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# Pathways for the decarbonisation of hydrogen, steel and cement : a modelling-based approach integrating demand and production

Kimon Keramidas

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## THÈSE

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## Trajectoires pour la décarbonisation de l'hydrogène, de l'acier et du ciment : une approche de modélisation intégrant demande et production

### Pathways for the decarbonisation of hydrogen, steel and cement: a modelling-based approach integrating demand and production

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# Table of Contents

## Contents

Table of Contents.....	2
Abstract.....	5
Résumé .....	6
Acknowledgments.....	7
List of figures.....	8
List of tables .....	9
List of abbreviations.....	10
1. Introduction .....	11
1.1. The multidimensional challenge of climate change .....	11
1.2. Emissions reduction strategies and hard-to-abate sectors .....	13
1.3. Materials and climate change.....	14
1.1. Industrial sub-sectors and materials selection for this work.....	18
1.2. Outline.....	20
2. State of the art of the modelling of decarbonisation options in industry .....	21
2.1. Industry decarbonisation studies.....	22
2.2. Methods for estimating materials demand .....	24
2.2.1. Drivers for materials demand .....	24
2.2.2. Projecting demand in the future.....	26
2.2.3. Econometric methods.....	26
2.2.4. Economy-wide intensity methods .....	27
2.2.5. Bottom-up methods.....	29
2.3. Methods for estimating materials production and associated emissions.....	30
2.3.1. Drivers for process and site selection .....	30
2.3.2. Projecting production in the future .....	32
3. Methodology: representing materials demand and production in a long-term energy system model .....	36
3.1. Choice of the tool.....	37
3.2. Description of the initial version of the POLES model .....	37
3.2.1. Model overview .....	38
3.2.2. Model sectoral details.....	40
3.3. Added value of this work .....	42
3.4. Methodology principles for new work.....	43

4.	From climate science to policy: the virtuous cycle of the Paris Agreement.....	46
4.1.	Historical retrospective.....	47
4.2.	Energy and employment transition implied by climate policy pledges: informing the global stocktake of the Paris Agreement.....	51
4.3.	Conclusion: the need to bridge the gap in policy ambition.....	66
5.	Hydrogen: an accelerator of the energy transition?.....	68
5.1.	Hydrogen: another energy carrier necessary for decarbonisation?.....	69
5.2.	What is the business model for green hydrogen?.....	72
5.2.1.	Where will green hydrogen be needed?.....	73
5.2.2.	What are the drivers to make green hydrogen competitive?.....	77
5.3.	Conclusion: will the hydrogen economy materialize this time?.....	82
6.	Iron & Steel decarbonisation: the promises of innovation and circular economy.....	84
6.1.	A sector dominated by coal and electricity.....	85
6.2.	Opportunities and roadblocks in the decarbonisation of the global steel sector: a demand and production modelling approach.....	89
6.3.	Conclusion: prioritizing action to align low-carbon investments.....	108
7.	Cement decarbonisation: a silver bullet challenge?.....	110
7.1.	A sector where CO <sub>2</sub> emissions are inherent to the process.....	111
7.2.	Opportunities and roadblocks in the decarbonisation of the global cement sector: a demand and production modelling approach.....	116
7.3.	Conclusion: prioritizing action among potential disruptive innovations.....	136
8.	General conclusion.....	138
8.1.	Summary of findings.....	138
8.2.	Discussion and limitations.....	140
8.3.	Research outlook.....	144
	References.....	146
	Annexes.....	156
i.	Outreach activities.....	156
ii.	Supplementary information to article 1: Energy and employment transition implied by climate policy pledges: informing the global stocktake of the Paris Agreement.....	157
iii.	Supplementary information on hydrogen demand and production modelling.....	168
	Enhancements in this work.....	168
	Setup of Hydrogen demand parameters.....	168
	Setup of Hydrogen production parameters.....	171

iv. Supplementary information to article 2: Opportunities and roadblocks in the decarbonisation of the global steel sector: a demand and production modelling approach .....	174
v. Supplementary information to article 3: Opportunities and roadblocks in the decarbonisation of the global cement sector: a demand and production modelling approach.....	196
vi. Additional results on drivers, demand and stocks.....	209

## Abstract

Limiting climate change while also increasing quality of life and well-being in a sustainable manner poses multifaceted challenges. Global CO<sub>2</sub> emissions should be reduced to net-zero by around 2050 while the demand of energy-intensive and CO<sub>2</sub>-intensive material goods is expected to increase.

This work focuses on hydrogen, steel and cement, whose combined production processes release more than half of the CO<sub>2</sub> emissions of the industry sector. It presents work that enriches the detail of industry sub-sectors decarbonisation pathways and consists in the state of the art in the way these issues are represented in integrated assessment models.

A global multi-regional energy system simulation model was modified to represent detailed bottom-up estimations of materials demand and multiple material production pathways. The new model was used to produce long-term scenarios, with different sets of assumptions on policies, technologies and material demand patterns, projecting material, energy and emissions flows to 2100.

Demand for all three materials was found to increase in the coming decades (+300-470% for hydrogen, +11-65% for steel, +0-32% for cement, in scenarios compatible with 1.5°C climate change, in 2050 compared to 2020), with a saturation in the second half of the century for steel and cement. Thanks to a climate policy signal sustained over time, it is possible to substantially reduce CO<sub>2</sub> emissions in the production of these materials (to net-zero for hydrogen, -82-87% for steel, -0-91% for cement, in 1.5°C-compatible scenarios in 2050 compared to 2020), thereby significantly contributing to the decarbonisation of industry (provide 55-67% of total industry mitigation in 1.5°C-compatible scenarios in 2050; total industry reduces emissions by 50-80%).

This work identifies opportunities and roadblocks in the decarbonisation of the global hydrogen, steel and cement sectors, including estimates of the feedback of climate policy on their demand, the role of material efficiency measures, recycling, electrification, carbon capture and new energy vectors like hydrogen itself. It provides a wide picture of material-specific mitigation options, investment needs and the effects of policy levers that are of interest to both policymakers and investors.

## Résumé

Limiter le changement climatique tout en augmentant la qualité de vie et le bien-être de manière durable pose des défis sur plusieurs points de vue. Les émissions mondiales de CO<sub>2</sub> devraient être réduites à net-zéro d'ici 2050 environ, tandis que la demande de biens matériels à forte intensité d'énergie et de CO<sub>2</sub> devrait augmenter.

Ce travail se concentre sur l'hydrogène, l'acier et le ciment, dont les processus de production dans leur ensemble sont responsables pour plus de la moitié des émissions de CO<sub>2</sub> du secteur industriel. Cette étude présente des travaux qui enrichissent le détail des trajectoires de décarbonisation de certains sous-secteurs industriels et consiste en l'état de l'art de la manière dont ces questions sont représentées dans les modèles d'évaluation intégrée.

Un modèle de simulation du système énergétique mondial a été modifié pour représenter des estimations ascendantes détaillées de la demande de matériaux et des trajectoires de production, pour des matériaux multiples. Le nouveau modèle a été utilisé pour produire des scénarios à long terme avec différents ensembles d'hypothèses sur les politiques, les technologies et les tendances de demande de matériaux. Le modèle projette des flux de matériaux, d'énergie et d'émissions jusqu'en 2100 pour plusieurs régions mondiales.

La demande pour ces trois matériaux devrait augmenter au cours des prochaines décennies (+300-470% pour l'hydrogène, +11-65% pour l'acier, +0-32% pour le ciment, dans les scénarios compatibles avec 1,5°C de changement climatique, en 2050 par rapport à 2020), avec une saturation dans la seconde moitié du siècle pour l'acier et le ciment. Grâce à une pression de politique climatique soutenue dans le temps, il est possible de réduire considérablement les émissions de CO<sub>2</sub> liées à la production de ces matériaux (jusqu'à net-zéro pour l'hydrogène, -82-87 % pour l'acier, -0-91 % pour le ciment, dans des scénarios 1,5°C, en 2050 par rapport à 2020), contribuant ainsi de manière significative à la décarbonisation de l'industrie (contribuent à 55-67 % de l'atténuation totale de l'industrie dans des scénarios 1,5°C en 2050 ; l'ensemble de l'industrie réduit ses émissions de 50 à 80 %).

Ce travail identifie les opportunités et les obstacles à la décarbonisation des secteurs mondiaux de l'hydrogène, de l'acier et du ciment, y compris les estimations de la rétroaction de la politique climatique sur leur demande, le rôle des mesures d'efficacité des matériaux, du recyclage, de l'électrification, de la capture du carbone et des nouveaux vecteurs d'énergie comme l'hydrogène lui-même. Cette étude donne une vue d'ensemble des options d'atténuation spécifiques à chaque matériau, des besoins d'investissement et des effets de politiques énergie-climat ; les résultats seraient intéressants à la fois pour les décideurs politiques et pour les investisseurs.

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This work is dedicated to the next generation, who will live to see these years that we have been talking about for so long – 2050 and 2100 – and will know whether the net-zero emissions challenge will be met.

## List of figures

Figure 1: World materials extraction .....	16
Figure 2: World CO <sub>2</sub> emissions, 2018.....	17
Figure 3: World industry emissions (energy + process).....	19
Figure 4: Man in an industrial landscape .....	21
Figure 5: The 9R framework for a circular economy hierarchy of actions.....	25
Figure 6: Example of Intensity of Use shape used for cement .....	28
Figure 7: Example of Intensity of Stock shape used for steel, with annual flow (red, left axis) and stock per capita (black, right axis) .....	29
Figure 8: Good code flow chart.....	36
Figure 9: POLES model general scheme.....	38
Figure 10. POLES model regional detail map.....	39
Figure 11: Schematic representation of depreciation and investments in POLES .....	40
Figure 12: Schematic view of the materials module of POLES for this work.....	43
Figure 13: Warming stripes of global temperature change (1850-2022) .....	46
Figure 14: GHG emissions under different scenarios and the emissions gap in 2030.....	48
Figure 15: World GHG emissions projections and resulting global mean temperature change with current, announced and Paris Agreement-compatible climate policies .....	49
Figure 16: Photo of the Apollo 13 spacecraft .....	68
Figure 17: Schematic of the functioning of the hydrogen economy .....	71
Figure 18: RD&D budget on hydrogen and fuel cells.....	72
Figure 19: Global demand for pure hydrogen, 1975-2018.....	73
Figure 20: World nitrogen-fertilizer use across different climate policy scenarios (left) and marginal abatement cost curves for select years (right) .....	74
Figure 21: Projections of hydrogen demand by end-use, world, Ref and 1.5°C scenarios.....	76
Figure 22: Schematic of the hydrogen production processes modelled in POLES .....	77
Figure 23: Hydrogen direct and indirect emissions (left-hand axis) and energy inputs (right axis), 1.5°C scenario, USA .....	79
Figure 24: Hydrogen production mix (left) and carbon content of hydrogen produced (right), World .....	80
Figure 25: Production costs of select hydrogen production processes.....	81
Figure 26: Urban landscape .....	84
Figure 27: Global steel production, 1930-2020 .....	85
Figure 28: World steel production, by process, 1980-2020.....	87
Figure 29: Construction materials, including mortar, arranged like a painter’s palette .....	110
Figure 30: Global cement production, 1950-2020.....	112
Figure 31: Schematic of the cement production process .....	113
Figure 32: Distribution of clinker production by process (GNR members, left; China, right).....	115
Figure 33: Global emissions by industry sub-sector, over time for 15C_CCS scenario (left) and in 2050 (right) .....	139
Figure 34: Production of nitrogen-based fertilizers (left axis) and production of hydrogen for ammonia (right axis) .....	169
Figure 35: Correlation between hydrogen for refineries and demand for diesel, world .....	170
Figure 36: Correlation between hydrogen for refineries and chemical industry value added, world.....	171

Figure 37: Main drivers for materials demand, 15C_CCS scenario.....	209
Figure 38: Schematic for the estimation of annual materials demand in POLES, India, buildings .....	210
Figure 39: Stocks per capita for steel (left) and cement (right), 15C_CCS scenario .....	211
Figure 40: Annual steel demand and total steel stock in use for China .....	212

## List of tables

Table 1: Main industry model characteristics of select integrated assessment models .....	34
Table 2: Hydrogen production processes efficiency (hydrogen output/energy inputs) .....	172
Table 3: Overnight investment costs for hydrogen production processes (USD/kW).....	172
Table 4: Key figures on hydrogen production.....	173

## List of abbreviations

BECCS	Bio-Energy for CCS
BF-BOF	Blast Furnace with Basic Oxygen Furnace (steelmaking process)
CCS	Carbon Capture and Sequestration
(B)CE	(Before) Common Era
CGE	Computable General Equilibrium (model type)
CO <sub>2</sub>	Carbon dioxide (molecule)
COP	Conference of Parties (UNFCCC)
DACCS	Direct Air Capture for CCS
DRI	Direct Reduction of Iron (steelmaking process)
EAF	Electric Arc Furnace (steelmaking process)
EU	European Union
G20	Group of 20 largest economies
GDP	Gross Domestic Product
GHG	Greenhouse gas
GJ	Giga Joule
GNR	Getting the Numbers Right (Global Cement and Concrete Association)
GW	Giga Watt
H <sub>2</sub>	Hydrogen (molecule)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IT	Information Technology
JRC	Joint Research Centre of the European Commission
kWh	Kilo Watt-hour
LULUCF	Land Use, Land Use Change and Forestry
Mt	Mega Tonne
(I)NDC	(Intended) Nationally Determined Contribution (UNFCCC)
NET	Negative Emissions Technology
OECD	Organisation for Economic Cooperation and Development
OPC	Ordinary Portland Cement
POLES	Prospective Outlook for Long-term Energy Systems (model)
PV	Solar Photovoltaics
R&D	Research and Development
RD&D	Research, Development and Deployment
SDG	Sustainable Development Goal
SMR	Steam Methane Reforming
SSP	Shared Socioeconomic Pathway
TRL	Technology Readiness Level
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USGS	United States Geological Survey

# 1. Introduction

## 1.1. The multidimensional challenge of climate change

We are living in a time when the issue of anthropogenic climate change is a major societal concern. Human activities have become such a dominant force in shaping the Earth's climate, environment and ecosystems that the term “Anthropocene” has been proposed to define the geological era in which we live in, succeeding or supplanting the Holocene. The mode of development pursued by all world countries has collectively resulted in serious effects on the global environment, with several planetary boundaries, i.e. “processes that are critical for maintaining the stability and resilience of Earth system”, already having been exceeded [1]. Along with the wider issue of sustainable development, climate change is perhaps the defining matter of our time.

This has been a long time coming. Globally, but more particularly in the countries of the Global North, the post-World War II period of 1940s to 1970s was marked by an unprecedented increase in material wealth and in energy consumption. The independence movements in the Global South saw the emergence of the system of national oil companies and international oil companies, a heritage of the colonial period, which still exists today. Expectations of the future were of a continued and eternal “progress”, that science would solve any problem of the human condition and that the next step for humanity would be space exploration. The 1970s saw the first dents in this optimistic outlook for human development, with the oil price shocks and the threat of inflation being the impetus for trying to do more with less. In what could be called a first wave of state intervention in energy markets, this period saw countries adopt energy policies related to energy efficiency (vehicle fuel economy standards) as well as energy conservation (vehicle speed limits, information campaigns on household energy consumption). The International Energy Agency, representing the interests of its member countries which are mainly developed economies and mainly energy importers, was created during that time. By extension, the following decades saw energy diversification towards fossil gas and nuclear power.

Even though the basics of greenhouse gases’ (GHGs) effect on atmospheric chemistry and temperature were known since the 19<sup>th</sup> century, and although the issue of human-caused climate change was put forward as a major concern by scientists to public bodies already in the 1970s – with the 1972 “Limits to Growth” report on the environmental consequences of unchecked growth, commissioned by the Club of Rome think tank, and a 1977 memorandum on the hazard of catastrophic climate change to the United States President by the chief science advisor – it was only in the 1990s that organized international forums started emerging.

The United Nations Framework Convention on Climate Change (UNFCCC), established in 1992, marked a significant step in addressing climate change at the international level, recognizing the importance of global cooperation. It laid the groundwork for subsequent agreements, with annual Conference of Parties (COPs), which culminated in the landmark Paris Agreement at COP21 in 2015, where the near-totality of the world’s countries pledged to limit global warming to well below 2 degrees Celsius above pre-industrial levels.

This increase in importance has developed hand in hand with the scientific consensus on the causes – and solutions – to climate change. The Intergovernmental Panel on Climate Change was established in 1988; throughout the years, its periodic Assessment Reports have offered snapshots of the increasing confidence with which the scientific community, composed of thousands of members

worldwide, has detected the existence of climate change and has attributed it to anthropogenic factors. This attribution increased from “likely” in 2001 (greater than 66% probability, Third Assessment Report) to “very likely” in 2007 (greater than 90% probability, Fourth Assessment Report) to “extremely likely” in 2014 (95-100% probability, Fifth Assessment Report) to “unequivocal” in 2021 (Sixth Assessment Report).

Still, climate change is but one element of a more complex puzzle of the future development of human societies and their relationship with the environment. Again, discourse around these concepts was spearheaded by and coalesced around United Nations initiatives. The Brundtland Commission, with its 1987 report on “Our Common Future”, played a crucial role in defining the need for sustainable development, emphasizing the concepts of basic needs for decent living as well as the limits imposed by a finite Earth. The concepts of inter-country equity as well as inter-generational equity would also enter the discourse in the debates about responsibility for solving the climate change issue. This report was followed by the Agenda 21 action plan in 1992, the Millennium Development Goals (MDGs) in 2000 and the Sustainable Development Goals (SDGs) in 2015.

In the MDGs, the issue of climate change was primarily addressed in Goal 7 on environmental sustainability. The MDGs recognized the importance of integrating climate action into broader development efforts, emphasizing the need for countries to adopt sustainable practices and reduce greenhouse gas emissions to combat climate change. However, the approach to climate change in the MDGs was somewhat limited in scope.

In the SDGs, climate action became a standalone goal, SDG 13. The SDGs emphasize the importance of mitigating greenhouse gas emissions, adapting to the impacts of climate change, and mobilizing resources to support climate action in developing countries. Moreover, the SDGs emphasize the interconnectedness of various global challenges, acknowledging that climate action is closely linked to poverty reduction, gender equality, clean energy, and responsible consumption and production. As a result, climate change is now firmly embedded in the global development agenda, reflecting a more holistic approach to achieving a sustainable future.

Today, the issue of climate change has become an agenda item for domestic policy as well as for international policy. For instance, in 2023, “European citizens identify climate change as the third most serious problem facing the world after poverty, hunger and lack of drinking water, and armed conflicts” [2]. The term “climate diplomacy” has emerged to describe a new form of way to conduct foreign policy, and climate-related discussions encompass an agenda from intellectual property of new technologies to financial transfers from rich to poor countries to support the effort of emissions reductions. Climate change has become a central question of our times, mobilizing the scientific community, policymakers, businesses and civil society alike. The Paris Agreement of 2015 defined a legal framework within which countries regularly submit their nationally determined contributions (NDCs) for greenhouse gases (GHG) mitigation by 2030, with increasing ambition as time passes; in 2020-2021 they are also expected to submit long-term strategies with a longer time horizon (2050 and beyond). Several large economies have announced long-term objectives to reach net-zero emissions in the coming decades, such as the EU and the USA (for 2050), China (for 2060) and India (for 2070). These aspirational goals have to be translated into concrete plans of action that can be implemented by each country or sector of the economy.

## 1.2. Emissions reduction strategies and hard-to-abate sectors

International treaties and cooperation on cross-border environmental issues have other precedents that have been successful. After concerns raised by scientists in the 1980s, the 1987 Montreal Protocol aimed at reducing the release of substances causing the depletion of the Earth's ozone layer. Action was quick; concentrations of ozone-depleting gases quickly peaked in 1997 and since then have dropped significantly, by 51% below peak in 2022 [3]. Despite this success, the time scales involved are important to underline. Mid-latitude concentrations of these gases are expected to return below 1980 levels by around 2050, about half a century after their peak; time scales are even longer for Arctic concentrations.

However, part of the reason of this success was the readily available technical solutions to the problem: the ozone-depleting (hydro)chlorofluorocarbons were replaced by hydrofluorocarbons, which in turn are being replaced by other chemicals (given these gases' additional role as contributors to global warming) while largely keeping the rest of the equipment and infrastructure associated with their use. The same cannot be expected to happen with the same ease for climate change. The main contributor to climate change, carbon dioxide (CO<sub>2</sub>), is mainly the result of combustion of fossil fuels, which are used in all human activities since the industrial revolution of the latter 18<sup>th</sup> century. A simple substitution of a single component is not the issue; the way that the energy system is constituted by a dense network of processes and interconnections makes this a very complex issue.

An increasing number of studies have attempted to provide solutions to the problem of how to reduce climate change-inducing greenhouse gas emissions. The prioritization between short-term and long-term action, the relative importance of sectors in the overall reduction, and the recommendations on what public policy should do, have all changed over time due to a number of factors. The data and knowledge around these issues has become better, the costs of options and their expected evolution are constantly changing, and the window of acceptability within which policy acts has experienced both periods of shrinking and growing.

The current consensus of key priorities for reducing GHG emissions focuses on four main levers [4]–[7], with all four needing a mobilization of investments at a wider scale than in the recent past:

- Limiting energy demand, by a combination of technological energy efficiency and behaviour change towards energy sufficiency, that leads to energy conservation;
- Shifting energy demand towards electricity and new synthetic energy vectors such as hydrogen; for this, key enablers in final demand sectors are batteries (notably thanks to their decreasing cost, enabling stationary electricity storage and electric vehicles in road transport) and heat pumps (space heating and cooling in buildings, together with the proven concept of the near-zero or positive energy building);
- Decarbonising the power sector, with a shift towards low-carbon power generation (notably thanks to the decreasing costs of wind and solar).
- Decarbonising the production of synthetic energy vectors such as hydrogen<sup>1</sup>, with a shift towards production using renewables.

While the above solutions are not the only possible ones in their respective sectors, they are expected to play major roles. This combination provides for substantive reductions that can be achieved in a

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<sup>1</sup> Hydrogen and hydrogen-derived energy vectors (ammonia, synthetic methane, synthetic liquid hydrocarbons)

timely manner and at an affordable cost, or at least comparatively cheaper. The remaining emissions are more challenging to decrease or eradicate, due to the higher cost of alternatives, the lack of technical solutions altogether or the challenges related to reducing the demand for the services and products provided by these sectors. These hard-to-abate sectors are agriculture, international transport (aviation, shipping) and industry.

The residual emissions give rise to the need for negative emissions technologies (NETs) that would actively draw down carbon dioxide from the atmosphere and store it, either in the form of vegetation (reforestation, landscape restoration) or in underground deposits (chemical capture of CO<sub>2</sub> from point sources or directly from the air). These present their own challenges in terms of side-effects, infrastructure needs and scalability. While they could be part of the solution, it is important to pursue emissions reductions in all sectors to reduce the need to rely on NETs [4], [8].

