydrogen as energy storage, fuel, or as feedstock for other goods.

# 2 A proposed framework to assess carbon lock-in risks in hydrogen and Power-to-X policy choices

## 2.1 General process

This section provides a structured approach to assess the carbon lock-in risks associated to hydrogen and Power-to-X development policy options and projects. The proposed framework is designed to systematically assess the potential impact of hydrogen-related policies, projects, or instruments in the context of the energy sector and can be applied by policy makers and for third-party policy assessment by a vast array of stakeholders.

The approach consists of a series of common questions, structured in four dimensions: I. Infrastructure and Technological Lock-in, II. Institutional Lock-in, III. Behavioural Lock-in, and IV. Policy and Regulatory Lock-in as a synthetic and systematic approach to assess these aspects discussed previously in this document.

The framework should be considered dynamic, with adjustments made as new information becomes available or as the national energy policy evolves.

For each question, a value is attributed to the policy or project under evaluation:

- If the answer is 'Yes' (the option exacerbates or preserves carbon lock-in), assign [-1].
- If the answer is 'No' (the option contributes to overcoming carbon lock-in), assign [+1].
- If the answer is ‘neutral or not applicable’ (the option has no evident effect on carbon lock-in), assign [0].

If the sum of the scores results in a positive value for a given dimension, the option should be considered as contributing to overcoming carbon lock-in, while if the sum of the scores results in a negative value should be considered as contributing to exacerbate or preserve carbon lock-in.

Notwithstanding the balance of positive and negative scoring, any positive answer suggesting that a given option might contribute to preserve or exacerbate carbon lock-in for any dimension needs to trigger an assessment of the strength of their contribution to locking-in high emissions technologies or practices.

The basic framework considers an unweighted sum of the results of each dimension, but the complexity of the general structure can be increased in response of multi-stakeholder assessments including experts from multiple disciplines and institutions, which are preferred to enrich the evaluation process and to ensure all relevant aspects of carbon lock-in are considered, and particularly for policies involving more than one government or private entity.

For a weighted application we suggest the adoption of the Analytic Hierarchy Process (AHP) to assign weights to each dimension and question according to their relative importance in Argentina's national circumstances, current and foreseen challenges, and strategic priorities. This process involves pairwise comparisons and expert judgment to attribute weights to the dimensions of the framework.

The procedure involves the definition and hierarchy of criteria, whose fulfilment is necessary to achieve an objective (in this case to overcome or minimise carbon lock-in), and the subsequent evaluation of the potential of different action alternatives to contribute to meeting these criteria, contributing to the prioritization of activities based on a multicriteria and collaborative analysis.

The prioritization of the criteria will be carried out through an analytic hierarchy process with multiple decision-makers. This methodology was developed in the 1970s at the University of Pennsylvania by Thomas L. Saaty, with the goal of contributing to decision-making through the valuation and hierarchy of multiple objectives (even purely qualitative ones), creating a framework for prioritizing alternatives that meet them, based on the comparison of pairs of criteria.

The methodology, created by Saaty, is based on algebraic foundations, and subsequent developments have incorporated tools that allow extending this methodology to group decision-making, weighting the priorities of decision-makers based on their own individual hierarchizations (Saaty, 1989; Saaty, 2008).

This methodology is robust in that it provides mechanisms that allow reconciling different scales of priorities defined by the actors involved in the decision-making process and checking the internal consistency of the criteria hierarchy.

The hierarchy of criteria through the process described by Saaty consists mainly of the following steps:

1. Definition of the problem and determination of the type of information required.
2. Hierarchical representation of the problem. Definition of the ultimate goal, then the broad, intermediate objectives, and the alternatives.
3. Construction of a pairwise comparison matrix for the relative importance of criteria.

The matrix is constructed through the comparison of pairs of criteria, based on their relative importance. For each pair of criteria, the involved experts will individually attempt to determine the relative value of each criterion over the other, according to a comparative scale.

For the weighted version of this framework, individual scores are combined through the application of the AHP-derived weights, in order to calculate a composite score for the policy, project, or technology under assessment.

Annex 1 includes a detailed description of the process.

## 2.2 Framing questions

Each of the proposed dimensions include 4 questions, which can be answered "yes", "no", or "neutral or not applicable", and a value is attributed according to the framework detailed in the previous section.