For aviation and shipping, new synthetic fuels derived from hydrogen or bio-sourced materials are touted as possible solutions. After technological breakthroughs in power, transport, and buildings, the decarbonisation of industry is the next step.

In the case of industry, this difficulty in reducing emissions arises from several factors: the underlying drivers for emissions, the demand for industrial products, are strongly increasing globally; several industrial processes involve high temperatures, and fossil fuels are particularly well-suited to provide this concentrated energy; certain processes (e.g., cement manufacturing, fertilizer and plastics production) inherently result in CO<sub>2</sub> or other GHG emissions as part of their chemistry (“process emissions”).

For industry, past environmental regulations have focused on the chemical and atmospheric (non-GHG) pollution emerging from industrial activities. Whatever reduction of CO<sub>2</sub> has happened, it mostly occurred as a side-effect of increased energy efficiency, itself being motivated by economic concerns: industry is a sector that is particularly exposed to international competition, resulting in an important pressure for facilities to be as efficient as possible or face closure and delocalisation.

Stronger reductions in CO<sub>2</sub> will thus require a deeper reorganisation of the industry. In order to best capture how the industry should move forward, it is important to address all these factors – demand for products, suitability of alternatives for high-temperature processes, mitigation of process emissions, and affordability – in an integrated manner.

### 1.3. Materials and climate change

Limiting climate change and reaching the Sustainable Development Goals (SDG) while at the same time increasing well-being poses multifaceted challenges to all aspects of human activities. Historically, higher income levels and well-being have been correlated with an increase in the demand of material goods, and more specifically of goods that are energy-intensive and CO<sub>2</sub>-intensive in their production.

With the increase of living standards and the rise of widely available consumer products after the second world war and with the rapid rise of middle-income countries, the world has been using more “stuff”. Fuelled by cheap energy and a favourable institutional environment, raw and intermediate materials and finished products are typically transported across the world as supply chains have

lengthened and have come to include more geographical sites, resulting in countries with complex and specialized economies. This process is generally designated as “globalization”.

This correlation will not necessarily hold in the future, as emerging economies do not need to follow the developmental pathway of already developed economies. “Low-tech” solutions have gained interest from civil society in Global North economies, popularizing the “do-it-yourself” approach and giving importance to social connections as well as local manufacture and durability [9]. Whether that will have a significant impact on materials use as a whole remains to be seen. It has also been suggested that countries with later economic development can occasionally skip certain development stages, thereby avoiding certain investments, and directly adopt the latest technologies available, resulting in a new development path – the idea of “leapfrogging” [10]. While there are successful examples of this, they often deal with information technologies and telecommunications or energy efficiency in rural areas; whether that can translate in significant materials savings is the topic of forward-looking studies that examine urban and spatial planning [11] or posit a relative decorrelation between economic growth and materials use [12]. Substitution of one material with another could change the demand prospects of individual materials significantly (for instance, wood products in construction [13], [14]), but it does not necessarily follow that the total material throughputs of the economy would decrease.

With large parts of the world population still to lift out of poverty and with a growing purchasing power of the middle and high income parts of the population, this process is not expected to reverse course. Consequently, the demand for materials is expected to continue increasing. According to the United Nations’ Environment Programme [15], the production of metal ores and non-metallic minerals is projected to more than double over the next 40 years, from 49 Gt in 2015 to 126 Gt in 2060 in a “Historical Trends” scenario where past relationships between materials use, economic growth and environmental indicators are kept (see Figure 1). Even in a “Towards Sustainability” scenario where a number of policies would be pursued “to improve resource efficiency, decouple economic growth from environmental degradation and promote sustainable production and consumption” (including policies towards 1.5C climate change), materials demand would be lowered, but it would still represent a doubling compared to 2015, at 104 Gt.

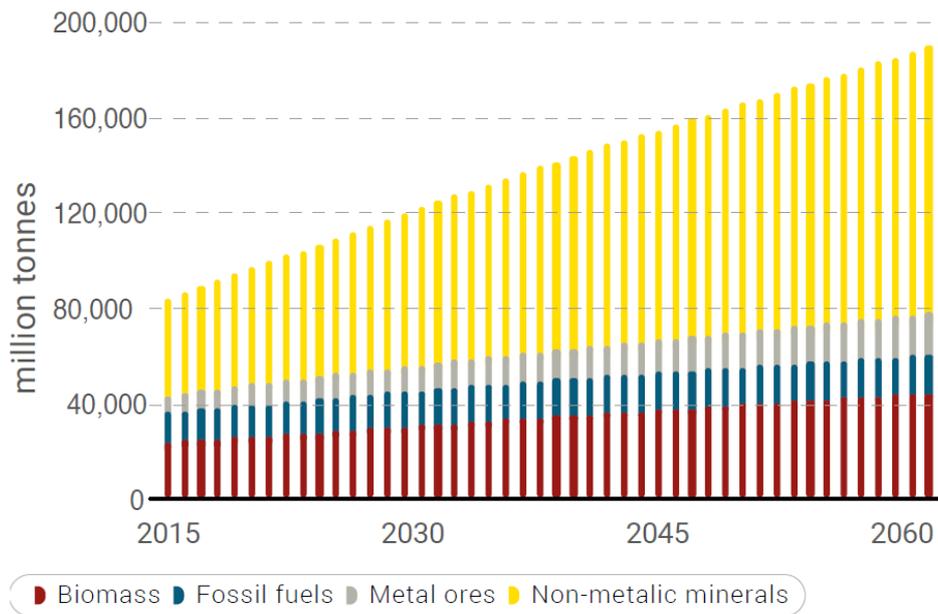


Figure 1: World materials extraction

Source: UNEP [15].

Moreover, non-energy materials production is responsible for a sizeable share of global CO<sub>2</sub> emissions and a large share of industrial CO<sub>2</sub> emissions [16] (see Figure 2). With growing materials demand, associated emissions are set to grow accordingly unless action is taken. The industrial sector is both an economic driver and a major emitter of greenhouse gas (GHG) emissions; however, GHG emissions are only one of the dimensions around which industry sector decisions are taken: an industrial strategy has multiple considerations, including those related to employment, trade balance, technological pioneering and specialization, defence and security, and others.

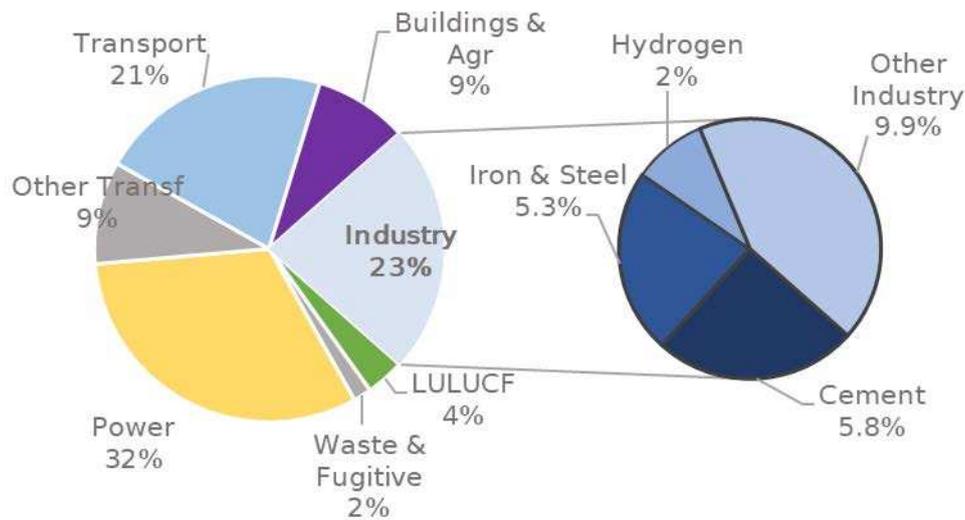


Figure 2: World CO<sub>2</sub> emissions, 2018

Note: Hydrogen emissions correspond to production of hydrogen as a feedstock or intermediate product for other industrial processes and products. Source: JRC Global Energy and Climate Outlook [17].

At the same time, the increasing importance of dealing with climate change has changed how state actors and industrial actors perceive the future. The ambitious 1.5°C target of the Paris Agreement came as a game-changer in how to approach projections of the future global energy system. Pathways to very deep emission reductions have to be examined much more closely taking into account as much as possible interactions of the energy system with other systems: social indicators, environmental indicators, physical flows, etc. The urgency of limiting climate change closes the era of cheap carbon-rich energy, with unclear implications on how labour and industrial production are organised at an international level.

The rationale of this work posits that the global future increase in quality of life and well-being should not be prevented by the global efforts to transition to a low-carbon/low-GHG economy. Thus, the question arises: **is it possible to reconcile increase in well-being for all (and associated materials demand increase) with aspirations of decarbonisation of the world economy?** Which materials would have to be examined in priority, and how one would go about representing them in a quantified way?

Global and regional pathways to decarbonisation should cover both aspects of materials **demand-side** (new uses, use efficiency, substitution) and **supply-side** of materials production (recycling, retrofitting existing capacities, new more efficient technologies, penetration of clean fuels).

The main goal of this work will be charting a way forward to ensure the industry energy transition in parallel with changes in the energy supply as required by the regional and global effort of decarbonisation. This work proposes to tackle these issues of demand and supply in an integrated way within an energy system model. The resulting projections of materials, energy and greenhouse gas emissions would be self-consistent; with a richer technological representation, they would provide a more precise picture of investment needs and the effects of policy levers that would be of interest to both policymakers and investors.

## 1.1. Industrial sub-sectors and materials selection for this work

The production of materials for semi-finished and finished goods is associated with industrial sub-sectors. Each material and sub-sector presents specific challenges in decarbonisation.

The public discussion on materials as strategic resources has often focused on materials with a relatively small-size market and associated to fast-growing high-tech industries (see the EU's regularly updated list of Critical Raw Materials [18]). Such materials are lithium and rare earth minerals.

Another group of materials are the base materials, which have a larger market in volume, and underlie many basic economic activities, from infrastructure to energy-consuming equipment. Such materials are steel, cement, glass, aluminium, copper.

Out of all the materials and industry sub-sectors, a select few were chosen for this study following certain criteria. The criteria considered were:

- How **critical** is the material to the economy? The concept of criticality can refer to its importance in a region's economy (in terms of associated economic activity, jobs or exports) or to its potential scarcity (geological scarcity or market scarcity due to above-ground bottlenecks, be they geopolitical or related to infrastructure). Widely used materials, or "base" materials, such as cement, steel, aluminium and glass, are essential in many activities but they are not scarce. "Niche" materials can be of paramount importance in specific sectors, such as neodymium for electric motors or germanium and gallium for semiconductors; they have smaller markets in volume but their supply is concentrated in few areas, making them potentially critical [19].
- How **energy-intensive** and **carbon-intensive** is its production? Such materials will be particularly targeted in the effort to reduce greenhouse gas emissions in the decarbonisation of the economy. Energy-intensive materials are often carbon-intensive as well due to the use of fossil fuels in their production, but not necessarily: certain materials can use a large amount of electricity (which can be low-carbon), such as aluminium. Materials that are associated to electricity-intensive processes are responsible for indirect emissions: the responsibility of their decarbonisation falls upon the power sector.
- As a corollary, the level of **enthalpy** needed for the production process can be important for the ease of decarbonisation. Low-enthalpy processes need lower temperatures, which can be more easily achieved with the use of electricity, for instance in the food and drink industry (<400 °C). High-enthalpy processes offer specific challenges where electrification is more difficult, such as in a cement kiln (1200-1800 °C) [20].
- Within a sector, how **heterogeneous** are the products and the processes? A sector with multiple products that each has distinct production processes is more complex to represent than one where the bulk of energy and emissions come from a single product and a single process. For instance, most (74%) of the energy consumption of the chemical sector in the EU over 2000-2015 came from the production of a handful of basic chemicals [21], but the remaining energy consumption refers to the production of thousands of specialized chemicals.

- Are **new and emerging uses** to be expected? Of particular interest, the low-carbon transition is expected to have a significant impact on specific materials due to the penetration of new technologies such as batteries for electricity storage (lithium), fuel cells (platinum), photovoltaic power (gallium) or nuclear power (zirconium) (see the regularly updated list of Critical Raw Materials of the European Commission [22]).

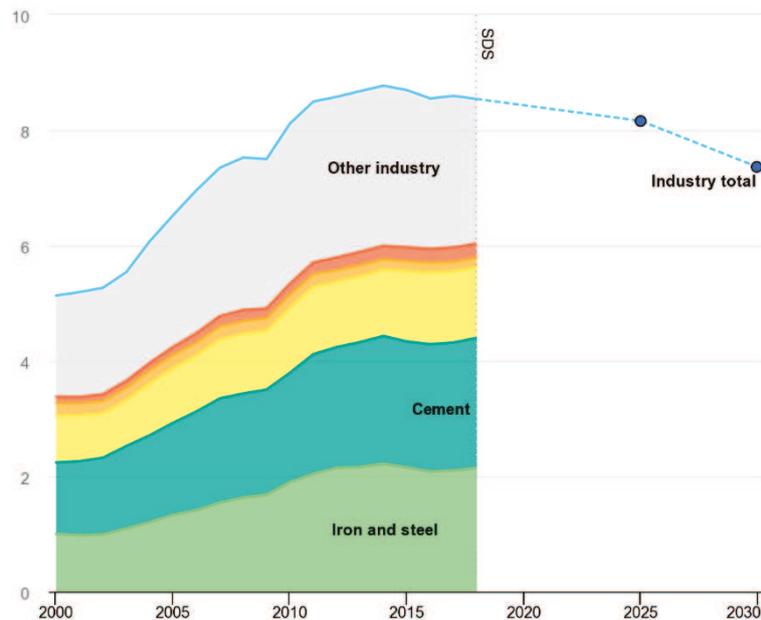


Figure 3: World industry emissions (energy + process)

Source: IEA, Sustainable Development Scenario [16]. From bottom to top: Iron and steel; Cement; Chemicals and petrochemicals; Pulp and paper; Aluminium; Other industry.

In the context of decarbonisation scenarios, the contribution of each sector to total emissions is very important. Out of total industry emissions (Figure 3), two materials stand out, **cement** and **steel**, each responsible for about a quarter of industry's emissions at the global level [16]: cement 2.3 GtCO<sub>2</sub> (6.7% of global CO<sub>2</sub><sup>2</sup>) and iron and steel 2.1 GtCO<sub>2</sub> (6.4%).

Beyond these two, the industry sector is very heterogeneous and the emissions contribution of individual sub-sectors is much smaller; for instance, the third most emitting sector, chemicals and petrochemicals, consists of thousands of products. Nevertheless, within chemicals, **hydrogen** was chosen as it finds itself at the crossroads of several issues. Depending on its use, hydrogen is a gaseous feedstock or an energy carrier, and so not exactly a "material". It is both an input to other industrial processes and an energy vector whose use is projected to grow significantly in the future. It is an intermediate product in the production process of nitrogen-based fertilizers, which is responsible for a sizable share of the chemicals industry emissions. Of the 1.2 GtCO<sub>2</sub> of emissions of the chemicals and petrochemicals sector [16], some 0.8 GtCO<sub>2</sub> are due to hydrogen production [23], itself mostly associated with ammonia and nitrogen-based fertilizers.

<sup>2</sup> CO<sub>2</sub> from energy combustion and industry, i.e. excluding land use CO<sub>2</sub>.

Other candidate materials are paper (0.3 GtCO<sub>2</sub> and 0.7% of global CO<sub>2</sub>), aluminium (0.2 GtCO<sub>2</sub> and 0.6%), glass (0.1 GtCO<sub>2</sub> and 0.4%), copper (0.1 GtCO<sub>2</sub> and 0.2%) and, both energy-intensive and widely used (see [16], [24]–[26]).

Certain other materials are projected to become increasingly important in low-carbon futures, such as lithium. However, their overall production process would result in relatively few emissions compared to the above materials, even if their production were to rise in the future; their use would result in other types of environmental issues such as chemical pollution and water use, not directly related to carbon and climate change.

In order to limit the scope and ensure that the chosen materials will be represented in a sufficiently detailed manner, we decided to focus this research work on just these three items: **hydrogen, steel and cement**.

## 1.2. Outline

The main part of this work is constituted by three articles submitted to scientific journals, each focusing on: energy and climate policies modelling; steel decarbonisation; and cement decarbonisation. An additional section focuses on hydrogen decarbonisation.

This document is structured in the following way:

- Section 2 presents the state of the art in industry decarbonisation studies, with a particular focus on the methodologies used to model materials demand and production.
- Section 3 presents the modelling tool that was selected for this study and the common modelling principles used for the demand and production of the selected materials.
- Section 4 presents an application of the modelling tool in the context of increasing ambition of climate policies worldwide.
  - It features the article *Energy and employment transition implied by climate policy pledges: informing the global stocktake of the Paris Agreement*.
- Sections 5, 6 and 7 then go into the detailed data and modelling work that went into each of the three industry sub-sectors – hydrogen, steel and cement – discussing views on the measures, investments and energy requirements for the decarbonisation of each.
  - Section 6 features the article *Opportunities and roadblocks in the decarbonisation of the global steel sector: a demand and production modelling approach*.
  - Section 7 features the article *Opportunities and roadblocks in the decarbonisation of the global cement sector: a demand and production modelling approach*.
- Finally, the conclusion, Section 8, brings together the key findings, looks at the main messages emerging from this study and what additional work could be envisaged.
- In the Annexes, supplementary material from the above work and articles provide more in-depth explanations on methodology, data sources and assumptions.

## 2. State of the art of the modelling of decarbonisation options in industry

“Reason shapes the future, but superstition infects the present.”  
- “*The State of the Art*” (1989 novella by Iain M. Banks, UK)



*Figure 4: Man in an industrial landscape*

*Source: Still from “Eraserhead”, 1977 film, directed by David Lynch, USA. Industry produces its own aesthetics.*

## 2.1. Industry decarbonisation studies

We conducted a horizon scanning of existing approaches on the issue of industry decarbonisation. Previous modelling work in this field has usually focused on a particular aspect of the problem. Many studies for the decarbonisation of industry exist, showing that this is technically and economically feasible, however each study had a specific methodology which presents its own strong and weak points.

In the literature, several studies use methods that are more adapted to other fields of study rather than strictly decarbonisation. Industrial Ecology (IE) methods aim at analysing the biophysical basis of supply chains and estimating environmental, economic and social impacts. They include environmental impact analysis studies tracking a particular product using **Life Cycle Assessment** (LCA; e.g., ecoinvent database [27]) and detailed engineering and accounting work tracking a particular material using **Material Flow Analysis** (MFA; e.g., copper flows analysis [28]). They are particularly suited for analysing an industrial sector and the sources of its emissions. Such methods are often static (a snapshot in time) and do not represent the dynamic transformation that would be needed for decarbonisation. Recent efforts have attempted to bring the industrial ecology world and the integrated assessment modelling world closer together [29], and this work forms part of this effort.

A simple method for obtaining projections of materials demand is to make use of the **IPAT method**<sup>3</sup>, or Kaya decomposition, wherein demand is the result of three basic drivers: population, economic growth (GDP) and material intensity of the economy. Expert judgement in the evolution of each of these drivers serves to build projections. This was used by the United Nations' International Resources Panel in their Global Resources Outlook [15] to produce multiple scenarios for several types of materials. There was no estimation of the costs and the associated industry energy use and emissions. Such scenarios are useful for illustrative purposes (see Figure 1).

The industry itself or think tanks have conducted studies and published **roadmaps**, which provide methodologies to introduce sustainability concerns in business practices, and are often aspirational rather than quantitative (e.g., World Business Council for Sustainable Development business association SDG Sector Roadmaps in 2018-2019 [30], Climate Strategies think tank report on climate-neutral industry in 2019 [31]). However, this is changing and more detailed studies have emerged. Oftentimes, the quantification is there but the model and method is not transparent (Material Economics 2018 report on circular economy [32]). Other times, the quantification is a result of gathering techno-economic elements and building scenarios based on expert judgement and stakeholder review, without an integration in a cross-sectoral model (studies on the decarbonisation of German and European industry in 2019 and 2021 [33]). The above is targeted at business investors and serve to prove the business case and technical feasibility of decarbonisation strategies, but the information they use is not completely transparent. Yet more recent studies are based on ad hoc modelling which is entirely open source (Mission Possible Partnership study on steel in 2022 [34]).

**Technological bottom-up models** can provide a very detailed view of the current configuration of industry sub-sectors; they include a high level of detail of processes, sub-processes, equipment and energy and emissions savings measures. They can project possible energy and emissions savings by making assumptions on the evolution of all the bottom-up drivers. Model setups with different

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<sup>3</sup> Impact (tons) = Population (capita) \* Affluence (GDP/capita) \* Technology (tons/GDP)

configurations result in different outputs for comparison. Such a model is the FORECAST model by Fraunhofer ISI [35], which was used to advise the European Commission [36]. They present the drawback that economic parameters are not part of the decision-making process; economic metrics are calculated ex-post, as a result of the technical choices.

Also of interest in this category, Madeddu et al. (2020) [20] assessed the technical potential for additional industry electrification in the EU. The wider use of existing electric technologies (heaters, boilers) in established applications and the use of new electric technologies (high-pressure heat pumps, electric kilns) in new applications could significantly reduce the reliance on combustion fuels. Though methodologically significant for subsequent use for projections, this study did not make use of modelling.

In addition, as interest in decarbonisation has increased, a number of **simple tools** have emerged that allow non-specialist users to build scenarios of emissions by manipulating simple assumptions. One such tool is PROSPECTS+, developed by NewClimate Institute and the Climate Action Tracker team (NewClimate Institute, Climate Analytics, Ecofys) [37]. It has been used to analyse the decarbonisation potential of the steel and cement industries [38]. It uses a simple intensity of use curve as a driver for demand (see section 2.2.4) and exogenous drivers for process mix, energy intensity and emissions intensity. It does not include any economic dimensions.

There are examples of materials use introduced in **computable general equilibrium** (CGE) models to project materials demand. Such work relies on social accounting matrices (SAMs) or multi-regional input-output (MRIO) tables, which add a materials dimension on economic flows: for each output (in monetary terms) of one sector that is used as input in another sector, a material content (or any other environmental metric) per unit of output is assigned. Such an environmentally-extended MRIO database is EXIOBASE [39]. The materials demand is indexed to the economic flows, which are projected by the CGE model; materials demand can increase or decrease depending on structural change and the growth of certain sectors and activities. The OECD conducted such an exercise with their ENV-Linkages model in 2019 [40]. Such an approach is rich, but lacks the technological detail of how decarbonisation is reached: mitigation is attained by carbon pricing and constant elasticity of substitution among inputs (fuels) to each economic activity. CGE models can be linked to more detailed techno-economic models to cover this gap, which is the subject of the article presented in section 4.2.

The tools that are most fit for purpose in producing techno-economic projections for decarbonisation are **integrated assessment** and **energy system models**, which, among other uses, serve as input to the IPCC in its Assessment Reports on how to mitigate emissions and avoid climate change as much as possible [41]. Such models integrate concepts of System Dynamics, wherein the interconnectedness of complex systems is represented by multiple internal feedback loops and effects with time delays. Models produce scenarios on the basis of multiple assumptions: socio-economic drivers, relationship between level of development and demand for energy services, efficiency and costs of technologies, and more. Models use different methodologies for how each sector is represented and what the model is designed to solve. For instance, they can consist in a **simulation** of how certain variables evolve over time under certain constraints; or they can consist in an **optimisation** of how certain variables should behave in order to attain an objective (like total cost minimisation). What such models have in common is a description of sectors that includes both technological and economic

characteristics, thus capturing inter-sectoral effects and inter-temporal effects. It is possible to assess where a scarce resource would be best allocated or where the effort to reduce pollution should be prioritised. This allows the assessment of pathways for future systems to some level of detail. For industry, the projections of both demand and production are made with varying levels of detail. Examples of methodologies are provided in the following sections.

As an illustration of the wealth of data that is produced, the scenarios data used as input to IPCC Assessment Report 6 (2022) is publicly available [42]. However not all the data natively produced by the models are public; for instance, industry sub-sector data is not available. 10 models reported CO<sub>2</sub> emissions from industry (with 59 scenarios having >90% emissions reductions in 2050 compared to 2010); 4 models reported data on steel and cement production; all 10 models reported hydrogen energy demand (but none reported data for hydrogen as a feedstock)<sup>4</sup>.

In the following sections we will present examples of studies and discuss specific methods that were used by energy system and integrated assessment models to estimate materials demand and industrial production.

## 2.2. Methods for estimating materials demand

Estimating the future evolution of physical materials needs forms the basis for then estimating greenhouse gas emissions associated with their production and use. We will consider what are the real-world drivers for estimating a material's demand and review different methods that have been proposed to mathematically project this demand in the future.

### 2.2.1. Drivers for materials demand

Determining the demand for a product can be complex as it arises from a combination of factors, encompassing consumer needs, technological advancements, and regulatory changes.

Demand for a product can be categorized into established and new uses.

Established uses are associated to well-known drivers, such as construction materials for buildings and infrastructure. Their demand is typically indexed to economic activity itself. New regulation might arise to reduce the amount of material used, because of upstream constraints in resource availability, to avoid production-side pollution or side-effects, or to increase the overall resource efficiency. New technologies might also substitute the use of one material with another for the same or similar role.

New uses and new products could arise that might quickly constitute a significant share of the total demand. The transition to a low-carbon economy is expected to be associated with increasing demand for specific materials, such as lithium for batteries, rare earths (neodymium, praseodymium, terbium and dysprosium) for permanent magnets in wind turbines and electric motors, amine solvents for carbon capture.

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<sup>4</sup> Model versions of the same core model are counted as a single model.

Also important in the context of climate change is that materials are used by the energy sector itself. The drive to decarbonise the energy sector will be accompanied by important infrastructure shifts and technology development. The increase in electrification will mean an increase in materials used in electric motors and power transmission and distribution. It will also mean an increase in materials used in power generation, the amount and content of which can vary greatly across the different power generation technologies.

In addition, the demand faced by industry is also determined by the recyclability of a material, and the level at which recycling is pursued. Collecting and recycling materials at the end of product life reduces the need for primary production of new material, but it comes at the extra cost of setting up collection infrastructure, sorting facilities and recycling facilities. Availability of collected material, accumulated impurities and recycled product quality are also determining issues.

Furthermore, the concept of a circular economy has gained traction in recent years due to a confluence of global challenges. Resource depletion and the accumulation of waste has put the extractivist model of development into question. The circular economy attempts to approach material use more holistically, from rethinking how we use a product, to how it is designed, manufactured and disposed of, while exploring synergies between industries that might convert one’s waste into another’s feedstock. The 9R framework (expanded from earlier R-frameworks, see Figure 5) has been proposed to conceptualize and provide a hierarchy of actions regarding a product’s life.

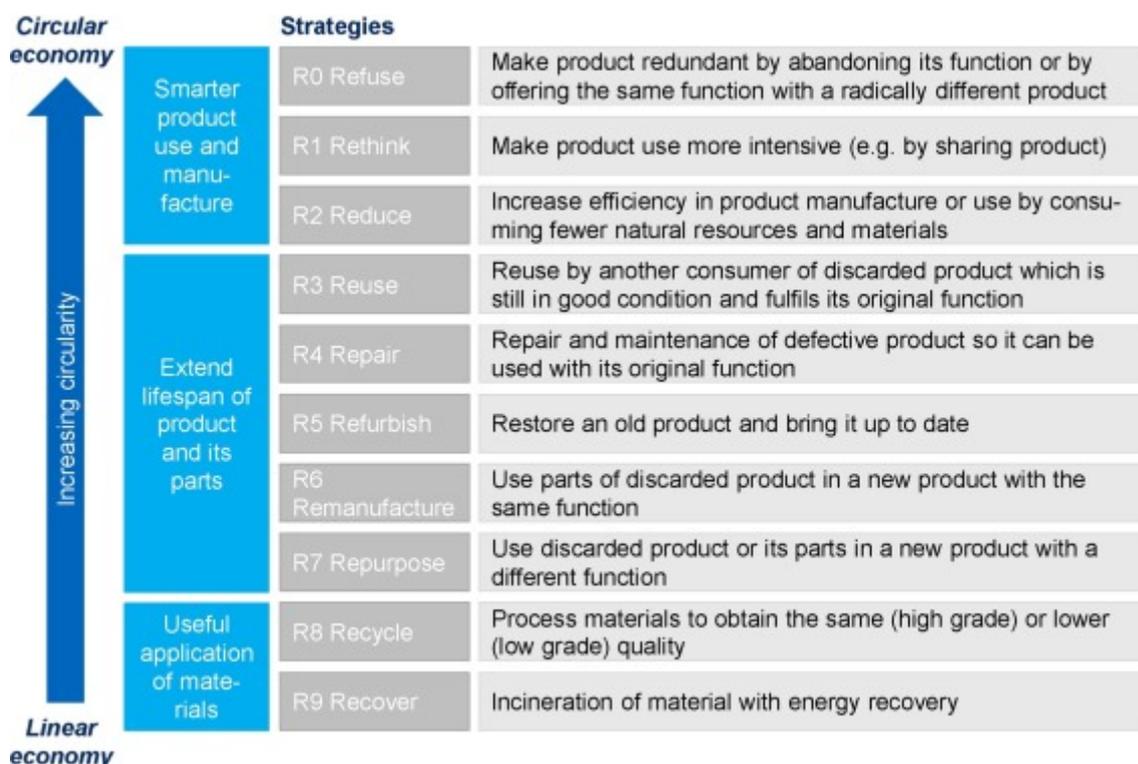


Figure 5: The 9R framework for a circular economy hierarchy of actions

Source: Kirchherr et al. (2017) [43].

The EU adopted a Circular Economy Action Plan in 2020 [44] and associated proposals in 2022; for instance, it included rules for construction materials, giving preference to recyclable or recycled materials, minimum recycled content obligations, setup of databases on products identification, use

and repair [45]. Private initiatives have proposed material passports for identifying which materials were used in the construction of a buildings and where, in order to facilitate their reuse at the end of the lifetime of the building [46].

All these actions are set to influence the expected demand for products in the future.

### 2.2.2. Projecting demand in the future

Not all industrial sector modelling methodologies include a projection of the demand of physical materials. Some methodologies base the demand for the industrial production sector on a pure linear extrapolation of past industrial activity trends, or on projections of economic activity such as GDP or sector value added. Quantities for physical demand is then derived using a simple quantity-activity relationship (elasticity). This is the case for most industrial sectors in the POLES model [47].

Other methodologies purely rely on expert judgement or, where relevant, stakeholder input, in which case the physical demand profile is a time series that is predefined as input in the modelling. For instance, this is the case in the regularly updated reference scenario of the EU, established in coordination between the European Commission and EU Member States representatives [48].

More detailed quantitative methodologies can be broadly categorized in three approaches: econometric; economy-wide intensity; and bottom-up [49], [50].

### 2.2.3. Econometric methods

The econometric approach relates annual apparent material demand to macro-economic variables. An affine function is constructed and its parameters are calibrated with regression analysis on historical time series. The equation takes the form of:

$$D_{m,t} = \sum_i \alpha_{m,i} \times X_{i,t} + \varepsilon_m$$

Where the *annual* demand  $D$  for material  $m$  at time  $t$  is the sum of the effects of macroeconomic drivers  $X$ , for each sector  $i$ , each weighted by the parameter  $\alpha$  (and  $\varepsilon$  a residual).

The macroeconomic drivers can be GDP, sector value added, industrial activity index, trade structure, market volatility, consumer price index. The regression can also be on a single driver, such as GDP.

A variant of this uses power laws instead of affine functions. The Global Change Analysis Model (GCAM), maintained by the US's Joint Global Change Research Institute, uses such a function for projecting the demand of cement [51]:

$$Dpc_t = Dpc_{t-1} \cdot \left(\frac{P_t}{P_{t-1}}\right)^\alpha \cdot \left(\frac{GDPpc_t}{GDPpc_{t-1}}\right)^\beta$$

Where demand per capita  $Dpc$  at each time step  $t$  is a function of the total price to supply cement  $P$  (i.e., cement production cost calculated within the model) with a price elasticity  $\alpha$  (constant,  $\alpha=-0.4$ )

and per capita income  $GDPpc$  with an income elasticity  $\beta$  (variable,  $\beta$  decreases from 1.264 to -0.252 depending on the level of income per capita).

Such econometric methods are adapted to economic models that might want to assess the interaction of macroeconomic indicators, such as investment, employment, inflation, trade and public or private debt (e.g., the dynamic stochastic general equilibrium model QUEST [52]). It is also more adapted to short-term projections of a few years, since it does not capture the evolving structure of the economy or the potential strengthening or weakening of the correlation between economic activity and the changing uses of materials.

#### 2.2.4. Economy-wide intensity methods

The intensity method can be distinguished in the Intensity of Use (IoU) method and the Intensity of Stock (IoS) methods. Both examine the needs of materials per unit of economic activity or per capita, but they differ on considering annual apparent *flows* (IoU) or in-use standing *stock* (IoS) of materials. Material flows constitute the annual demand of market (plus stock variations), while material stocks constitute the result of flows cumulated over time (minus the retirement of equipment when it reaches the end of its lifetime).

The **Intensity of Use** concept was first proposed in the 1970s by the International Iron and Steel Institute (currently World Steel Association) [49] and was applied to several metals and minerals [53]. The curve correlates the level of annual demand per unit of GDP with the state of economic development. The curve follows the development of a country as its level of richness grows (which would also be grossly equivalent to the passage of time): a strong phase of infrastructure construction, followed by a peak, a decrease and a relative stabilization to a level above zero. The logic of this “inverted U” shape is that economic development follows an industrialization phase (with an important role for material-intensive construction and manufacturing industry); then as per capita income continues to grow, industrial structures shift towards less material-intensive sectors (such as services), resulting in a decline of the material intensity of use. This had been applied to the POLES model in a previous version (see Figure 6), using the following equation from [54]:

$$\frac{PGC_t}{PGC_{t-1}} = \exp\left(\alpha \cdot \left[\frac{1}{GDPpc_t} - \frac{1}{GDPpc_{t-1}}\right] + \beta \cdot [GDPpc_t - GDPpc_{t-1}]\right)$$

Where the variation of annual consumption per unit of GDP  $PGC$  at time  $t$  is a function of per capita income  $GDPpc$ .

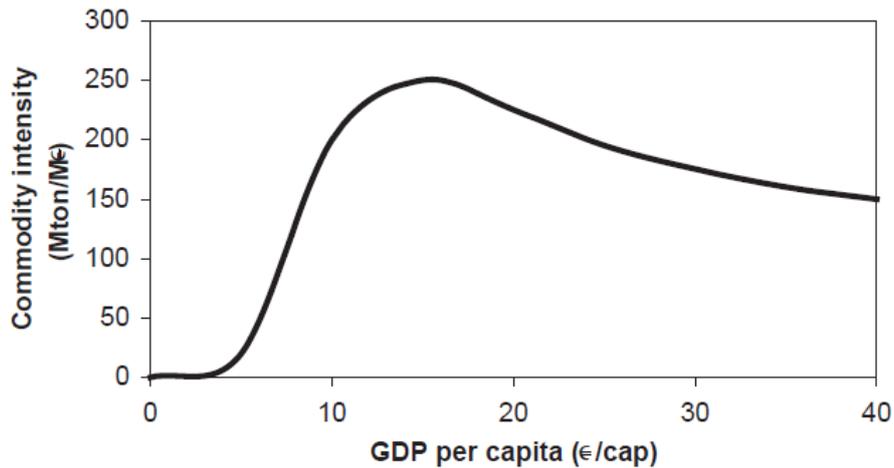


Figure 6: Example of Intensity of Use shape used for cement

Source: Szabó et al. (2006) [55].

This has been described as the *dematerialization* of the economy [53]; this effect is, however, relative, since the decrease is to a non-zero value: the absolute level of demand of material continues to grow with the economy, there is no complete decoupling of economic activity and material demand.

Using this curve as a basis for projections makes the assumption that such a correlation will continue to hold true in the future and be valid across countries. A country might choose to follow a different development path, using perhaps other materials; or, future structural changes and new uses of materials might result in lower or higher intensity levels compared to the historical data that was used to build the curve (“leapfrogging” in the case of more efficient use).

The Intensity of Use is used by both research and industry analyses. For example, the world energy system model POLES [47] and the world energy-land integrated assessment model IMAGE [56] use it as a basis for steel demand. The cement industry uses it to benchmark countries with each other by plotting observed demand per capita versus GDP per capita; as per [57] in the Global Cement Magazine: “*This relationship is well known and has been widely used in the past to both judge the relative economic growth between nations and forecast likely cement consumption rates as a given nation’s GDP increases*”.

The **Intensity of Stock** concept looks at the cumulated effect of annual demand in how flows are the result of constituting a stock. Annual flows are then the mathematical derivative of the stock over time. An illustration of this is given in Figure 7. The concept follows the logic that demand serves to build up a stock to serve a particular need or service (e.g. living spaces, fleet of vehicles, transport infrastructure). As an economy grows over time, the stock is constituted until it reaches a saturation level where all needs or services are met. This results in an S-shaped curve, from which annual demand is derived, peaking at the stock inflection point. Once services are met and the stock constituted, the overall stock follows the evolution of population.

A number of parameters can influence the stock levels across countries, apart from population and the level of economic development, such as: local resources, common practices, spatial planning, population density. An important lever for decarbonisation could be to identify the drivers with which development can result in lower levels of stock [12], [58]. Unlike leapfrogging, which rather looks at

technological efficiency (see section 1.3), this approach is wider in scope and with higher potential implications.

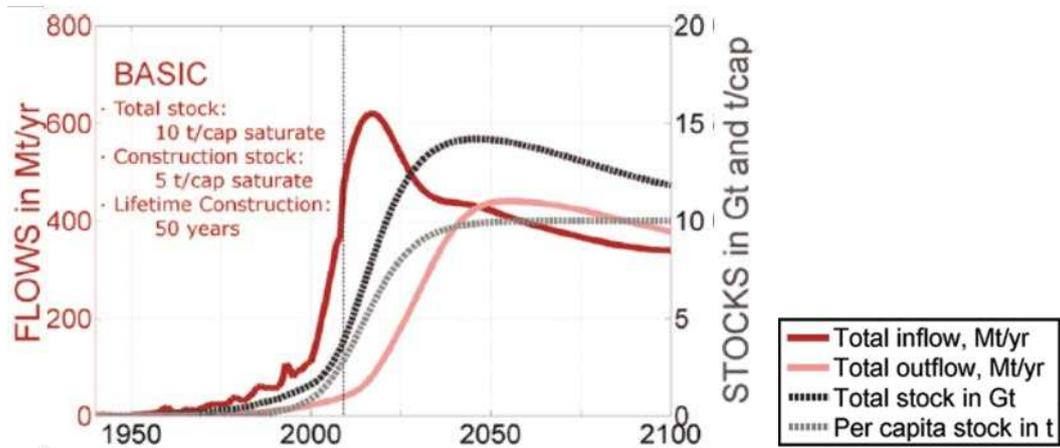


Figure 7: Example of Intensity of Stock shape used for steel, with annual flow (red, left axis) and stock per capita (black, right axis)

Source: Pauliuk et al. (2012) [59]. The long-term decrease in stock is related to the long-term peak and decrease in population.

The Intensity of Stock concept is used as a counterpoint to the Intensity of Use concept in that it attempts to link material demand to an actual need to satisfy a material stock, rather than forming a law derived from observed annual statistics regardless of the resulting cumulated demand [59].

The method consists in establishing a mathematical equation for the evolution of the stock and calibrating parameters with curve-fitting. Kermeli et al. (2022) [56] find a good fit for the steel stock with an S-shaped equation:

$$S_t = \frac{S_{sat}}{1 + \exp(a - b \times GDPpc_t)}$$

Where the stock  $S$  at time  $t$  is a function of the saturation level  $S_{sat}$  and per capita income  $GDPpc$ .

The method results in independent parameters, inflection points and saturation levels for each region. Different levels of saturation levels across region could come from regional specificities in materials used or in different patterns of spatial planning.

### 2.2.5. Bottom-up methods

The bottom-up method decomposes total demand for a material into end-uses and associates activity indicators for each end-use with specific material consumption levels.

The annual consumption  $C$  of a material is calculated as the sum of sub-consumptions over the end-uses  $u$ :

$$C_t = \sum_u SMC_{u,t} \cdot Act_{u,t}$$

Where *SMC* is the specific material consumption for a particular use and *Act* is the activity indicator for that use.

For instance, the activity indicator can be the number of vehicles sold in a year and the specific material consumption the amount of material per vehicle. The specific material consumption can be kept constant, assuming the same material need for the same service provided; changes in material demand would only come from the underlying activity. Or it can vary, due to material efficiency (e.g. vehicle body light-weighting), substitution (e.g. use of other metals or carbon fibre instead of steel in a vehicle body), or even increased use for the same service (e.g. consumer preference for larger cars).

This more engineering approach, compared to the more economic approaches above, is aided by databases set up by Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) studies of **static material demand**. MFA provides insights in the physical flows of materials across borders and from raw ore to finished product. LCA has taken specific products or technologies as a point of reference and provided upstream and downstream material flows and associated environmental indicators. Both analysis types have resulted into global models with material stocks and flows (e.g. Copper Flow Model, in Glöser et al. (2013) [28]; or databases with multi-regional input-output (MRIO) tables including materials (e.g., EXIOBASE [60]); or energy and mass balance studies from individual industries for the aim of process optimization, taking into account multiple inputs (including energy) and aiming for better environmental performance (including greenhouse gases emissions. This line of activity has been particularly active over the past twenty years and especially focuses on materials such as metals, with the possibility of recycling motivating the tracing of material flows (e.g., International Copper Study Group [61]).

The above has been implemented in models for projecting **dynamic materials demand**. Energy system models have associated specific material demand to energy technologies or energy services and have based materials demand projections on the energy modelling framework (e.g., Hache et al. (2020) [62]). Materials representation in macroeconomic models have used coefficients of physical material use per unit of economic activity and have based materials demand projections on the economic modelling framework, such as social accounting matrixes, the evolution of total factor productivity and constant elasticity of substitution across capital, labour and other inputs like materials (e.g., OECD (2019) [40]).

### 2.3. Methods for estimating materials production and associated emissions

Demand for a product is met by production, either at the local scale or at a larger, regional or global, scale. We will consider what are the real-world drivers for assessing how and where a material is produced, and we will review different modelling methods for estimating the associated industry energy demand and emissions.

#### 2.3.1. Drivers for process and site selection

As an economic activity open to international trade and competition, industry makes decisions based on long-term planning and optimisation of costs. The decision to build and operate a production

facility will involve considerable upfront investment and engage operational expenditure for decades. The sizing and location of a production facility depend on a number of factors.

A site has to consider the existence of supply chains and infrastructure, for both receiving feedstocks and exporting products. The quality and potential quantity of a resource and how easily it can be transported are deciding factors. A site would have to plan for sufficient stockpiles of feedstocks to be able to produce continuously while feedstocks are replenished. For example, a cement factory is typically situated in close proximity to a limestone quarry, given the high transport costs entailed by the high volumes of material to move around, and at the receiving end of a coal supply line by rail. A steel factory is typically situated in proximity to a harbour, where it can receive iron ore and export semi-finished goods, given the comparatively lower costs involved in the transport of lower volumes of materials.

Among the main inputs to production are energy and labour. The price of energy is an important factor in site selection, with industrial consumers entering into long-term contracts with energy and electricity providers. Labour costs are also a factor; depending on the material and process, the amount of labour needed might vary, as does the distribution of labour across specialized and non-specialized work. In the case of base materials with large production volumes like steel and cement, centuries of process optimisation have resulted in a low number of employees needed per tonne of output.

The choice of technology or process type will have to take into account the state of the art of different options and the expected progress of emerging solutions. Technologies and processes might experience incremental changes, thanks to optimization and know-how acquired by on-site experience; or, they might be the result of more fundamental R&D that is progressively brought to the market with public or private investment push.

Local regulations also play a role. Ideally, these should reflect societal priorities and social acceptability. A location might provide tax rebates or energy subsidies to an industry in order to attract economic activity and increase employment. Conversely, a location might have more strict regulation on the environmental effects of industrial production. Environmental externalities are the consequences of industrial processes that affect the environment and society but not directly factored into the cost of production. Regulating such externalities, either by putting a price on them or establishing standards for maximum quantities of a species released into the environment, forces the industry to internalize their cost and plan accordingly.

While chemical and air pollution externalities have a long history of regulations, the incorporation of CO<sub>2</sub> and GHG pollution is more recent. Regulators face the issue of quantifying the level of acceptable pollution and of putting a price on these emissions. This has given rise to concepts such as the social cost of carbon [63], where the (discounted) cost of various impacts are aggregated into a single value, putting a price on each emission that is avoided, in a cost-benefit analysis type of approach. Conversely, the carbon budget approach first determines the desired maximum amount of emissions, itself determined by considerations of their impacts; in a second step, the price is determined in order to reach this amount, either by setting it directly (taxation) or as a result of a market equilibrium (cap and trade system).

In a context of ambitious decarbonisation, regulating and putting a price on CO<sub>2</sub> emissions is something that is expected to play a growing role in an increasing number of countries. Individual installations will have to optimise on multiple constraints, both on CO<sub>2</sub> and other types of pollutants. While climate mitigation can yield significant co-benefits in air quality, the choice of technology is important: for instance, biomass use as a substitute for fossil fuels and CCS as emissions avoidance can both result in increased air pollution [64].