I. Infrastructure and Technological Lock-in

- Does the option result in additional infrastructure development that enables increased fossil fuel production?
- Does the option target the use of hydrogen or derivatives in sectors where electrification is technically and economically feasible?
- Does the option include the overhaul or lifespan extension of infrastructure or assets extending fossil fuel production, transmission, or consumption?
- Can the option contribute to potentially extend the lifespan of GHG intensive infrastructure or facilities?

II. Institutional Lock-in

- Does the option increase the level of influence of fossil fuel incumbent stakeholders?
- Does the option increase institutional support to fossil fuel production, consumption, or the construction of GHG intensive assets?

- Does the option create or reinforce barriers to entry for new actors in the green hydrogen and PtX markets?
- Does the option perpetuate regulatory or market structures that disadvantage new, low-carbon hydrogen and PtX technologies?

III. Behavioural Lock-in

- Does the option increase the complexity of the decision-making process for the procurement of hydrogen, its derivatives or compatible assets?
- Does the option increase the uncertainty regarding future regulations or incentives for the adoption of demand-side PtX technologies or its alternatives? (i.e. does it result in a wait and see attitude?)
- Does the option reinforce industry habits biased towards fossil fuel technologies?
- Does the option decrease the competitiveness of direct electrification of industrial processes where this is technically and economically viable?

IV. Policy and Regulatory Lock-in

- Does the option create or maintain regulatory barriers that implicitly or explicitly favour continued investment in fossil fuel infrastructure?
- Does the option rely on carbon sources to produce hydrogen derivatives that would otherwise need to phase out to achieve net zero emissions by 2050?
- Does the option establish disadvantages through unequal regulatory or fiscal treatment compared to fossil fuel technologies?
- Does the option increase the complexity, cost, or timeframes for permitting and licensing processes for the development of new renewable energy or PtX projects, or the retrofit of existing facilities towards the production or use of hydrogen derivatives?

## 2.3 Final steps

The framework allows for a nuanced assessment by distinguishing between policies that actively contribute to overcoming carbon lock-in, those that are neutral, and those that may exacerbate the problem.

The output of the process should include a summary of the assessment results, including both the weighted (or unweighted) scores, and complementary qualitative insights, to present a nuanced view of the option's potential impact on carbon lock-in.

While the framework can be used to assess individual policy options and processes, the power of the analysis increases when it is used to assess different alternatives and relying in multiple and diverse stakeholders, which may have different priorities and opinions on how the different dimensions contribute to carbon lock-in.

The criteria for this framework and weighting should be regularly reviewed to incorporate new data, include change or update in national priorities and in commitments, technological advancements, and shifts in the energy landscape to ensure that the framework remains aligned with national and global sustainability targets.

# 3 Conclusions and recommendations

The current energy landscape is still reliant on fossil fuels, which poses significant barriers to the adoption of low-carbon technologies such as green hydrogen and Power-to-X (PtX).

Path dependence and carbon lock-in are deeply rooted in the energy sector of several countries, evidenced by existing infrastructures, institutional practices, price signals, market behaviours, and policy frameworks, even a cultural understanding and assessment of the issues, that favour the continued reliance on fossil fuels for energy purposes, exacerbated by increasing fiscal and macroeconomic imbalances.

In this context, decisions focused on short-term (mainly financial) benefits might compromise developing countries' ability to diversify their sources of income and to significantly contribute to the global action to address climate change while developing domestic value chains adapted to emerging technologies, such as hydrogen and PtX as well as resource endowment.

The development and application of the proposed evaluation framework provide a structured approach to understand the impacts of different potential policies and projects on carbon lock-in and to avoid or minimise increasing this dependence.

An effective implementation of this framework requires careful consideration of the long-term implications of energy choices, particularly in hard-to-abate sectors and in the context of the federal system's complexity.

Finally, while carbon lock-in can be unavoidable for some policy options preferred due to strategic or economic implications, or in the case of those considered relevant because of their potential short-term positive impacts in light of pressing macroeconomic circumstances, this framework can also be used to assess how different variations of a given policy option might increase flexibility and mitigate the risk of carbon lock-in through a sensitivity analysis which can be compounded with additional metrics, such as mitigation potential, government revenues, job creation and others.

# 4 Annex 1: Synthetic description of an application of the Analytic Hierarchy Process

The methodology proposed below is based on the principles of the Analytic Hierarchy Process (AHP) and Multi-Criteria Analysis (MCA). It is an approach that measures the extent to which different mitigation measures contribute to various criteria, weighting these criteria, and providing a ranking of measures based on their contribution.

This methodology is a useful tool for evaluating alternatives that involve multiple (and sometimes contradictory) objectives, high uncertainty, many stakeholders, and impacts that cannot be quantified monetarily.