An element that might become important in future decisions in certain installations will be the issue of CCS infrastructure, i.e. how to evacuate the captured CO<sub>2</sub> from the installation and where to transport it to. This infrastructure still needs to be built. A site that is in proximity of a potential site for long-term CO<sub>2</sub> sequestration (saline aquifer, depleted oil and gas field) will face lower costs and implement CCS solutions more easily [65].

### 2.3.2. Projecting production in the future

#### *Choices in the detail of representation*

Methods to project the energy needs and GHG emissions of materials production, i.e. the processes in industries of mining and refining into finished goods, vary in granularity and detail, in the processes, technologies and efficiency and mitigation options that they can represent.

The representation can be devoid of process and technology detail, based only on the production activity, an efficiency influenced by endogenous (the energy prices) or exogenous (autonomous trend) factors, with the efficiency of a backstop technology acting as a floor for how efficient the sector can get. Within the sector, competition between fuel sources is based on their cost (which can incorporate the cost of environmental externalities, such as a pricing of CO<sub>2</sub> emissions). This is the case of the models IMACLIM by CIRED [66] and POTEnCIA by JRC [67].

More detailed methods include individual process or technologies, with a cost-based competition across processes; and, where relevant, a nested cost-based competition between fuels within each process. Processes can be broken down further by production step, with the representation of specific infrastructure or components. Total costs can include fixed costs (investment costs amortized over the equipment lifetime) and fuel costs; there can be additional preference factors unrelated to pure economics (reflecting inertia or risk averseness or country specificities observed on the historical mix). The choice of which processes to include can depend on their technology readiness level (TRL) and the time horizon considered. Such models are more usually at country-scale or regional scale, such as Fraunhofer ISI's FORECAST [35] and E3M's PRIMES [68], but this is progressively the case too for some sectors in global models as well, such as IMAGE [69].

Other methods take different approaches, by making a complete list of mitigation or energy efficiency measures and their costs of implementation, sequencing them into marginal efficiency or marginal abatement cost curves (MACCs); projections look up these curves depending on the prices environment. This was popularized by the consultancy McKinsey & Company in 2009 [70] and is still used in bottom-up assessments [71].

The choice of process mix, fuel mix or mitigation/efficiency option can, itself, follow different methods. It can be a linear choice following the cheapest option and moving towards costlier options

progressively, within boundaries (“winner takes all”, see the MARKAL/TIMES family of models [72]); or it can be based on a distribution function allowing for a mix of options with shares based on their cost (e.g. logit function, see the GCAM model [73]).

Finally, the method can vary on the granularity and geographical-spatial resolution of the production capacities: it can include individual plants with site-specific techno-economic parameters and discrete options; or it can represent the total stock of capacities with averaged information on lifetimes, depreciation and options. A more detailed approach is used by power expansion planners (e.g., the Antares simulator model [74] used by the French and European electricity Transmission System Operators); the more aggregate approach is used in most of the global energy system and integrated assessment models.

Depending on the geographical scope of the model, international trade of commodities can be included; or, domestic production can be set to satisfy only domestic demand. For instance, the scenarios used to set the 2050 net-zero emissions target in the EU (using the PRIMES model) were designed with a limitation of imports of biomass to 4-6% of biomass energy use [75].

#### *Past experience in industry sub-sectors modelling*

Several projects have focused on strengthening the modelling representation of industrial sub-sectors. In particular<sup>5</sup>:

- ULCOS (Ultra-Low CO<sub>2</sub> Steelmaking), project funded by the EU (FP6), 2004-2010. This consisted in R&D into steelmaking processes with physical prototypes and techno-economic modelling of their uptake using the POLES model. See Birat (2020) [76].
- ADVANCE (Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies), project funded by the EU (FP7), 2007-2013. Among other research topics, this project explored a more detailed representation of energy services and end-uses, as well as identifying key aspects on how to represent cement demand and the cement industry sector in integrated assessment models. See this project’s cement modelling guideline [77].
- REINVENT (Realising Innovation in Transitions for Decarbonisation), project funded by the EU (Horizon 2020), 2016-2020. It focused on the decarbonisation of four industry sub-sectors (meat/dairy, paper, plastic and steel). It made use of the IMAGE model, with a particular focus on demand management and circular economy [78].
- NAVIGATE (Next generation of advanced integrated assessment modelling to support climate policy making), project funded by the EU (Horizon 2020), 2019-2023. Among other research topics, this project aimed at improving the representation of industry in integrated assessment models in order to produce more detailed and technology-rich decarbonisation pathways. See this project’s mission statement [79]<sup>6</sup>.

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<sup>5</sup> This list is incomplete. More projects exist, in particular projects aiming at enhancing a single model.

<sup>6</sup> This work contributed to the research conducted within the NAVIGATE project. See the forthcoming publication: Bauer et al. (forthcoming), *Integrated strategies minimize hard-to-abate industry sector CO<sub>2</sub> emissions in low-emission scenarios*.

The Integrated Assessment Modelling (IAM) Consortium documentation [80] and Edelenbosch et al. (2017) [81] present a comparison of the industry module characteristics of several global IAMs. A summary of how different models tackle these issues is presented in Table 1. Sub-sectors where the modelling includes physical production (as opposed to modelling based on an activity indicator such as GDP or value added) are noted with a star (\*).

Table 1: Main industry model characteristics of select integrated assessment models

Model	Number of industrial sub-sectors breakdown	Industry sector drivers for total energy demand	Representation of specific production processes	Determination of energy efficiency and technology mix
<b>AIM-CGE</b>	7 (Iron and steel, chemicals, non-metallic minerals, food processing, pulp and paper, construction, others)	Cost of energy, sector value added	No	Cost of energy
<b>COFFEE</b>	6 energy services (heat steam, HVAC, light, motor, other)	Sectoral value added	No	Exogenous efficiency
<b>DNE-21+</b>	6 (Iron and steel*, cement*, pulp and paper*, aluminium, some chemicals* (ethylene, propylene and ammonia))	Population and GDP	Yes	Technology costs and energy prices determine market share
<b>GCAM</b>	3 (Cement*, nitrogenous fertilizers*, others)	GDP; fertilizer demand from land use model	No	Exogenous efficiency improvement rate
<b>IMACLIM-R</b>	Energy-intensive vs. non energy-intensive industries	Population, productivity, resources, energy prices	No	Energy prices and autonomous efficiency improvement
<b>IMAGE</b>	3 (Steel*, cement*, other)	Sectoral value added; material intensity of GDP for steel and cement	Yes (steel, cement)	Technology costs and energy prices determine market share
<b>MESSAGE</b>	Thermal and electric demand of total industry, non-energy use, cement process emissions	Population and GDP	No	Energy prices
<b>POLES</b>	4 (Iron and steel*, chemicals and petrochemicals, non-metallic minerals, others)	Sectoral value added; material intensity of GDP for steel; energy costs	No	Energy prices and autonomous efficiency improvement
<b>REMIND</b>	4 (Iron and steel*, cement*, chemicals, other industry)	Population and GDP	No	Energy prices and autonomous efficiency improvement
<b>TIAM-UCL</b>	5 (Pulp and paper*, chemicals, iron and steel*, non-metallic minerals*, other)	GDP, sectoral value added	Yes	Energy prices

*Source: adapted from Edelenbosch et al. (2017) [81] and IAMC documentation [80]. A star (\*) denotes representation of physical material flows. The POLES version described here was the starting point for this work (no bottom-up representation of non-energy hydrogen, steel and cement demand, no representation of individual production processes for steel and cement).*

The representation of physical demand is not systematic in these models. Among these 8 models, the most frequent sectors that are singled out are cement and non-metallic minerals (6, 4 with physical demand), iron and steel (5, 4 with physical demand), chemicals (5, only 2 with physical demand for specific chemicals), pulp and paper (3, 2 with physical demand).

For all of these models, demand is projected in a stylized way with correlations to macroeconomic drivers such as GDP and population (and sectoral value added, itself derived from GDP and population).

Although price-induced energy efficiency is a feature of all models, it often consists in the effect of price on a single parameter defining the entire sector's energy efficiency. Few models represent actual production technologies and production capacities, with process-specific energy intensities, and which would compete on the basis of total costs to result in a sector-wide energy efficiency. Only 3 models have explicit technologies for materials production, as opposed to a single energy intensity:

- DNE-21+ (7 processes for iron and steel; 4 for cement; 3 for pulp and paper; 2 for aluminium; 1 for ethylene/propylene; 3 for ammonia) [82]
- IMAGE (8 for steel; 4 for cement) [69]; more recent work presents significant enhancements (additional processes for steel and cement, physical demand and new processes for paper and pulp, chemicals and food processing) [78], [83]
- TIAM-UCL (1 process for each product broken down into production steps) [84]

The documentation wiki of the Integrated Assessment Modelling Consortium also includes a wealth of information [80].

Each model presents its own strong points and weaknesses. Each model has decided to model a specific industry sub-sector in its specific manner, with differences in methodology, coverage of both demand and production, and granularity and exhaustiveness of technologies. Importantly, all models evolve with time and become richer in the topics they can address and the detail with which they represent development pathways. This can be the result of a specific research question (e.g., how to estimate prices in a market, how to estimate future terms of trade) or of the desire to include recent evolutions in policy or technologies (e.g., new investments in infrastructure, new production processes).

This work contributes to that modelling tool development effort with its own stepwise specific configuration of modelling improvements. We propose to enrich one of the models above, the POLES model, with the aim to enhance how such a model represents industry decarbonisation pathways. Compared to the models discussed above, this enhanced version tackles both materials demand and production within the same tool, with more detail for both these aspects compared to earlier versions.

### 3. Methodology: representing materials demand and production in a long-term energy system model

"If my work has tested the foundation of my beliefs, science has been and continues to be my guiding light."

- "Redux" (1997 episode of *The X-Files*, Chris Carter, USA)

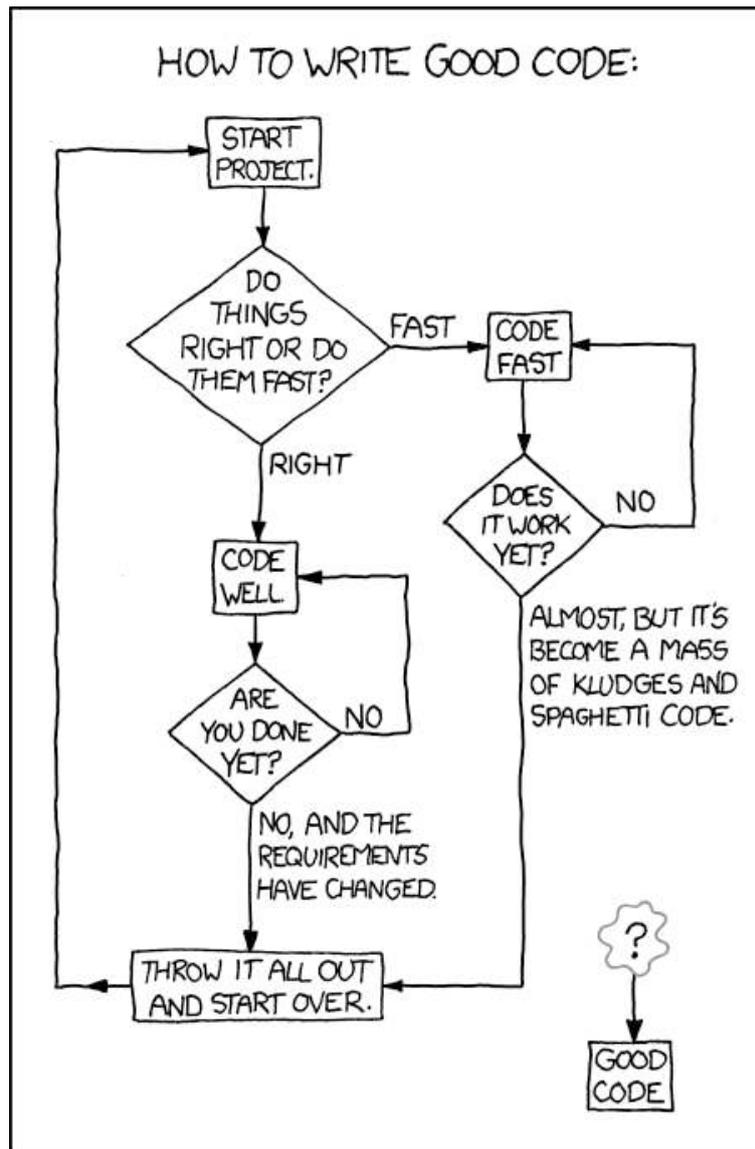


Figure 8: Good code flow chart

Source: xkcd web comic<sup>7</sup>. There is no single recipe.

<sup>7</sup> <https://xkcd.com/844/>

### 3.1. Choice of the tool

For this work, the POLES model was chosen, for several reasons:

- the model covers the entire energy value chain, from extraction to transformation to consumption and represents many energy vectors, making it relevant for projections of emissions of the principal greenhouse gas, CO<sub>2</sub> related to energy and industry;
- the model already explicitly represents certain sectors relevant for the research question (electricity production, hydrogen production);
- the model covers the entire world, with a high level of geographical detail (54 countries and 12 regions), making it relevant for international issues such as the assessment of energy and goods trade or the economic assessment of climate change mitigation;
- the model combines hourly time steps (power system) and annual time steps and can be ran to 2100, making it relevant for long-term strategies for large shifts in patterns of energy production and consumption [5], [85], [86];
- the model is actively used, maintained and developed continuously for over 25 years, ensuring that it has remained relevant and fit for purpose [87]–[89].

The above reasons make POLES particularly fit as a tool to address the research question of integrated demand-production for several materials.

In the following sections, the initial version of the POLES model is described, followed by a summary description of the changes implemented in this work; the detailed description of changes is described in the sections dedicated to each material.

### 3.2. Description of the initial version of the POLES model

The POLES (Prospective Outlook on Long-term Energy Systems) model was initially set up to address the system-wide international issue of climate change mitigation strategies and has been used to comment and inform the international climate negotiations of the United Nations Framework Convention on Climate Change process (e.g. Kyoto Protocol of 1997, Paris Agreement of 2015).

POLES is being used by the GAEL laboratory in Grenoble, France; the Joint Research Centre of the European Commission in Seville, Spain; and the private consultancy Enerdata in Grenoble, France. The first scientific publication making use of POLES is from 1990 [90]. Since 2015, it is used by the European Commission in its annual Global Energy and Climate Outlook report series<sup>8</sup> [17].

A short description of the model is found below, with a particular focus on hydrogen and industry. A more comprehensive description of the model can be found at the JRC [47], at the Integrated Assessment Modelling Consortium documentation wiki<sup>9</sup>, and in the supplementary information of the articles of this work, included as Annexes of this report.

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<sup>8</sup> This author is a main contributor since 2015 and lead author since 2018 of this series of reports.

<sup>9</sup> [https://www.iamcdocumentation.eu/index.php/Model\\_Documentation\\_-\\_POLES](https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_POLES)

### 3.2.1. Model overview

POLES is a world energy-economy model of the energy sector, with complete modelling from upstream production through to final user demand (see general scheme in Figure 9). It follows a year-by-year recursive modelling, with lagged adjustments of supply and demand by world region.

It is a partial equilibrium model (as opposed to a general equilibrium model), meaning that the effects of price changes only impact the energy balances in the next time steps: there is no feedback of energy prices and policy action (e.g., carbon pricing) on economic activity.

It is a simulation model (as opposed to an inter-temporal optimization model), meaning that the investment decisions are made with limited foresight of the future evolution of the parameters; this is also known as “myopic foresight”. The projections made by POLES represent cost-efficient pathways within the scope of these definitions of model category.

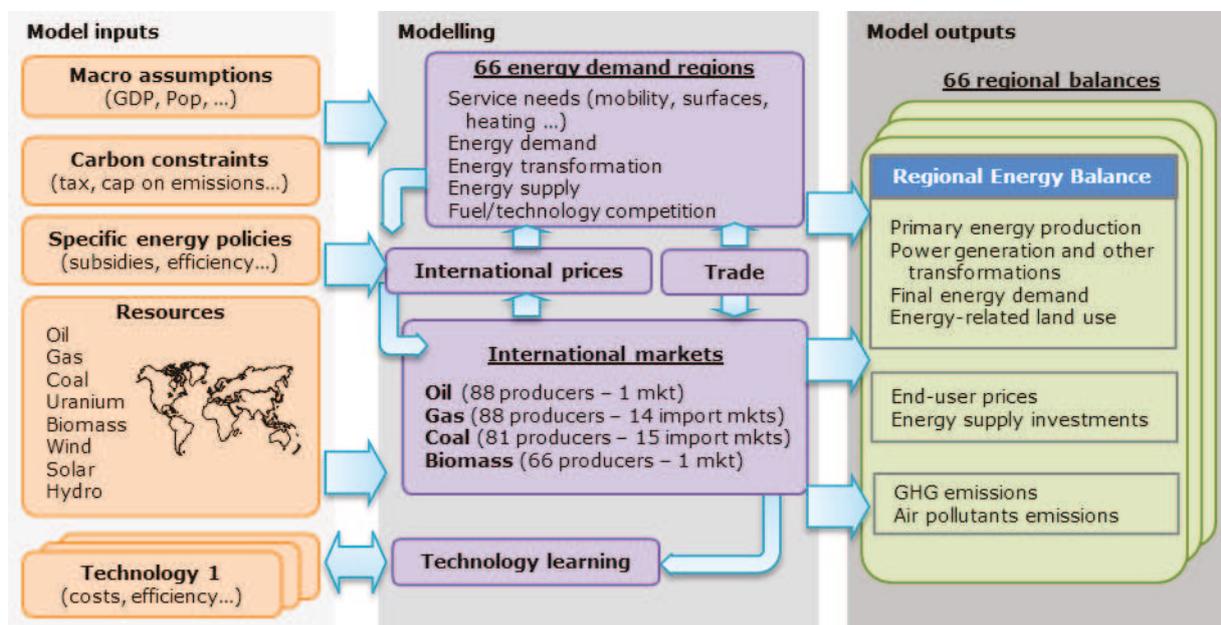


Figure 9: POLES model general scheme

Source: JRC POLES documentation [47].

The model distinguishes 14 fuel supply branches and 15 final demand sectors.

The model decomposes the world energy system into 66 regional entities: 54 individual countries and 12 residual regions (see Figure 10), to which international transport sectors (air and maritime) are added. This includes an explicit representation of the world’s largest economies, OECD and G20 countries.

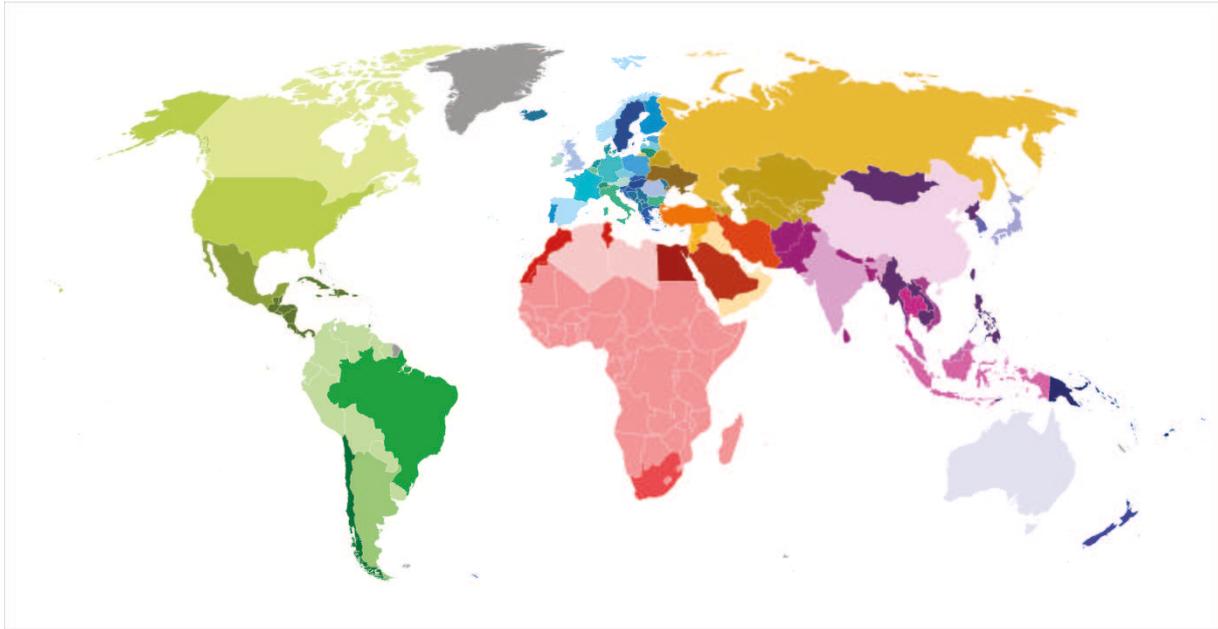


Figure 10. POLES model regional detail map

Source: JRC POLES documentation [47].

The POLES model simulates technology dynamics in the decision-making process. The need for new energy equipment and the competition across options is represented as follows (see Figure 11):

1. The estimated future sectoral demand drives the total stock (or capacity) depending on:
  - sectoral activity,
  - energy prices, both short- and long-run, with a distributed lag structure over time and possible asymmetries between the increasing or decreasing price effect,
  - and local technological characteristics and trends;
2. The installed equipment can meet part of the total demand, once depreciation (scrapping) has been taken into account (based on average lifetime of the equipment or detailed vintage of the equipment in the power sector);
3. The remaining needs after contribution of the un-scrapped equipment is covered by a competition between options (fuels or technologies). The market shares of competing options (technologies, fuels) follows a portfolio approach, based on:
  - their relative cost and performance, which includes the investment cost, the lifetime, a time discounting factor (made of a discount rate and a sector-specific risk preference factor), the fuel utilisation efficiency and the fuel price;
  - a weighting factor representing non-cost elements like preferences or policy choices (calibrated on historical data, allowing a realistic characterization of the behaviour of economic agents); it can evolve exogenously over the simulation to capture infrastructure developments, technology choices, etc..

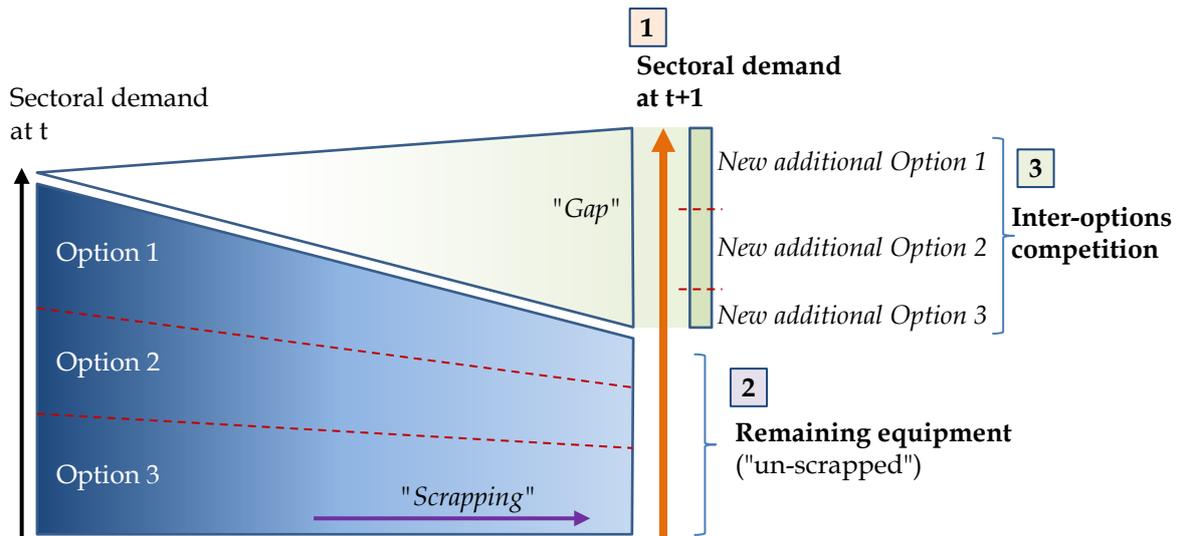


Figure 11: Schematic representation of depreciation and investments in POLES

Source: JRC POLES documentation [47].

This mechanism, with sector-specific adjustments, is applied to fossil fuel supply, the power sector, hydrogen production and final demand sectors.

### 3.2.2. Model sectoral details

#### Primary energy supply

Fossil fuels (oil, gas and coal, each with different resource types) are modelled from reserves, to discoveries to production. International prices are endogenously calculated, taking into account production costs and transport costs; specifically, there is a representation of gas trade infrastructure (pipelines, liquefied gas ships).

The potential and production cost for bio-energy (several types) is derived from information provided by the specialised model GLOBIOM-G4M [91]. Biomass can be traded, either in solid form or as liquid biofuel.

Wind and solar are associated with potentials and supply curves per country. Six representative days of a year define wind and solar supply curves per hour per region.

#### Power system

The power system describes the capacity planning of new plants and the operation of existing plants. Electricity demand is built from sectoral demand in a bottom-up manner. Capacity planning considers the existing structure of the power mix (vintage per technology type), the expected evolution of the load demand, the production cost of new technologies and the resource potential for renewables. The operation matches electricity demand considering the installed capacities, the variable production costs per technology type and the contribution of flexible means (stationary storage, vehicle-to-grid, demand-side management). The electricity price for the final demand sectors is endogenously calculated.

## **Hydrogen and derived fuels production**

Multiple hydrogen production pathways are represented. This is discussed more in detail in section 5.2 and in annex iii. CO<sub>2</sub> from direct air capture can be combined with hydrogen to produce synthetic fuels (either methane or liquid hydrocarbons). Their supply costs are endogenously calculated.

Hydrogen and liquid synthetic fuels can be traded bilaterally between each region, taking into account multiple choices and associated costs (pipeline, liquefied hydrogen ship, ship carrying hydrogen converted into ammonia and reconverted into hydrogen upon arrival) [92].

Hydrogen can be used in final energy demand sectors mixed with the natural gas distribution grid up to a maximum of 12% in energy terms, with a cost-based competition with natural gas.

## **Other energy transformation**

The model also describes other energy transformations sectors: liquid biofuels, coal-to-liquids, gas-to-liquids, centralised heat production.

## **Final energy demand: Industry**

The model distinguishes four main industrial sub-sectors: iron and steel; non-metallic minerals; chemicals (energy uses and non-energy uses are differentiated); other industry.

Enhancement of the iron and steel sub-sector and the cement sub-sector (which constitutes the majority of the energy demand of the non-metallic minerals sub-sector) are the object of sections 6.2 and 7.2. This includes the use of hydrogen and hydrogen-derived methane.

The other industrial sub-sectors use sector value added as the activity indicator. Each sub-sector has a single energy intensity that evolves with price-induced efficiency, with limited substitutability between thermal fuels and electricity.

## **Final energy demand: other sectors**

The energy demand for residential and services buildings is detailed per end-use: space heating, space cooling, water heating, cooking, lighting, appliances.

Several transport modes are represented, with a differentiation of goods and passengers transport: road (motorcycles, cars, light transport, heavy trucks, busses); rail; domestic water and maritime; international maritime; air (domestic and international). Different engine types are considered for vehicles in each mode.

Hydrogen can be used in fuel cells in road vehicles and maritime vessels, with a cost-based competition in the choice for new vehicles/vessels. Hydrogen-derived liquid fuels can be used in road transport, maritime and aviation, with a cost-based competition with other liquid fuels (oil products and biomass-derived liquids) within internal combustion engine vehicles/vessels/aircraft.

Finally, the energy demand for agriculture is driven by the value added of agriculture.

## Greenhouse gas emissions

All main GHGs are covered: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF<sub>6</sub>).

The CO<sub>2</sub> amounts produced by fossil fuel combustion are deduced with emission factors. By convention, the use of biomass with CCS results in a net-negative CO<sub>2</sub> balance.

Other GHG emissions (including CO<sub>2</sub> from industrial processes) are based on sector-specific activity drivers (e.g. oil and gas industry, mining, iron and steel making, waste, etc.) but can be mitigated if policies are introduced (following sector-specific marginal abatement cost curves).

Emissions from agriculture (CH<sub>4</sub> and N<sub>2</sub>O), forestry and land-use, land use change and forestry (LULUCF; CO<sub>2</sub>) are derived from information provided by the specialized GLOBIOM-G4M model.

### 3.3. Added value of this work

This work builds upon previous work in this field, namely: JRC work in steel [93], cement [55] and paper [94] production; ULCOS work on steel production [95]; the FONDDR project work in steel, cement and aluminium demand and production and glass demand [96]; Enerdata work on steel and copper demand [97] (including this author); IAMs work on cement production [98]; the WETO-H2 study [99] on hydrogen production.

Some of the above publications have resulted in modelling code and accompanying data which, following the completion of each publication, were kept throughout the years to the most recent version of POLES. For some other of the above publications, the code and data was not used beyond their scope.

The work conducted in this study consisted in modelling code enhancements and data updates for both of those cases, and their integration in a complete version of the model. The changes compared to the most recent initial version of the POLES model are noted in the following sections; summarily, they are:

- Section 5: Hydrogen
  - Demand: inclusion of new demand types for industry that do not refer to hydrogen combustion or use in fuel cells (oil refineries, chemical industry, steel production, fertilizer production); inclusion of hydrogen mixed with fossil gas in the gas distribution network for combustion in buildings and industry; inclusion of hydrogen use in the production of synthetic fuels (synthetic methane, synthetic liquids), themselves used in several transport modes and industry.
  - Production: full update of techno-economic parameters; inclusion of additional technologies; distinction of components in electrolysis technologies to take into account the simultaneous learning of power production technologies; inclusion of CCS retrofit options.
- Section 6: Steel
  - Demand: complete review of parameters.

- Production: reintegration of module (developed for a specific project but not used in the main model since about 2003); update of techno-economic parameters; addition of new fuels (biomass) and production pathways (hydrogen reduction); inclusion of technology- and fuel-specific preference factors; update of production and capacities statistics.
- Section 7: Cement
  - Demand: complete review of parameters.
  - Production: reintegration of module (developed for a specific project but not used in the main model since about 2004); update of techno-economic parameters; addition of new fuels (biomass) and production pathways (electrification of pre-heater, electric kiln, CCS); inclusion of technology- and fuel-specific preference factors; update of production and capacities statistics.

### 3.4. Methodology principles for new work

The approach chosen consisted in identifying a limited number of demand sub-sectors that explain the majority of the energy demand and emissions in industry; and in identifying a limited number of production processes that can cover residual, dominant and emerging technologies. As described in section 1.1, the materials and industry sub-sectors that were chosen were hydrogen, steel and cement. Each of the next sections focus on the assessment of each sub-sector (5: hydrogen; 6: steel; 7: cement).

The overall scheme of the materials demand and production module enriched and developed in this work is given in Figure 12. The method uses work already developed in POLES model code in particular from Hidalgo et al. (2005) [93] and Szabó et al. (2006) [55].

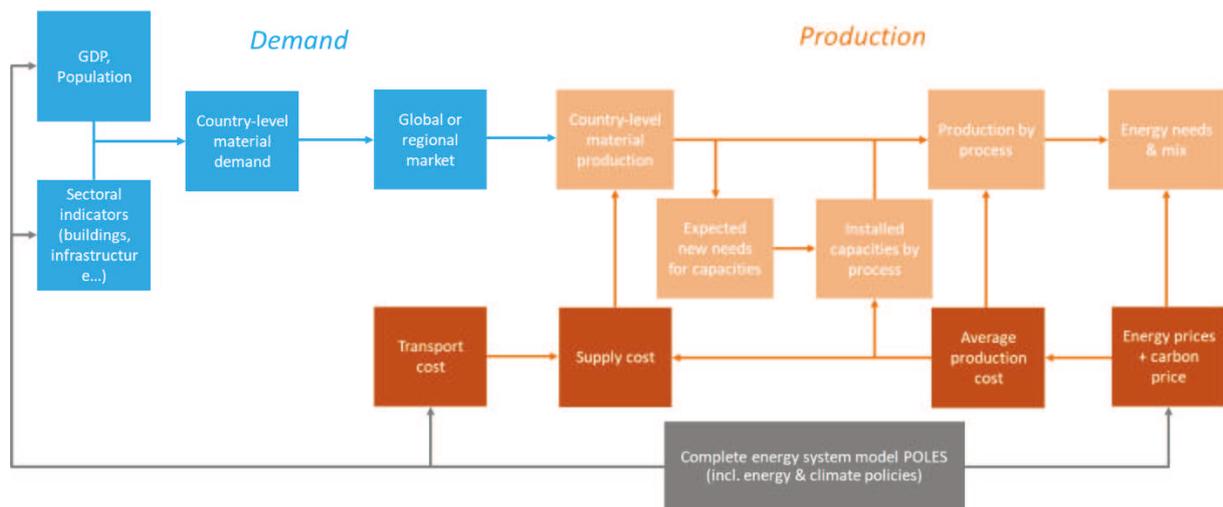


Figure 12: Schematic view of the materials module of POLES for this work

Source: own work.

For projections of demand, a bottom-up method (specific material content per use type) was chosen as a basis (i.e., the method described in section 2.2.5). Apparent demand is reconstructed from statistics on production and net trade. This makes use of drivers from the rest of the model, on energy-

using equipment and infrastructure, themselves based on trends and macroeconomic drivers (population and GDP). Effectively, the bottom-up method is equivalent to the intensity of stock approach but using the underlying drivers as the constituents of the stock. The annual material flows are derived from how the stock evolves, itself based on how the energy-using equipment or infrastructure is projected. Income per capita is used as an indicator of the level of development; as it increases, demand for equipment increases and, depending on the type of equipment, might saturate. More information on the underlying drivers can be found in the supplementary information in the annexes iv, v and vi.

For projections of production, investment in production capacities expansion is calculated based on the growth of production in past years. The choice among capacities is made using a logit distribution with total costs (amortized fixed costs and fuel costs) and preference factors unrelated to pure economics (reflecting inertia and country specificities observed on the historical mix); in addition, there is the possibility to retrofit certain processes into others (in particular for retrofitting CCS). The choice among fuels within each process is made using a logit distribution with user costs (including efficiency and carbon pricing and any process-specific constraints). The method is similar to other parts of the POLES model (see Figure 11).

The future technologies considered were limited to those with a technology readiness level today that have a reasonable chance to represent a sizable share of production capacities in the time horizon of the study<sup>10</sup>. The evolution of process efficiency and investment cost for new installations is set exogenously.

Each option has to be evaluated with several inter-related criteria in order to assess whether it is likely to make a significant impact in emissions projections:

- Costs: what is the option's cost compared to current alternatives? what will be the impact on the final user and can we expect price-induced effects on the overall demand for the final product?
- Maturity: at which stage is the option in terms of maturity level? If more R&D and policy support is needed, is it expected that the option could be readily available in the time scale of this exercise (the 2030 and 2050 time horizons)?
- Scalability: can the option be ramped up in such a way as to cover a significant share of demand or production within a reasonable timeframe? Is it constrained by non-cost elements to a certain market segment?

Net trade is the result of the difference between demand and production, with production being allocated on the basis of installed production capacities, production costs (including raw materials costs and an estimation of labour costs) and transport costs. The price of the material is calculated in a bottom-up manner, with production costs (including raw materials, labour costs, energy costs, pricing of emissions) and transport costs, with the assumption that supply chain bottlenecks are only transient and that price manipulation (like cartels) does not occur.

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<sup>10</sup> The time horizon is typically 2050, i.e. about an investment cycle away; it extended here to 2100 in order to assess how mitigation efforts result in a certain level of climate change (global mean temperature) by the end of the century, in accordance with the main objective of the Paris Agreement.

Given the global scope of the research question and the hybrid top-down/bottom-up approach of the modelling tool, certain simplifications had to be made. For instance, the projections of the materials demand side are based on aggregate indicators already present in the model (such as GDP, population, buildings floor space, road vehicles, power generation capacities).

- **Vintages:** all calculations, demand and production, are based on stocks with an average lifetime (as opposed to age cohorts).
- **Products granularity:** demand is simplified to a single product, without distinguishing sub-products (e.g. metal alloys, cements with different compressive strength) or intermediate products (e.g. steel rods and sheets, clinker) and their trade.
- **Production capacities granularity:** production capacities are classified into process categories each represented with a set of techno-economic parameters (efficiency and cost evolving over time versus a best-available technology) without further granularity (sub-components, process flows that might differentiate a plant from another).
- **Geographical granularity:** data is aggregated at the level of countries or country regions. The overall approach follows the existing architecture of the model.

Finally, the **perimeter** of study for the supply of materials is only their production industry. The energy and emissions needed to produce the inputs to the production process are not included unless explicitly mentioned: for instance, this will be the case for the indirect emissions associated with hydrogen production (section 5.2.2), as they represent an important part of the overall life cycle emissions of hydrogen. Specifically, the energy and emissions of mining activities to produce energy inputs, iron ore and limestone are not considered in this study. Although considerable, energy needs for mining and quarrying (and their associated emissions) are a small share of the overall energy use in manufacturing industry. Energy use in the mining and quarrying industry stood at 3.0 EJ in 2017 (mostly consisting in diesel and electricity), which is 2.5% of total energy use in industry [100]. Although the mining industry faces its own challenges regarding resources depletion and increasing energy use with decreasing ore grades, this is not a challenge for iron and limestone extraction specifically.

## 4. From climate science to policy: the virtuous cycle of the Paris Agreement

“We will keep going, we will keep going, because there is no such thing as fate. Because we never really come to the end.”

- “*The Ministry for the Future*” (2020 novel by Kim Stanley Robinson, USA)

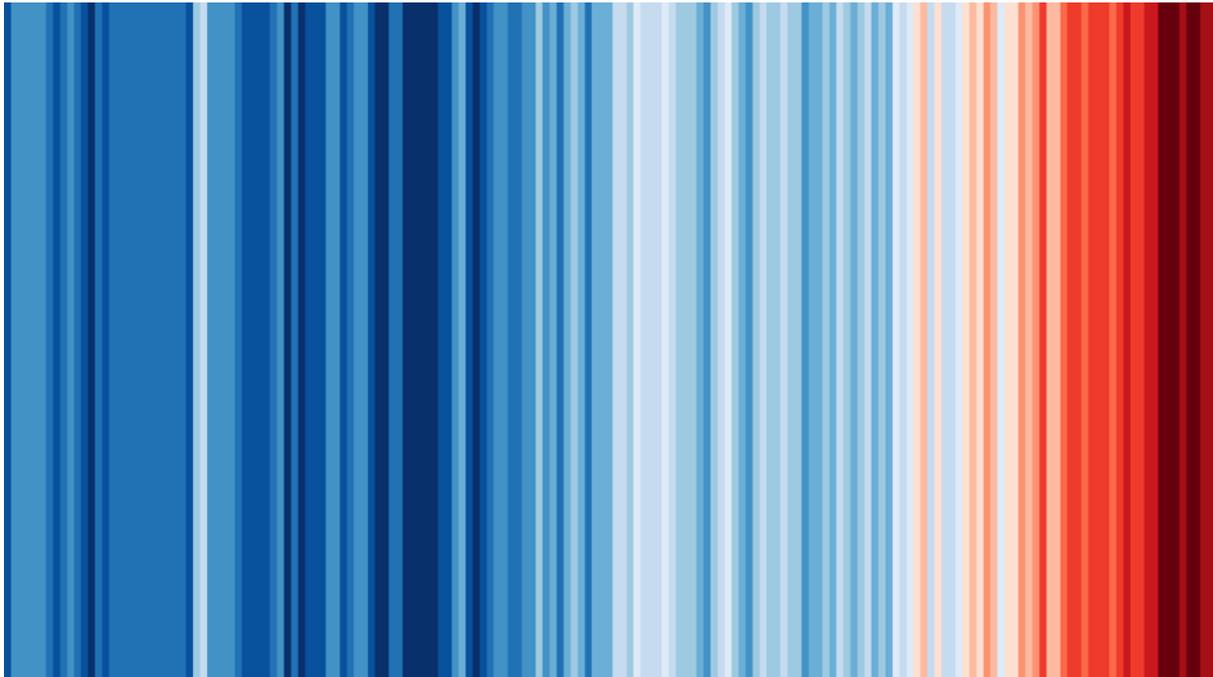


Figure 13: Warming stripes of global temperature change (1850-2022)

Source: Ed Hawkins, University of Reading<sup>11</sup>. The average global temperature in 2022 was about 1.15°C above the 1850-1900 average<sup>12</sup>.

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<sup>11</sup> <https://showyourstripes.info/>

<sup>12</sup> <https://public.wmo.int/en/media/press-release/global-temperatures-set-reach-new-records-next-five-years>

#### 4.1. Historical retrospective

International treaties on reducing the effects of climate change have been increasing in ambition ever since the establishment of the UNFCCC in 1992. The first important treaty was the Kyoto Protocol in 1997, which aimed at reducing GHGs to “a level that would prevent dangerous anthropogenic interference with the climate system” (without defining that level precisely). Its objectives included voluntary targets for GHG reductions in 37 countries (plus the EU-15 at the time) for two commitment periods, 2008-2012 and 2013-2020. The process was plagued by important countries not ratifying the treaty (USA), withdrawals (Canada) and large emissions reductions in reforming economies due not to dedicated efforts but to economic restructuring following the fall of the Soviet Union.

In preparation of the COP that resulted in the Paris Agreement, countries submitted their voluntary targets for emissions reductions, the Intended Nationally Determined Contributions (INDCs), with a time horizon of 2025-2030. The Paris Agreement defined the framework with which countries would continue submitting targets with an eye towards increasing domestic ambition. Regular 5-year updates are requested. A first wave of updates, the NDCs, was submitted in the 2018-2020 period, for 2030-2035 targets. Several analyses regularly provide estimates on how far the collective NDC targets are compared to emissions reductions compatible with the Paris Agreement target of 1.5°C [7], [17], [101]. This results in an emissions gap compared to pathways compatible with the long-term objective of 1.5°C climate change (see Figure 14).

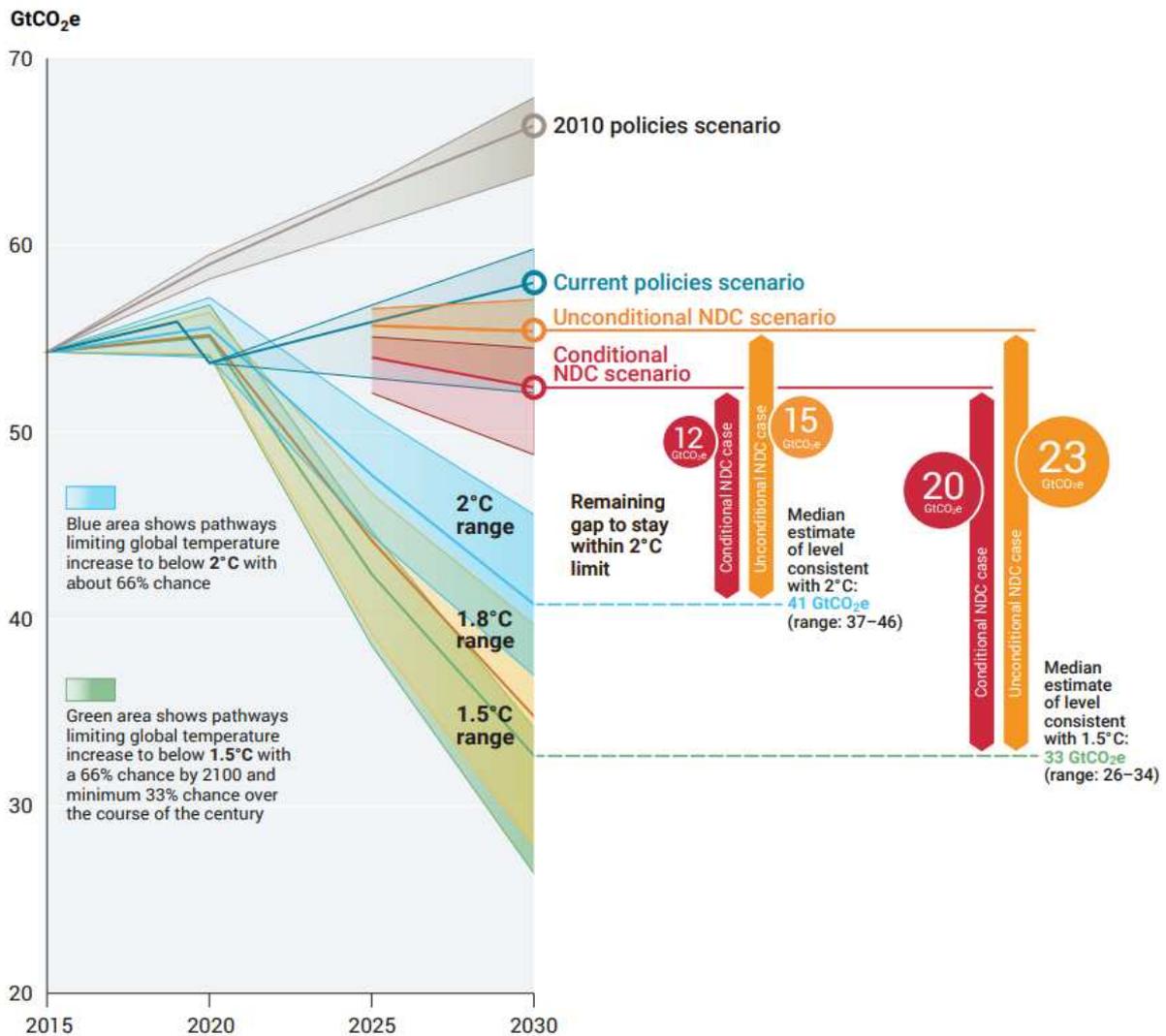


Figure 14: GHG emissions under different scenarios and the emissions gap in 2030

Source: UNEP Emissions Gap Report 2022 [7]. Note: lines note median estimates, shaded areas note tenth to ninetieth percentile range.