Operationally, the proposed methodology for prioritizing mitigation measures is structured in 6 steps:

1. Establish the decision context
2. Identify and define the mitigation measures to be analyzed
3. Define the prioritization criteria to be considered for evaluating the mitigation measures
4. Rank the prioritization criteria, reflecting their relative importance in the decision-making process ("valuation")
5. Analyze the expected performance of each mitigation measure in relation to each criterion ("scoring")
6. Combine the criteria values and scores to obtain a final value for each measure

This process involves a "decision group" composed of experts who are responsible for valuing the criteria and scoring the measures in relation to the criteria.

The final product of this methodology is a "Contribution Matrix" and a ranked list of mitigation measures based on their contribution to the different criteria defined previously. Additionally, if information on timelines and investments is available, the result is a diagram that jointly visualizes the global contribution of each measure to the different criteria, its cost, and its execution time.

The methodology proposes two distinct stages. On one hand, the "technical stage" involves creating the Contribution Matrix by selecting the mitigation measures to be evaluated and the prioritization criteria against which the analysis will be developed. On the other hand, the "valuation and prioritization stage" involves the decision group valuing the criteria and scoring the mitigation measures according to their contribution to each of these.

Given that as the number of alternatives increases, the pairwise comparisons required for relative valuation can become excessively numerous, the final valuation of each criterion and the contribution of each measure to the different criteria are established by consensus, introducing a modification to the methodology proposed by Saaty. If consensus cannot be reached, the simple average criterion will be used.

The diagram in Figure 3 below illustrates the proposed methodology.

***Figure 3: Schematics of inputs and outputs resulting from the proposed methodology***

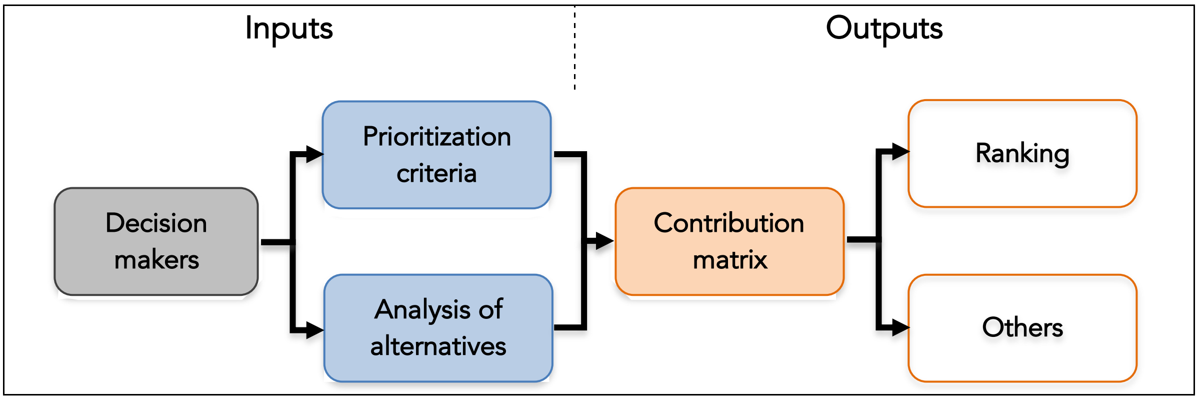


***Figure 4:** Inputs and Outputs of the Proposed Methodology*

| Inputs | Outputs |
|---|---|
| Relevant Stakeholders<br>Prioritization Criteria | Contribution Matrix<br>Analysis of Alternatives<br>Contribution Ranking |

### Step 1: Establish the Decision Context

First, the objective of the analysis must be defined, and the experts and decision-makers who will form the decision group must be identified.

### Step 2: Identify and Define the options to be Analyzed

The identification of the options to be prioritized

### Step 3: Define the Criteria to be Considered for Analyzing the Consequences of the options

The criteria used to prioritize the mitigation measures to be considered are grouped into three categories:

- Mitigation Potential
- Costs
- Co-benefits

The mitigation potential of each measure will be estimated according to the "Methodology for Estimating Mitigation Potentials", based on the reference technology (and emissions) being displaced, the rate of new technology adoption, and several other factors.

The costs of each considered mitigation measure will be estimated according to the "Methodology for Costing Mitigation Measures", based on the analysis of Investment and Financial Flows (I&FF).

The co-benefits considered for evaluating the contribution of different mitigation measures will be extracted from the "Methodology for Analyzing Co-benefits", which considers economic, social, and environmental benefits.