Following the Paris Agreement, countries are also invited to submit their long-term low greenhouse gas emission development strategies (LT-LEDS) with a time horizon of 2050 and beyond.

Every five years, the UNFCCC parties (countries) are planned to take stock of the implementation of the Paris Agreement. This global stocktake (GST) assesses the collective progress towards achieving the long-term goals of the agreement and, in turn, inform the preparation of the next round of NDCs updates. This first GST is planned for the COP of November/December 2023.

It is clear that there are large differences in historical responsibility for past emissions (also depending on how far back in time accounting should start) and large differences in the institutional and financial capabilities for countries to act on reducing their emissions. However, throughout this process, in a spirit of transparency and constructive collaboration, instead of a top-down process stemming from a central authority, the target-setting is voluntary.

The energy system model POLES has been used extensively to assess the effect of technologies and policies. Its use over a long period of time allows the comparison of different projections exercises over the years and assess whether the emissions gap has been closing (see Figure 15).

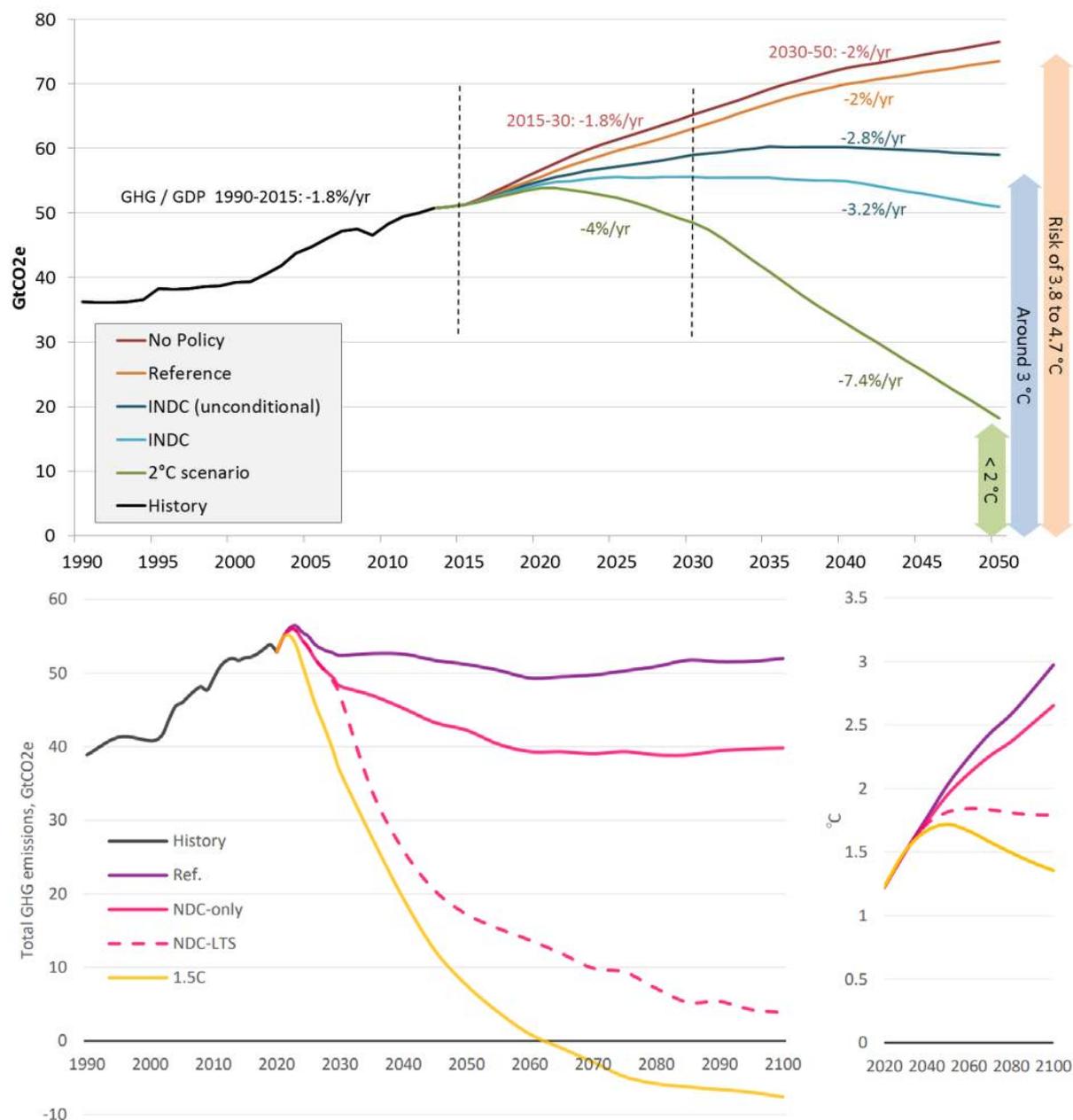


Figure 15: World GHG emissions projections and resulting global mean temperature change with current, announced and Paris Agreement-compatible climate policies

Source: JRC Global Energy and Climate Outlooks 2016 [102] and 2022 [92]: two reports six years apart.

In the next section, we will see how an energy system model can be used to project country-level and global-level emissions under a set of different assumptions, and quantify the effect of NDC targets and long-term strategies. The energy system model is complemented by a macroeconomic model that includes feedbacks of the decarbonisation effort on sectoral and overall economic activity and employment. This use of two inter-linked specialized models showcases the ability of quantitative tools to jointly provide insights on multiple aspects of a complex issue. The work developed in this section then forms the basis on which the next sections build upon, by enhancing the modelling and refining the projections.

## 4.2. Energy and employment transition implied by climate policy pledges: informing the global stocktake of the Paris Agreement

*The following scientific article was published in the journal One Earth (Cell group) in November 2023. It was previously made available publicly as a preprint in June 2022<sup>13</sup>.*

*This paper is derived from work done for the JRC Technical Report Global Energy and Climate Outlook 2021 [17], for which I was the main author, having co-conceived the research question and the modelling framework, and carried out the technical work and analysis for the energy part. For this manuscript, I co-conceived the approach and was the main modeller for the energy part; I participated in all steps of drafting this manuscript and responding to reviewers' comments.*

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<sup>13</sup> [https://papers.ssrn.com/sol3/papers.cfm?abstract\\_id=4141955](https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4141955)

## Article

# Stocktake of G20 countries' climate pledges reveals limited macroeconomic costs and employment shifts

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**SCIENCE FOR SOCIETY** The first global stocktake of the Paris Agreement reveals that the world is not on track to limit warming to safe levels. The stocktake signals the need for nations to enhance decarbonization pledges to meet the 1.5°C temperature target. Nations' pledges and efforts to decarbonize have so far been limited, in part because of concerns that transitioning from fossil fuels toward system-wide electrification will have negative economic effects. Focusing on G20 nations, the analysis reveals that increased ambition in line with a 1.5°C pathway not only avoids significant economic costs (less than 0.5% of the 2040 global GDP) but also supports an employment transition by shifting fossil fuel jobs to electricity and non-energy sectors. These findings should encourage nations when renewing pledges ahead of the forthcoming COP28.

## SUMMARY

Reaching the Paris Agreement temperature targets requires a substantial increase in individual countries' ambition to reduce GHG emissions. Research on the macroeconomic implications of global decarbonization pathways is limited, often focuses on the energy sector, and ignores shifts toward non-energy sectors, leading to concerns regarding unemployment and economic losses. We aim to analyze the mitigation options to bring emissions in line with ambitious climate targets and evaluate the macroeconomic consequences of this energy transition to investigate these concerns. Here, we assess G20 countries' pledges announced up to and during COP26 using a modeling toolbox that links energy system, macroeconomic, and climate models. Our results show that the macroeconomic costs associated with the decarbonized pathways amount to less than half a percent of the global GDP by 2040, with electrification moving jobs toward energy-intensive industry, construction, and manufacturing sectors and partially offsetting losses in fossil fuel sectors. Pursuing efforts to a 1.5°C level requires immediate action, with announced policy targets leading to an implied temperature change of 1.8°C by 2100.

## INTRODUCTION

The 2015 Paris Agreement aims to reduce global greenhouse gas (GHG) emissions to limit global temperature increase “to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C levels.”<sup>1</sup> To reach these emission reductions, the Agreement establishes a policy framework under which countries submit their nationally determined contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC), further inviting submissions of their long-term low GHG emission development strategies (LTSs). The

NDCs describe the actions to which parties commit to reach the Paris Agreement's temperature goal. The Agreement urges new NDC submissions from countries every 5 years to progressively reflect higher ambition. Nonetheless, the contributions from the first round of NDCs (submitted mainly in 2015 and 2016) are insufficient to meet the temperature targets.<sup>2,3</sup> A second round of submissions provided new or updated contributions to the UNFCCC (including LTSs) during the Conference of the Parties 26 (COP26) in Glasgow in November 2021, but less progress in increasing climate ambition was made during COP27 in Sharm el-Sheikh. However, reaching the Paris Agreement temperature targets



requires a substantial increase in individual countries' ambition, both in the short term to 2030 and in the long term.<sup>4–7</sup> The Group of 20 (G20) countries accounted for nearly 75% of global GHG emissions in 2019.<sup>8</sup> Taking stock of the G20 countries' updated NDCs and announced LTSs during COP26 helps to collectively inform their contribution to closing the emissions gap to a 1.5°C-compatible pathway (the ambition gap<sup>4</sup>), whether a recurrent challenge to all countries refers to the implementation of additional policy measures to reach the announced targets (or the implementation gap).<sup>4</sup> In this regard, the global stocktake (GST) in 2023 is scheduled to take stock of the implementation of the Agreement and assess its progress toward long-term goals, informing countries to update their actions under the relevant provisions of the Agreement.<sup>1</sup>

While several studies estimate that policies currently in place lead to a global warming increase close to 3°C or more by the end of the century, with the inclusion of net zero pledges for the long term, global warming may be limited to 2°C or even less.<sup>9–16</sup> The existing literature offers in-depth and technology-rich studies on the implications of ambitious climate policy for the energy sector<sup>17</sup> and related sectors, such as international aviation and shipping.<sup>18,19</sup> However, research on the macroeconomic implications of global decarbonization pathways is less widespread. Existing studies tend to focus on particular countries<sup>20–23</sup> or on the energy sector,<sup>24–27</sup> and a narrow sectoral scope ignores economy-wide effects and potential labor market shifts toward non-energy sectors.<sup>28</sup> Recent studies have assessed the impacts of climate policies on energy jobs globally under decarbonization scenarios,<sup>16,24,25,29</sup> concluding that net energy jobs increase globally by 2050, with renewable energy jobs partially or fully compensating for job losses in the fossil fuel sector. The economy-wide implications of the energy and employment transition implied by climate policy pledges remain a gap in the literature; hence, capturing the effects of the announced targets to assess the impacts on energy and non-energy sectors contributes to closing this gap. Understanding the implications of labor market transitions is also key to informing when and where additional action is needed to achieve a 1.5°C target while filling an important gap in the literature and contributing to the technical discussions of the GST and the policy design process.

Here, we assess all relevant pledges announced up to and during COP26 using a modeling toolbox that links energy system, macroeconomic, and carbon cycle-climate models. We aim to analyze the mitigation options to bring emissions in line with ambitious climate targets and the macroeconomic consequences of this energy transition to a low-carbon economy under three different scenarios (current policies, announced policy targets, and a 1.5°C-compatible pathway). We find that limiting global warming to well below 2°C above pre-industrial levels and pursuing efforts to a 1.5°C level requires substantial further actions, with announced policy targets leading to an implied temperature change of 1.8°C by 2100. Because all G20 countries have announced net zero targets during COP26, the ambition gap is nearly closed by 2050, gearing climate policy toward increased ambition. The macroeconomic costs of this transition to the decarbonized pathways are, however, less than half a percent of the global gross domestic product (GDP) by 2040. Electrification moves jobs toward energy-intensive industry, construction, and manufacturing sectors while partially offsetting losses in fossil

fuel sectors and promoting employment in the electricity sector, which increases by 34.9% under a 1.5°C pathway from a current policies scenario in 2050.

## RESULTS

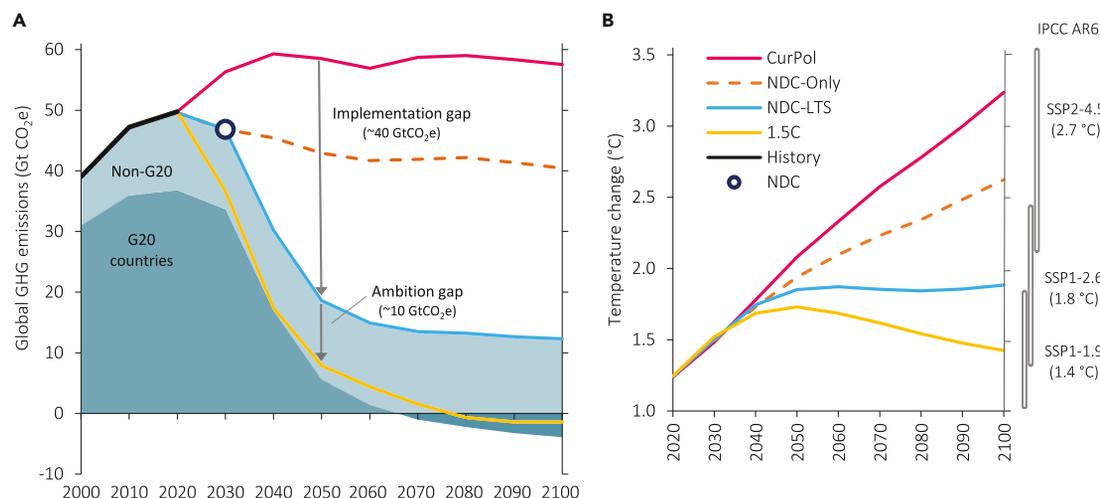
### Methods summary

We rely on a modeling toolbox to consistently build and assess decarbonization pathways in the long term. We start from the POLES-JRC model,<sup>30</sup> which is a global multi-region energy-economy partial equilibrium simulation model, in a yearly recursive framework, covering the CO<sub>2</sub> emitted from fossil fuel combustion and industrial processes, non-energy GHG land-use-related emissions, and non-CO<sub>2</sub> Kyoto GHGs: methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF<sub>6</sub>), with CO<sub>2</sub> equivalence based on the global warming potential (GWP)-100 (Fourth Assessment Report [AR4]). The model describes how multiple energy resources are transformed, resulting in flows from upstream energy production to final user demand. Based on GHG and air pollutant emissions projected in POLES-JRC, we obtain global average temperature projections with the online tool liveMAGICC,<sup>31,32</sup> a carbon cycle-climate model frequently used in the Intergovernmental Panel on Climate Change (IPCC) assessments. Next, we link POLES-JRC to the computable general equilibrium (CGE) model JRC-GEM-E3<sup>33</sup> through the Platform to Integrate, Reconcile, and Align Model-based Input-Output Data (PIRAMID) tool.<sup>34</sup> In particular, we calibrate the JRC-GEM-E3 to reflect the same macroeconomic drivers (e.g., GDP, population) as POLES-JRC. The coupling of the JRC-GEM-E3 baseline to POLES-JRC is done by fixing the economic values of energy purchases based on energy prices and quantities from POLES-JRC in the PIRAMID tool. The tool uses the multiregional generalized RAS method<sup>35</sup> to reconcile and project forward-in-time input-output tables based on the Global Trade Analysis Project (GTAP)10 databases.<sup>36,37</sup> The projected tables incorporate the economic transactions implied by energy use by sector or final demand in POLES-JRC. The data for the projected macroeconomic baselines and the energy balances used in the analysis are available from the European Commission.<sup>8,38</sup> **Table S1** lists the different data sources used.

In this paper, we use JRC-GEM-E3 to assess the employment transition implied by NDC and LTS targets (NDC-LTS scenario) as well as under a 1.5°C-compatible pathway (1.5C scenario) in contrast to a projected baseline with current policies (CurPol). The JRC-GEM-E3 model is a global, multiregion, multi-sector, dynamic-recursive CGE model especially designed to analyze energy, climate, and environmental policies, with a detailed representation of the power sector. For the policy scenarios, information describing decarbonization patterns in key mitigation sectors (electricity, transport, heating) is passed from POLES-JRC to JRC-GEM-E3.<sup>39</sup> We refer to **Figure S1**, which provides a schematic overview of the modeling toolbox, while other studies<sup>8,30,39–41</sup> provide a more detailed description of the models' functionalities and their coupling.

### A sizable emission gap still remains

Our scenarios show a clear departure from historical trends and the projected CurPol regarding GHG emissions (**Figure 1A**). CurPol and technology improvements are only sufficient to



**Figure 1. Projected global GHG emissions and mean temperature change above pre-industrial levels by scenario**

Global GHG emissions projections (in gigatonnes of carbon dioxide equivalent [GtCO<sub>2</sub>e]) and as a share of the G20 and non-G20 countries for the NDC-LTS scenario (A) and projection of the global mean temperature change (in degrees Celsius, °C) above pre-industrial levels with 50% probability (B). GHG emissions from land use are harmonized with the IPCC AR6<sup>42</sup> data for the climate calculations in liveMAGICC.<sup>31,32</sup> IPCC (2021)<sup>42</sup> best temperature estimates are shown in parentheses with the very likely temperature due to climate uncertainty for selected scenarios. The G20 countries included in our analysis are Argentina, Australia, Brazil, Canada, China, India, Indonesia, Japan, Mexico, Russia, Saudi Arabia, South Africa, South Korea, Türkiye, United Kingdom, United States, and the European Union (EU), while in our analysis and presentation of the results, France, Germany, and Italy are accounted for within the EU.

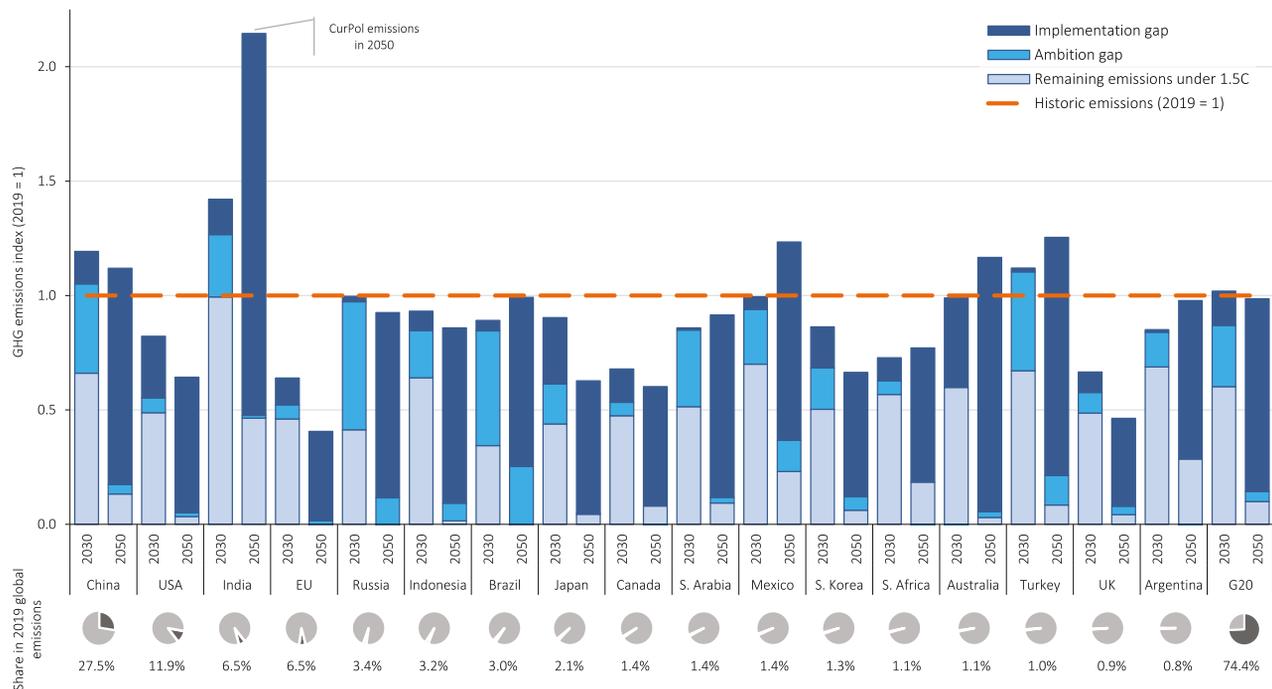
stabilize global emissions by 2035–2040, close to a 60 GtCO<sub>2</sub>e annual level, implying that the global average temperature continues to rise and exceeds 3°C by the end of the century compared with pre-industrial levels (3.2°C median, ranging from 2.5°C–4.5°C with a 66% probability) (Figure 1B). In line with den Elzen et al.,<sup>16</sup> announced targets for the short term bend the GHG emissions trajectory in the NDC-only and NDC-LTS scenarios, with global GHG emissions reaching, annually, 47 GtCO<sub>2</sub>e by 2030. When comparing the NDC-LTS with the CurPol scenario, we observe a sizable reduction of 28 GtCO<sub>2</sub>e in global annual GHG emissions by mid-century, particularly from G20 countries, that leads to an implied median temperature change that amounts to about 1.8°C by 2100 (dark blue line in Figure 1B), ranging from 1.4°C–2.8°C with 66% probability. Our estimate lies within the (very likely) range of the SSP1-RCP2.6 scenarios and coincides with the best estimate of a 1.8°C rise by the end of the century from the IPCC AR6.<sup>42</sup> While global warming remains below 2°C by the end of the century,<sup>12,13</sup> the objective of the Paris Agreement of limiting global warming to well below 2°C, preferably to 1.5°C, compared with pre-industrial levels, is not fully achieved.

The projected temperature increase in the NDC-only scenario is in line with other studies in the literature, in which the conditional NDC pledges lead to a temperature increase of about 2.6°C (median, ranging from 2.0°C–3.7°C with a 66% probability) by the end of the century despite using a different extrapolation method beyond 2030.<sup>15,43,44</sup> This result, however, substantially contrasts with the estimate of the NDC-LTS scenario (+1.8°C by 2100), and the 24.3 GtCO<sub>2</sub>e difference in the GHG emissions between these scenarios (in 2050) reveals that the world is crucially dependent on delivering on the LTS to promote early structural changes and keep global warming below 2°C.

In Figure 1A, the difference in the GHG emissions trajectory of the CurPol and the NDC-LTS scenarios provides the implementation

gap,<sup>4</sup> which reflects the additional policy measures the announced targets require to be reached. Further, to limit global warming to 1.5°C levels by 2100, more ambitious targets would be needed both in the short term, for achieving a more substantial decline of emissions toward 2030, as well as in the long term. Therefore, we obtain the ambition gap<sup>4</sup> by taking the difference in the GHG emissions trajectory of the NDC-LTS and the 1.5C scenarios. When looking at the contribution at the regional level, implementing G20 countries' long-term strategies promotes a steep reduction in global GHG emissions over 2030–2050. In the 1.5C scenario, the contribution at the regional level is calculated based on a least-cost approach, so climate change mitigation occurs in the regions and sectors with the lowest marginal abatement costs. Other important considerations include national circumstances and equity principles, which can be relevant for a fair distribution of efforts. Conversely, the NDC-LTS scenario translates regionally differentiated policies that reflect fair and equitable contributions, as countries follow the “common but differentiated responsibilities and respective capabilities” principle in their submissions to the UNFCCC. Because G20 countries are currently the main GHG emitters, the strong mitigation effort shifts the balance of global GHG emissions, making non-G20 countries (with full conditional implementation of NDCs) the main global emitters by 2050 (Figure 1A).

A comparison with GHG emissions in 2019 (orange dashed line in Figure 2) suggests different trends of the CurPol emissions by mid-century, with several of the G20 countries still close to (or even above) 2019 levels. An increasing implementation gap over 2030–2050 (dark blue bars in Figure 2) reinforces the need to immediately adopt policies to achieve their LTS targets. Early action will limit climate policy costs, and previous work has illustrated the cost of delayed action.<sup>45,46</sup> Notably, the cost of inaction might be reinforced for countries where CurPol emissions are projected to grow (e.g., India, Mexico,



**Figure 2. Implementation and ambition gaps and remaining GHG emissions indexed by region (2019 = 1) under the 1.5C scenario**

The bars in their full height show the level of GHG emissions in 2030 and 2050 under the CurPol scenario. Pie charts indicate the country's share in 2019 global emissions based on the European Commission.<sup>8</sup> G20 countries are ranked from the highest to lowest emitter (left to right). The position of the pie charts is cumulative (and proportional to 360°) and shows that G20 countries account for nearly 75% of the global GHG emissions.

and Türkiye) as the implementation gap further increases over time. Conversely, the decrease in the ambition gap from 2030–2050 (sky blue bars in Figure 2) highlights the role of announced net zero targets in getting the world closer to a 1.5°C pathway, but still with a sizable implementation gap to be closed in the short term.

Because all G20 countries have announced net zero targets during COP26, the ambition gap is nearly closed by 2050—an important outcome because these countries represent about 75% of global GHG emissions (see the pie charts at the bottom of Figure 2). Overall, we identify substantial heterogeneity between G20 countries in terms of closing the ambition gap.

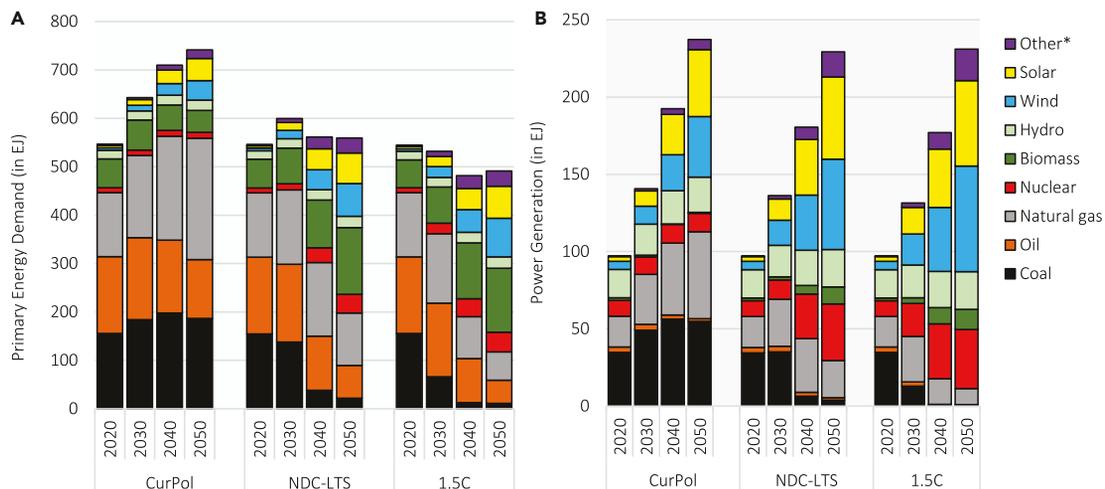
### Clean electricity is key to a low-carbon economy

Our findings indicate that a robust transition toward a low-carbon economy would rely primarily on transforming the energy system, with emission reductions in the power sector contributing the most toward realizing the emission targets in 2030. At the global level, energy efficiency gains considerably reduce primary energy demand in the NDC-LTS and 1.5C scenarios. The main change in primary energy demand from the CurPol to the NDC-LTS scenario is due to the phase-out of coal. In contrast, the largest difference in primary energy demand when moving from the NDC-LTS to the 1.5C scenario comes from the reduction in natural gas in 2050 (Figure 3A). Biomass plays an important role as a primary energy source under both scenarios by mid-century, providing solids and liquids to the final energy mix. Most importantly, we note a strong decarbonization of power generation in 2030 at the global level, with a shift from coal and (to a lesser

extent) natural gas toward low-carbon sources, mainly wind, solar, and nuclear (Figure 3B).

In all scenarios, we project increased electrification of final demand with declining technological costs and changes in end-use equipment and favorable policies leading to lower emissions intensity in the power sector. Although originating from different starting points, in Figure 4, we find that all countries move to the bottom right of the figure, meaning that they increase the share of electricity in final demand while decreasing the emissions intensity in the power sector. In the short term, electrification of final demand does not change substantially between scenarios, but we observe that emissions intensity (on the vertical axis of Figure 4) does. Nonetheless, in the long term, most countries (and the world) reach around 50% of electrification in final demand, with the emissions intensity in power generation sharply declining to less than 100 gCO<sub>2</sub>e/kWh under the NDC-LTS and to less than 30 gCO<sub>2</sub>e/kWh under the 1.5C scenario.

The downward movement is not homogeneous across countries, and we find different patterns across regions/countries in Figure 4. For instance, over 2020–2030, the United States show a steeper vertical movement, while China and India still present high emissions intensity in power generation and, consequently, move horizontally as electrification in final demand grows. We observe similar horizontal trajectories across scenarios in the European Union (EU) and Brazil, which either suggests that CurPol in power generation are ambitious (e.g., Green Deal, in the case of the EU) and/or that power generation is already a low-carbon-intensive sector, which is the case in Brazil.



**Figure 3. Global primary energy demand and power generation**

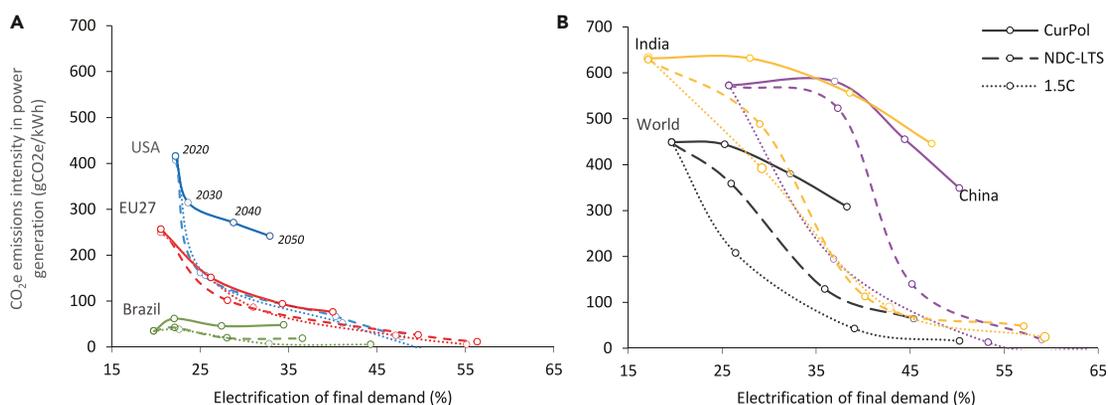
Global primary energy demand (A) and power generation (B) based on the physical energy content (in exajoule [EJ]) over 2020–2050 by scenario. \*Other, geothermal and ocean.

Nonetheless, the decarbonization of the power sector alone is insufficient for the 1.5°C target. Mitigation is also needed in the agriculture, forestry, and land use (AFOLU) sector, particularly through improved agriculture practices and deforestation control, as countries resort to the land use sink to reach climate neutrality. In this regard, suitable abatement options vary by region and over time. The AFOLU sector plays a crucial role in GHG emissions mitigation in relatively lower emitters, like Africa and Latin America. In contrast, the power sector stands as the prime driver in main emitter regions, like China and India. As mitigation increases over time (2030–2050), the area of the circles in Figure 5 becomes larger, particularly in China and India, where the share of power generation in the total mitigation potential under the 1.5C scenario is above 60% in 2030. Consequently, global mitigation also increases, reaching about 50 GtCO<sub>2</sub>e in 2050, with a substantial contribution from the decarbonization of the power sector, especially in the short term in China and India, as illustrated in Figures S2–S4.

Decarbonizing the power sector is an essential enabler of further emission reductions in other sectors, such as buildings, transport, and industry, through electrification of energy uses (e.g., electric vehicles, heat pumps, and industrial processes). In terms of global mitigation under the 1.5C scenario, while the power sector (39%) and AFOLU (13%) represent a significant share of the total mitigation potential (as illustrated in Figure 5), the remaining sectors contribute to 48% of the total mitigation potential (4% waste, 4% buildings, 9% transport, 14% energy, and 17% industry). Overall, we find countries moving toward the middle in Figure 5, meaning that their mitigation portfolio broadens over time—i.e., after having taken care of their respective low-hanging fruit abatement options, hard-to-decarbonize sectors become more relevant in the total mitigation potential.

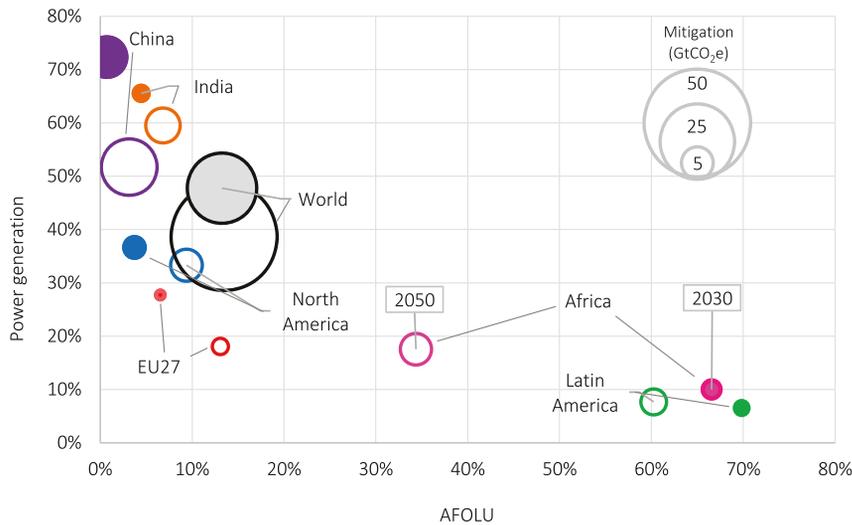
### Macroeconomic impacts of the transition

Our results reveal that the costs of the transition to a decarbonized economy under the NDC-LTS and 1.5C scenarios



**Figure 4. Share of electrification in final demand (%) and CO<sub>2</sub> emissions intensity (gCO<sub>2</sub>e/kWh) by selected countries/regions under the CurPol, NDC-LTS, and 1.5C scenarios**

The figure is divided into two panels to avoid overlapping lines and improve visualization: regions with CO<sub>2</sub> emissions intensity lower than 450 gCO<sub>2</sub>e/kWh in 2020 (A) and regions with CO<sub>2</sub> emissions intensity greater than 450 gCO<sub>2</sub>e/kWh in 2020 (B).



**Figure 5. Share of agriculture, forestry, and land use (AFOLU) and power generation in total GHG emissions mitigation under the 1.5C scenario compared with CurPol in selected countries/regions in 2030 (solid fill) and 2050 (no fill)**

Remaining values to 100% are abatement options in other sectors (e.g., transport, buildings).

the NDC-LTS and 0.8% under the 1.5C scenario relative to CurPol in 2040. The investment in power technologies stands out as the prime driver of the transition (84% and 62% increase under the NDC-LTS and 1.5C relative to CurPol, respectively), and we find a positive correlation between investment expansion and output growth in agriculture and construction sectors,

are less than half a percent of the global GDP by 2040 (Table 1). In other words, we project a 2.70% growth per annum in the GDP under both scenarios, while under the CurPol scenario, the GDP is projected to grow 2.72% per annum over 2020–2040. We note that uncertainty grows as we project further in time. Hence, we specifically analyze the macroeconomic impacts for 2040 to offer more practical implications, rather than by mid-century (e.g., 2050). The output (production) of fossil fuel sectors considerably decreases (e.g., 26.1% oil products and 46% gas in the 1.5C scenario), led by the phase-out of coal (87.8%), while agriculture (including biomass production), electricity generation, and construction increase 4.4%, 5.2%, and 1.1%, respectively (in the 1.5C scenario). Investments in renewables in power generation and the need for additional transmission systems promote growth in the construction sector. At the same time, biomass production expands as another source of mitigation in various regions. We also observe the growth of industrial sectors related to final uses (e.g., transport and other equipment goods) that also deliver abatement equipment (e.g., electric goods), contrasting with energy-intensive industries, where a general “capital deepening” occurs, with investment flowing more into energy efficiency measures.

Regarding changes within global energy supply chains, the analysis of trade flows reveals an increasing concentration in the gas market into a few exporting countries (e.g., the Gulf area and Australia). A similar trend appears in the crude oil market, where exports from Gulf countries and Russia remain relatively stable under the NDC-LTS scenario, while marginal players (e.g., African countries, Canada, and Mexico) lose market share. The scenarios do not consider any long-term strategic decisions of economies to move away from Russian exports because of the Russian invasion of Ukraine. Global trade of oil products decreases, particularly from leading exporters (e.g., exports from the United States decrease, on average, 3.4% per annum over 2020–2050). However, the decrease in trade is even stronger for coal, with an average drop of 4.8% per annum under the 1.5C scenario between 2020 and 2050. The structural change of the energy system implies substantial additional investment, leading to an increase in total global investment of 1.0% under

the NDC-LTS and 0.8% under the 1.5C scenario relative to CurPol in 2040. The investment in power technologies stands out as the prime driver of the transition (84% and 62% increase under the NDC-LTS and 1.5C relative to CurPol, respectively), and we find a positive correlation between investment expansion and output growth in agriculture and construction sectors,

which is not the case in energy-intensive industry and transport. In addition to sector-specific results for output and investment, Table 1 shows results for employment in 2040 by scenario. We simulate two tax recycling schemes and two labor market closures in the JRC-GEM-E3 model. The recycling schemes cover carbon pricing revenues directly recycled by governments to households through lump-sum (LS) transfers or a tax rebate (TR), in which the revenue is used to lower labor taxes. Regarding the labor market closure, in the fixed setup, we assume that the determinants of unemployment in the long term are not affected by the climate policy and that the net effect on overall employment is zero (i.e., a perfect labor market with adjustments of wages, in which the aggregate employment is stable in the long term). Alternatively, the endogenous setup relies on the efficiency wage approach to represent regional unemployment according to a wage curve mechanism,<sup>47</sup> in which the key assumption is that unemployment is the negative of employment, meaning that unemployment represents the gap between labor supply and a fixed labor force.

By 2040, a global transition of jobs from fossil fuel- to low-carbon-oriented sectors is expected (Table 1), in which the fossil fuel industry experiences the most significant losses compared with the CurPol scenario, especially due to the coal phase-out. Rebates on labor taxes help promote employment in labor-intensive sectors (e.g., agriculture and forestry), particularly in the 1.5C scenario, which shows a remarkable positive change in these sectors than in the NDC-LTS compared with CurPol. Nonetheless, the different recycling schemes hardly affect the transition of jobs in the energy sectors. In terms of labor market closure, the total number of jobs decreases (0.3%–0.6% under the NDC-LTS and 1.2%–1.6% under the 1.5C scenario) as lower real wage rates push workers voluntarily out of the market (endogenous setup), particularly in the transport and services sectors, which grow less than in CurPol over time.

Output changes are also reflected in employment numbers (e.g., in fossil fuel sectors). Figure 6 reports the projected changes in global labor demand in 2030 and 2050 by scenario, ranked by the absolute change in the number of jobs by sector. The deployment of renewables and greater electrification

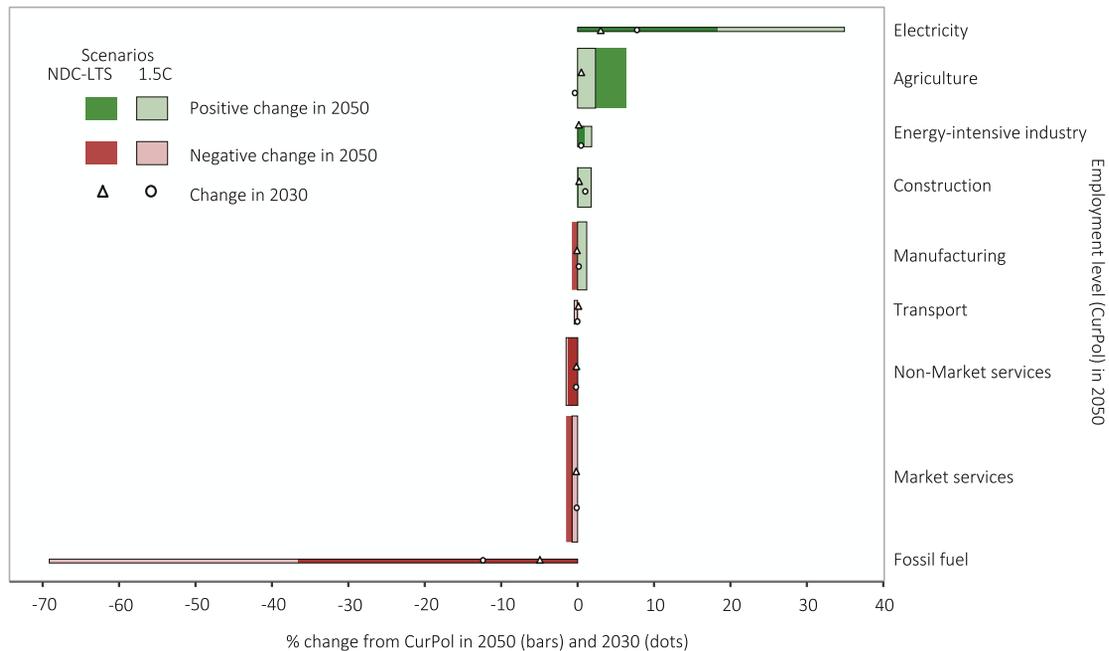
**Table 1. Global sector-specific output, investment and employment in 2040 by scenario, and under different tax recycling schemes and labor market assumptions**

% change from CurPol Scenario	Output level		Investment		Employment							
	NDC-LTS	1.5C	NDC-LTS	1.5C	NDC-LTS				1.5C			
Carbon revenue recycling Labor market <sup>a</sup>	LS fixed	LS fixed	LS fixed	LS fixed	LS fixed	LS endog	TR fixed	TR endog	LS fixed	LS endog	TR fixed	TR endog
Global <sup>b</sup>	-0.4	-0.5	1.0	0.8	-	-0.6	-	-0.3	-	-1.6	-	-1.2
Agriculture and forestry	5.2	4.4	5.1	4.6	3.9	3.8	4.1	4.1	3.5	3.2	3.7	3.5
Livestock	-1.9	-2.7	-0.4	-1.2	0.8	0.5	0.8	0.7	-1.5	-2.2	-1.6	-2.1
Coal	-73.5	-87.8	-76.9	-87.3	-66.8	-66.9	-66.8	-66.9	-86.8	-86.2	-86.1	-86.1
Crude oil	-22.0	-25.7	-19.0	-24.8	-12.9	-13.6	-15.1	-15.2	-25.4	-24.9	-26.6	-26.5
Oil products	-22.2	-26.1	-16.1	-21.4	-10.9	-11.8	-11.0	-11.5	-20.3	-22.3	-20.3	-21.9
Gas	-25.4	-46.0	-20.1	-41.5	-15.6	-15.7	-16.0	-15.9	-43.3	-43.2	-43.6	-43.4
Electricity	3.9	5.2	84.1	62.1	15.2	14.8	15.2	14.9	25.7	23.3	25.0	23.6
Ferrous metals	-0.4	-0.1	4.6	10.4	1.4	0.8	1.4	1.0	2.0	-0.1	2.4	0.8
Non-ferrous metals	0.1	-0.5	1.9	3.7	1.3	1.0	1.1	0.9	2.4	1.0	2.7	1.5
Chemical products	-0.8	-0.9	1.0	0.8	0.1	-0.3	0.1	-0.3	0.7	-0.7	1.1	-0.3
Paper products	-0.5	-0.4	0.9	1.7	-0.2	-0.9	-0.3	-0.7	0.1	-1.9	0.1	-1.5
Non-metallic minerals	-0.1	-1.1	1.5	1.5	-0.2	-0.6	-0.1	-0.4	-0.1	-1.2	0.0	-0.8
Electric goods	0.6	1.7	0.8	2.8	0.1	-0.3	0.1	-0.2	3.4	1.5	4.1	2.4
Transport equipment	0.4	0.4	2.4	2.8	-0.7	-1.5	-0.8	-1.3	0.3	-1.7	0.4	-1.2
Other equipment goods	0.0	0.3	0.8	2.0	-0.8	-1.4	-0.7	-1.1	0.2	-1.9	0.8	-1.1
Consumer goods industries	-0.7	-0.7	0.6	1.3	-0.4	-1.0	-0.4	-0.8	-1.0	-2.7	-1.0	-2.4
Construction	1.0	1.1	2.0	2.9	0.4	-0.1	0.5	0.2	0.8	-0.6	0.9	-0.1
Transport	-1.5	-1.7	2.3	2.3	0.3	-0.7	0.2	-0.5	0.0	-3.0	-0.5	-3.0
Market services	-0.3	-0.1	0.1	0.5	-0.9	-1.7	-0.9	-1.4	-0.6	-2.7	-0.7	-2.4
Non-market services	-0.3	-0.2	0.1	0.4	-0.7	-1.2	-0.7	-1.0	-0.8	-1.9	-1.0	-1.8

LS, lump-sum transfers to households; TR, tax rebates on labor taxes.

<sup>a</sup>Fixed (fixed) or endogenous (endog) regional unemployment rates.

<sup>b</sup>Output shows global GDP change from the CurPol scenario.