### Step 4: Ranking the Prioritization Criteria ("Valuation")

The valuation of the prioritization criteria will be carried out through an analytic hierarchy process based on the comparison of pairs of criteria according to the methodology developed in the 1970s at the University of Pennsylvania by Thomas L. Saaty.

In the context of this work, the valuations of experts within the framework of the analytic hierarchy process will be carried out by the relevant actors identified in Step 1.

The hierarchy of criteria through the process described by Saaty consists mainly of the following steps.

- Definition of the problem and determination of the type of information required.
- Hierarchical representation of the problem: definition of the ultimate goal, then broad intermediate objectives and alternatives.
- Construction of a pairwise comparison matrix for the relative importance of criteria through the comparison of pairs of criteria and ranking based on their relative importance to the decision-maker.

### Step 5: Analyze the expected performance of each mitigation measure in relation to each criterion ("scoring")

This step again involves the decision-making group. The experts are asked to assign a value from 1 to 10 (10 being the highest score) to each of the measures evaluated, based on their potential to satisfy the criteria defined in the previous step, regardless of the hierarchy of each of them. From this score, a matrix is obtained.

### Step 6: Combine the criteria values and scores to obtain a final value for each measure

The first step consists of obtaining the "contribution matrix". The coordinates of the contribution matrix are equivalent to the product between the score assigned to each alternative according to its contribution to the satisfaction of each criterion and the value obtained for that criterion in step 4.

Based on the sum of the contributions of each measure to the fulfillment of the different criteria, weighted by the relative importance of each criterion, the ranking of mitigation measures is obtained according to their overall contribution.

If data or estimates of costs and execution times for the different measures are available, a Contribution-Timeframe-Investment (C-P-I) diagram can be developed, which allows visualizing the relationship between the contribution of each alternative to the fulfillment of the criteria, its execution time and the investment required to carry them out.

An alternative to this is the C-R-I diagram, which replaces the investment term with the expected reduction in emissions.

# 5 References

Arthur, W. B. (1989). Competing technologies, increasing returns, and lock-in by historical events. The Economic Journal, 99(394), 116-131.

Belton, V. & Stewart, T. J. (2002) Multi Criteria Decision Analysis – An Integrated Approach, New York: Springer.

Bento, N. (2010). Is carbon lock-in blocking investments in the hydrogen economy? A survey of actors' strategies. Energy Policy 38 (2010) 7189–7199

Brezis, E. S., Krugman, P. R., & Tsiddon, D. (1993). Leapfrogging in International Competition: A Theory of Cycles in National Technological Leadership. The American Economic Review, 83(5), 1211–1219. http://www.jstor.org/stable/2117557

Carlino, H; Caratori, L and Carlino, M. (2024) Fiscal Federalism and Environmental Governance: Implications for the Development of Green Hydrogen in Argentina. PtX Pathways Project.

Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ). (2023). EU requirements for renewable hydrogen and its derivatives. International PtX hub.

Economic Consulting Associates. (2015) Carbon lock-in toolkit. Submitted to the Department for International Development of UK.

Eitan, A. and M. P. Hekkert (2023). Locked in transition? Towards a conceptualization of path-dependence lock-ins in the renewable energy landscape. Energy Research & Social Science.

Erickson, P., Kartha, S., Lazarus, M. and Tempest, K. (2015) 'Assessing carbon lock-in', Environmental Research Letters, 10(8), p. 084023. doi:10.1088/1748-9326/10/8/084023

Fisch-Romito, V., Guivarch, C., Creutzig, F., Minx, J. M. and Max W Callaghan. (2020). Systematic map of the literature on carbon lock-in induced by long-lived capital. Environ. Res. Lett. 16 (2021) 053004

Fundación Torcuato Di Tella. (2022). Elementos para una Estrategia Climática de Largo Plazo. Decarboost, 2022.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Research Policy, 31(8-9), 1257-1274.

Griffiths, S.; Sovacool, B., Kim, J; Bazilian, M.; Uratani, JM. (2021). Industrial decarbonisation via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options, Energy Research & Social Science 80 (2021) 102208

Grübler, A. (1998). Technological change. Annual Review of Energy and the Environment, 23(1), 217-262.

Haoqi, Q.; Libo W; Weiqi, T. et al. (2017). "Lock-in" effect of emission standard and its impact on the choice of market-based instruments. Energy Economics.

Hoffman, K. y Kunze, R. (1973) Álgebra Lineal, México D.F.: Prentice Hall.

IEA (2022). World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A).

IEA (2024). Renewables 2023. Analysis and forecasts to 2028

Jaffe, A. B., Newell, R. G., & Stavins, R. N. (1995). The energy paradox and the diffusion of conservation technology. Resources for the Future

Janipour, Z., et. al. (2020). What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production. Energy Research & Social Science.

Katz, M. L., & Shapiro, C. (1985). Network externalities, competition, and compatibility. The American Economic Review, 75(3), 424-440.

Kaya, F & Kader, R. (2021) Overcoming Lock-In and Path Dependency: Hydrogen Energy Transitions. Master's Thesis, KTH, School of Industrial Engineering and Management (ITM).

Klaus Goepel (2013) AHPcalc V 8.5.13, BPMSG.

Leleur, S. (2008) Principles and Methodology for Planning in a Complex World, Forlag: Polyteknisk.

Liebowitz, S. J.; Margolis, Stephen E. (1995). Path dependence, lock-in and history. Journal of Law, Economics, and Organization. 11: 205–226.

Narasimhan, R., Nair, A., Griffith, D.A., Arlbjørn, J.S. and Bendoly, E. (2009), Lock-in situations in supply chains: A social exchange theoretic study of sourcing arrangements in buyer–supplier relationships. Journal of Operations Management, 27: 374-389. https://doi.org/10.1016/j.jom.2008.10.004

New Climate Institute. (2023). The role of hydrogen in decarbonisation - investment opportunities for Latin America. Decarboost.

Oh, D. & Yeon, Y. (2022). Unveiling Fossil Greenwashing : Hidden Emissions of Korea's Hydrogen Scheme. Solutions for Our Climate (SFOC)

Pacheco, J.F y Contreras, E. (2008) Manual metodológico de evaluación multicriterio para programas y proyectos, Instituto Latinoamericano y del Caribe de Planificación Económica y Social (ILPES), Santiago de Chile, Naciones Unidas.

PNUMA (2004): "CDM Sustainable Development Impacts", Programa de Naciones Unidas para el Medio Ambiente (PNUMA), desarrollado para el proyecto PNUMA 'CD4CDM'

Potashnikov, V.; Golub, A.; Brody, M.; Lugovoy, O. (2022). Decarbonizing Russia: Leapfrogging from Fossil Fuel to Hydrogen. Energies 2022, 15, 683. https://doi.org/10.3390/en15030683

Rosenow, J & Lowes, R. (2021). Will blue hydrogen lock us into fossil fuels forever? One Earth. VOLUME 4, ISSUE 11, P1527-1529

Saaty, T.L. (2008) Decision making with the analytic hierarchy process, Int. J. Services Sciences, Vol. 1, No. 1.

Saaty, T.L. (2008) Decision making with the analytic hierarchy process, Int. J. Services Sciences, Vol. 1, No. 1.

Saaty, T.L. and Alexander, J. (1989) Conflict Resolution: The Analytic Hierarchy Process, New York: Praeger.

Saaty, T.L. y Alexander, J. (1989) Conflict Resolution: The Analytic Hierarchy Process, New York: Praeger.

Saaty, T.L. y Vargas, L.G. (2006) Decision Making with the Analytic Network Process: Economic, Political, Social and Technological Applications with Benefits, Opportunities, Costs and Risks, New York: Springer.

SAyDS. (2019). Guía para la elaboración de una Evaluación Ambiental Estratégica.

Secretaría de Energía (2023). Balance Energético Nacional 2022.

Seto, K., et. al. (2016). Carbon Lock-In: Types, Causes, and Policy Implications. Annual Review of Environment and Resources.

Simmie, S. (2012) Path Dependence and New Technological Path Creation in the Danish Wind Power Industry, European Planning Studies, 20:5, 753-772

Sutton, J. (2007). "Sunk Costs and Market Structure: Price Competition, Advertising, and the Evolution of Concentration," MIT Press Books, The MIT Press, edition 1, volume 1, number 0262693585.

UK DETR (2009) Multi-criteria analysis: a manual, Department for the Environment, Transport and the Regions, Reino Unido.

Unruh, G. C. (2006). Escaping carbon lock-in. Energy Policy 30 (2002) 317–325.

Zhu, Ying (2003) : Leapfrogging into hydrogen technology: China's 1990-2000 energy balance, WZB Discussion Paper, No. SP III 2003-116,Wissenschaftszentrum Berlin für Sozialforschung (WZB), Berlin