**Figure 6. Global transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenarios**

The labor market is fixed and with LS transfers to households of carbon revenues (LS fixed in Table 1). The horizontal axis shows the percent change in sectoral employment relative to the CurPol scenario, and the vertical axis shows the level of employment under the CurPol scenario in the year 2050. The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.

promote jobs in the electricity and construction sectors, which absorb the workforce from fossil fuel and agriculture sectors, as biomass production expands by 2050.

At the global level, the electricity sector jobs grow 18.3% in the NDC-LTS scenario and 34.9% in the 1.5C scenario relative to the baseline with CurPol (Table S2), partially offsetting job losses in fossil fuel sectors. This pattern is also observed at the regional level (Figures S5–S13). We find a positive impact of renewable energy on the number of jobs in Europe (Figure S5) under the NDC-LTS and 1.5C scenarios, which leads to important changes in the number of jobs in the electricity sector by mid-century.<sup>22</sup> Labor demand increases in energy-intensive industries because of enhanced competitiveness in transport, construction, and manufacturing. Changes in North America (Figure S6) follow a similar pattern, with electrification moving jobs toward electricity, energy-intensive industry, construction, and manufacturing sectors, particularly under the 1.5C scenario. Beyond the effects of coal phase-out and renewables deployment over the labor market in Asia (Figure S7), agriculture has a prominent role in Latin America, Africa, and Eurasia (Figures S8–S10), with job opportunities arising from crops and biomass production. As global demand for oil products reduces, jobs in the construction sector decrease in the Middle East from 2030 onward (Figure S11), while labor demand in the construction sector is propelled in Oceania (Figure S12).

## DISCUSSION AND CONCLUSION

By assessing all relevant pledges announced up to and during COP26 within a consistent modeling toolbox, this paper finds that (if achieved) the updated NDCs and LTSs pledges stabilize

global GHG emissions over the following decades, leading to declining emissions toward 2050. Assuming full implementation of net zero targets limits the global mean temperature increase to 1.8°C at the end of the century (with CurPol leading to a temperature change in excess of 3°C). This finding echoes the conclusion from other studies<sup>9–12,14,42</sup>—immediate action is required to achieve well below 2°C and pursue efforts to reach a 1.5°C temperature increase above pre-industrial levels by the end of the century. Based on the targets described in Table 2, we further analyze what it can take for the G20 countries to reach net zero, informing the first GST under the Paris Agreement with important messages, especially for policymakers. Increased short-term ambition through climate mitigation policies to address the implementation gap is required (e.g., power sector decarbonization with a shift toward low-carbon sources). Several countries (e.g., China, India, Russia, Saudi Arabia, and Türkiye) do not have targets (let alone policies) consistent with the 1.5°C target (Figure 2), implying a substantial ambition gap in 2030 and the need to ratchet up their targets as a priority. Conversely, with long-term targets set for most large emitters, the ambition gap largely disappears by 2050. However, as the implementation gap remains, a strong need prevails to set up climate mitigation policies and pursue climate action.

We note that the interpretation of the economic results does not include the benefits of climate policy in the form of avoided climate damages or co-benefits, such as cleaner air.<sup>48</sup> Future work could enhance the analysis by including these dimensions, reducing the total costs of the climate policy scenarios. The effects of the energy transition *within* sectors are not fully captured (e.g., structural changes in supply chains, shifts in the production

**Table 2. NDCs and net zero targets of G20 countries ranked by the share of 2019 global GHG emissions**

G20 countries	Global GHG emissions, 2019 (including LULUCF) (%) <sup>a</sup>	NDC (conditional) target (reduce all GHG emissions by 2030, unless noted) <sup>b</sup>	Net zero target (all GHG emissions, unless noted) <sup>c</sup>
China	27.5%	peak CO <sub>2</sub> emissions before 2030, 65%+ lower carbon intensity in 2030 relative to 2005, around 25% non-fossil primary energy use	2060 (CO <sub>2</sub> only)
United States	11.9%	50%–52% below 1990 levels	2050
India	6.5%	reduce GHG intensity of GDP by 45% by 2030 from 2005 level, 50% non-fossil electricity generation capacity by 2030, 500 gigawatts (GW) of renewables in electricity generation capacity by 2030	2070
European Union (EU)	6.5%	55% below 1990 levels	2050
Russia	3.4%	30% below 1990 levels	2060
Indonesia	3.2%	reduce LULUCF emissions to only 22 Mt and limit total GHG emissions to 1.68 GtCO <sub>2</sub> e by 2030	2060
Brazil	3.0%	50% below 2005 levels	2050
Japan	2.1%	46% below 2013 levels	2050
Canada	1.4%	45% below 2005 levels	2050
Saudi Arabia	1.4%	reduce 278 MtCO <sub>2</sub> e by 2030 relative to BAU scenario	2060
Mexico	1.4%	36% below BAU scenario (0.99 GtCO <sub>2</sub> e in 2030)	50% below 2000 levels by 2050
South Korea	1.3%	40% below 2018 levels	2050
South Africa	1.1%	Decarbonizing the power sector by 2050, expansion of electric vehicles and carbon capture and storage (CCS) for producing synthetic fuels	2050 (CO <sub>2</sub> only)
Australia	1.1%	26%–28% below 2005 levels	2050
Türkiye	1.0%	21% reduction in GHG emissions from BAU in 2030, interpreted as 116% increase from 2012 GHG emission levels	2053
United Kingdom	0.9%	68%+ below 1990 levels	2050
Argentina	0.8%	19% below 2007 levels	2050 (CO <sub>2</sub> only)

Submissions up to 12 October 2021 included.

<sup>a</sup>GHG emissions in 2019 (including land use, land-use change, and forestry [LULUCF]) based on the European Commission.<sup>8</sup>

<sup>b</sup>Targets from the UNFCCC registry<sup>66</sup> and as announced during COP26.

<sup>c</sup>Considering pre-COP26 submissions to the UNFCCC registry and COP26 announcements. Some countries may have confirmed their net zero targets in subsequent submissions to the UNFCCC registry (e.g., South Korea), while some may not yet have done so (e.g., India).

of internal combustion engine vehicles to electric vehicles) and are a potential source of future modeling developments. Further, the transition of jobs does not necessarily imply a direct transfer from one sector to another because skills are not directly interchangeable and may actually reflect that new workers entering the labor force follow a different career (also because part of the workforce will retire before 2050). In addition, we do not consider the territorial dimension of certain sectors (e.g., fossil fuel jobs might be small on the aggregate regions but concentrated at the sub-regional level).

Using comprehensive bottom-up modeling of energy systems globally, we show that closing the implementation and ambition gaps could be achieved through substantial decarbonization of the power sector by mid-century, which further

enables GHG emissions mitigation through the electrification of energy uses in other sectors (e.g., buildings and transport). We account for updated technology cost projections to assess the impacts on the global economy because of an underlying shift in investment and a transition in the labor market from fossil fuels toward sectors that deliver clean energy. The methodological improvements in this study helped to extend previous work from Vandyck et al.<sup>40</sup> and provide detailed employment results by region, sector, and scenario based on updated policies, jobs data, and near- and long-term climate policy pledges. Unlike Vandyck et al.,<sup>40</sup> in which the policy scenarios project a decrease in total global investment (0.4%–0.6%), we find that total global investment grows by 1% compared with CurPol. The different sign of investment change compared

with Vandyck et al.<sup>40</sup> is mainly driven by a more consolidated coupling of the POLES-JRC to the JRC-GEM-E3 model in the current model version. As a result, increased electrification (e.g., in transport and buildings) induces additional direct investments, with energy investments reaching 4.5% of total global investment under the NDC-LTS scenario in 2040, while the additional electricity demand also triggers more investment into renewable energy generation technologies (electricity sector in Table 1). This effect is also visible in an increase in electricity generation, which contrasts with the decrease in the output of electricity globally projected by Vandyck et al.<sup>40</sup>

As a key outcome for the technical assessment of the GST, we find that the macroeconomic costs of this transition to the decarbonized pathways are less than half a percent of the global GDP by 2040. We consider results for 2040 because it illustrates the transition between achieving NDC targets and mid-century pledges. Deploying renewables, increased efficiency in the energy systems, and enhanced electrification fosters employment in certain energy-intensive and manufacturing industries (e.g., in the 1.5C scenario, jobs in ferrous metals grow up to 2.4%, in non-ferrous metals up to 2.7%, and in electric goods up to 4.1% when using TRs to lower labor taxes). Because of the transition in the power sector, investment positively drives employment levels in the construction sector (up to 0.9% with TRs in the 1.5C scenario), particularly because of the infrastructure expansion required in the energy transition. Electrification and bioenergy, as core mitigation options, offer increasing employment opportunities, particularly in the electricity production (increases up to 15.2% and 25.7% under the NDC-LTS and 1.5C scenarios, respectively) and agriculture sectors, with the latter, as a labor-intensive sector, absorbing jobs under both scenarios in 2040 (increases up to 4.1% and 3.7% under the NDC-LTS and 1.5C scenarios, respectively). Net energy jobs increase globally by 2050, with renewable energy jobs partially compensating for job losses in the fossil fuel sector. We estimate 10.9 million (1.5C) to 16.8 million (NDC-LTS) net energy jobs in 2050 relative to 2015 (Table S2), in the range of 8 million of the well below-2.0°C scenario in Pai et al.<sup>24</sup> to 28.6 million net energy jobs of the 100% renewable energy scenario in Jacobson et al.<sup>25</sup> Moreover, under the 1.5C scenario, we estimate that 75% of the total renewable energy jobs relate to solar and wind power generation when accounting for direct energy jobs and indirect jobs in the construction sector (but not including the manufacturing of renewable energy equipment). At the same time, the results in Figure S13 show that global energy jobs follow a similar trend as the well below 2°C scenario in Pai et al.<sup>24</sup> and increase by nearly 50% from 2020–2050.

We expand the existing knowledge on the energy and employment transition implied by climate policy pledges by looking at regional and sectoral levels in detail, thus providing new insights concerning shifts in energy jobs. As ambition increases (from CurPol to the 1.5C scenario), net energy jobs decrease in fossil fuel-exporting countries, whereas increased ambition promotes more energy jobs in China and the EU by 2050. In all regions, we observe that the deployment of renewables and greater electrification promote jobs in the electricity sector, absorbing the workforce from the fossil fuel sectors, which face the most substantial decrease in employment but represent only a relatively small share of the overall labor market.<sup>40</sup> We find that, by 2030, the

overall changes in employment levels are relatively small.<sup>16</sup> However, differences across sectors already emerge, with fossil fuels and electricity reaching around 10% of change, while the remaining sectors stay close to CurPol levels. The renewable energy sector growth also positively affects the number of jobs indirectly because of the links to other economic activities. Therefore, under the 1.5C scenario, in 2050, we find that employment increases by 2.3% in the agriculture sector (e.g., bioenergy-related activities) and by 1.8% in the construction sector, further amplifying the offset promoted by the number of direct renewable energy jobs.

Based on the best available science, the GST scheduled for November 2023 also aims to indicate options for closing the implementation (and ambition) gap. We quantify the gaps in this paper; delivering on the announced climate policy targets would imply global warming of 1.8°C by 2100 compared with pre-industrial levels. Because no significant changes in ambition were proposed during COP27, our results based on announcements made in the context of COP26 are relevant to inform the GST by assessing how far the individual pledges align with the Paris Agreement temperature target. Our results further shed light on the macroeconomic implications of implementing the pledges and what further transitions would need to happen to reach the 1.5°C target. We conclude that the effects of the new/updated NDCs and announced LTS may have substantial implications for the labor market and should be carefully considered in the output of the GST. Great attention should be given to renewables jobs in particular, given that (re)training cannot occur on the job.<sup>49</sup> Our study captures the upstream and downstream supply chain linkages implied by the announced pledges informing the global and regional economy-wide effects on the labor market, thus filling an important gap in the literature and contributing to the technical discussions of the GST. Decarbonizing the power sector enables mitigation through electrification in other sectors of the economy while promoting jobs that are shifted away from fossil fuels to other sectors.

## EXPERIMENTAL PROCEDURES

### Resource availability

#### Lead contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact, Rafael Garrafa (rafael.garrafa@ec.europa.eu).

#### Materials availability

This study did not generate new unique reagents.

#### Data and code availability

All data presented in this paper are available in this paper's supplemental information and have been deposited into and are publicly available at Zenodo: <https://doi.org/10.5281/zenodo.8052969>. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

### Modeling framework

POLES-JRC endogenously calculates international energy prices. Lagged supply and demand adjustments allow describing full development pathways by world region. The model provides full energy and emission balances for 66 countries and regions worldwide, including an explicit representation of G20 countries. The technology costs in POLES-JRC are continuously updated and aligned with investment patterns with country behavior. POLES-JRC technology costs (investment costs) are documented in Duan et al.<sup>50</sup> and Krey et al.<sup>51</sup> Modeling intercomparison exercises (e.g., Bertram et al.<sup>52</sup>) also

illustrate the robustness of the POLES-JRC assumptions on technology costs, while we constantly track the most recent technology deployment and follow announced and under-construction projects. Based on GHG and air pollutant emissions projected in POLES-JRC, we obtain projections of the global average temperature with the online tool liveMAGICC,<sup>31,32</sup> a carbon cycle-climate model frequently used in the IPCC assessments. Agriculture and land historical emissions are harmonized to national inventory data (when not available, they are harmonized to data from the Food and Agriculture Organization); emissions projections are obtained by reporting changes from interpolating the output of multiple scenario runs of the GLOBIOM model<sup>53</sup> that varied on biomass use and carbon price.<sup>54</sup>

The JRC-GEM-E3 model simultaneously computes the market equilibrium (supply and demand) in the goods and services markets and production factors (labor and capital) markets. Economic agents optimize welfare (households) and costs (firms), and market prices guarantee a global equilibrium endogenously. The modeling toolbox captures the energy transition in rich technological detail based on the outcomes of the bottom-up POLES-JRC model while simultaneously accounting for economy-wide job impacts across sectors in the multiregional input-output (MRIO)-CGE framework of the JRC-GEM-E3 model, including indirect (because of linked economic activities) and induced jobs (because of income spending). The International Labor Organization (ILO) database<sup>55</sup> is used to project the labor force, unemployment rate, and share of skilled and unskilled workers in the long term. We extend the work of Vandyck et al.<sup>40</sup> by projecting the number of workers in the energy sectors based on employment factors (number of jobs/energy unit produced) for the countries available in the dataset provided by Pai et al.<sup>24</sup> In the JRC-GEM-E3 model, we multiply the total output of the energy sectors to calculate and project the total number of jobs in those sectors by 2050. In a final step, the labor compensation in JRC-GEM-E3 is adjusted accordingly to project the multiregional input-output tables as the baseline scenario.<sup>38</sup>

### Scenarios

We assess three different scenarios: (1) CurPol, (2) announced policy targets (NDC-LTS), and (3) 1.5C. In all scenarios, we account for the effects of the coronavirus disease 2019 (COVID-19) pandemic on the energy system by using updated macroeconomic figures (annual GDP growth revised for 2020–2027) and include revised parameters to describe short- and long-term effects on transport. These adjustments include a pathway of passenger and goods activity levels for 2020–2023, structural changes in passenger mobility by mode (induced by the pandemic compared with earlier behavior), and decreased rate of stock of vehicles turnover for 2020–2022.<sup>8</sup>

(1) The CurPol scenario is built on existing climate and energy policies; we do not include additional policies compared with what had been legislated as of 2019 (i.e., policies that have not been translated into a legal framework, such as laws, decrees, resolutions, or concrete action plans). Exogenous macroeconomic projections for GDP and population<sup>56–60</sup> and endogenously calculated energy prices and technological developments specific to the POLES-JRC model, combined with the effect of enacted policies, are used to calculate projections of the energy system and GHG emissions. Consequently, this scenario may differ from energy and emissions projections from official national sources (e.g., business as usual [BAU] scenarios) and international organizations. Garaffa et al.<sup>61</sup> provides a comprehensive list of policies considered in this scenario, and the carbon price is one element of many other instruments. Because we do not increase the stringency of other policy targets, we keep the carbon prices constant post 2030. It would be challenging to balance the increasing stringency of carbon prices with other targets; countries that have specific targets for renewables or energy efficiency may have lower carbon prices than countries that only state an emission target without information on how to achieve it. For the latter, the emission target is achieved only via a carbon price, which may be a more conservative approach compared with other studies (e.g., Aleluia Reis and Tavoni<sup>13</sup> and the European Commission<sup>62</sup>).

(2) The NDC-LTS scenario considers the policies of NDCs in the medium term and the LTSs in the longer term, assuming that the objectives in the NDCs (including conditional objectives) are reached in 2025–2030. To this end, carbon prices and other regulatory instruments are put in place on top of the existing, legislated measures of the CurPol scenario to achieve the different elements that may be included in the pledges. In the case where the NDC has more than one element (e.g., China's NDC includes targets for non-fossil primary energy use and carbon emissions intensity and peaking),

multiple instruments are used simultaneously: carbon pricing, energy efficiency measures in the form of energy taxation, and support to renewables. Apart from the carbon price, which is kept constant, instruments are progressively phased out when the NDC objectives are reached. Lacking any clear policy indication as to the fate of these policies after 2030, carbon prices in the NDC-LTS and the NDC-only scenarios were kept constant after 2030. Beyond 2030, the objectives of the countries' LTSs, where they exist, are pursued with the carbon price; if the country has not announced an LTS, then it is assumed that no additional effort is made, and carbon prices are frozen at their 2030 level. The NDC-LTS scenario also considers decarbonization proposals related to international aviation and maritime transport fuels (international bunker fuels). International bunkers accounted for 4.3% of 2019 global GHG emissions.<sup>62</sup> Policy instruments for GHG emissions reduction of international bunker fuels (e.g., efficiency improvements, carbon intensity targets) were modeled according to the International Maritime Organization (IMO) GHG strategy<sup>63</sup> and the International Civil Aviation Organization (ICAO) goals.<sup>64</sup> We note that the NDC-LTS scenario was designed to first achieve the NDC target, with net zero as subsequent targets, which may imply steep GHG emissions reductions between the NDC and the net zero targets. When it was not possible to solve POLES-JRC for a pathway with both of these targets, the net zero target year was slightly relaxed in certain countries. We do not consider other feasibility dimensions, such as social or institutional constraints, which can limit the ability to implement steep trajectories in the real world.<sup>65</sup> Table 2 describes NDCs and net zero targets of G20 countries, while Garaffa et al.<sup>61</sup> provide a comprehensive list of policies considered in this scenario.

As an additional sensitivity, we modeled a NDC-only scenario, where the effect of the LTSs was removed from the NDC-LTS scenario to quantify the impact of each set of objectives; in this NDC-only scenario, carbon prices of the NDC-LTS scenario were kept constant after 2030. While we take stock of all updates in the NDCs and LTSs announced during COP26, we highlight the G20 countries' transition as main global GHG emitters. Table 2 presents the NDCs and net zero targets of G20 countries ranked by the share of 2019 global GHG emissions. The net zero targets reflect the announcements made during COP26 (with submissions up to October 12, 2021, included). Because the timing of the policy process varies, several countries have announced net zero targets, but not all have submitted LTSs. Countries may also review their NDCs according to more recently announced net zero targets, which reinforces the need for assessing their contributions to the UNFCCC registry<sup>66</sup> on a systematic basis.

(3) The 1.5C scenario assumes a global GHG trajectory consistent with a likely chance of meeting the Paris Agreement temperature goals. This scenario was designed with a global carbon budget of approximately 500 GtCO<sub>2</sub> cumulated net emissions over 2018–2100 and a 50% probability of not exceeding 1.5°C of global warming at the end of the century compared with pre-industrial levels. The carbon price is differentiated across regions according to their per-capita income, with wealthier regions having a higher carbon price and poorer regions progressively catching up to that price; this was done according to the schedule described in Garaffa et al.<sup>61</sup> The differentiation attempts to reflect a possible staged implementation of climate policies to account for each country's financial capacity and response flexibility. This scenario does not consider financial transfers between countries. The mobilization of biomass as an energy resource is kept lower than 170 EJ/year for all years to reflect the use of only sustainably grown biomass,<sup>18</sup> and the use of negative emissions technologies is relatively limited (lower than 14 GtCO<sub>2</sub>/year in 2100). Moreover, CO<sub>2</sub> capture and direct air capture technologies are made available progressively beyond 2030 (lower than 7 GtCO<sub>2</sub>/year in 2050). Given these economic and technological constraints, the overshoot of the temperature target was kept slightly above 1.7°C (reached in 2050), closer to the range of C2 scenarios.<sup>67</sup> The scenarios submitted to the IPCC AR6 cycle<sup>67</sup> comprise eight different climate categories (C1–C8). C1 and C2 include scenarios compatible with an average global warming of 1.5°C by the end of the century, considering no or limited overshoot (peak warming of 1.6°C) and high overshoot (peak warming of 1.7°C), respectively.

### SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.onear.2023.10.012>.

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## AUTHOR CONTRIBUTIONS

Conceptualization, R.G., M.W., and T.V.; validation, R.G., M.W., T.V., K.K., A.D.R., F.F., A.S., S.T.-M., A.S.R., and P.R.; writing – review & editing, R.G., M.W., K.K., A.D.R., A.D.V., and P.D.; energy and climate system model runs, K.K., F.F., S.T.-M., B.S., J.D., P.R., and A.S.; macroeconomic model runs, R.G., M.W., L.R.L.S., and K.W. All authors collectively performed the policy analysis of the announced pledges. All authors were responsible for the writing of the original draft.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

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### 4.3. Conclusion: the need to bridge the gap in policy ambition

We have seen how an energy system model was applied to produce a set of projections for GHG emissions taking into account country policies and announced objectives; these emissions are then translated into global mean temperature changes using a simplified climate model, and into economic activity and employment impacts using a macroeconomic general equilibrium model. Such a process allows to conduct a global stocktake of the collective effort to reduce emissions. By building scenarios where different sets of policies are included, their incremental effect can be assessed.

Even within one model, there are multiple ways to project pathways for current policies and for emissions resulting in reaching the 1.5°C objective. The pathway can be determined by different assumptions on demography and economic growth; relationship between macroeconomic drivers and energy services needs; technology costs and availability; the treatment of non-energy system emissions, in particular the definition and starting point of land use emissions and sinks; assumptions on price elasticities and rate of the renewal of the stock of energy-consuming equipment; and more. The projections presented here consist in “middle of the road” scenarios: certain assumptions were taken from internationally recognized institutions (e.g. macroeconomic parameters); the development of new technologies and options is gradual and no single solution is responsible for emissions mitigation (e.g., technologies like DACCS and options like the LULUCF sink are not relied upon excessively); climate policy is implemented gradually to reflect possible real-world implementation (e.g., carbon prices follow sigmoid shapes and not sudden jumps). All of this fine parametrization gives ground for producing possible alternative scenarios or sensitivity analyses, which will be explored in the next sections.

With the above set of projections, certain key findings can be identified on the status of climate policies in the eight years since the Paris Agreement. Current adopted policies by world countries along with the expected evolution of technology costs lead to global GHG emissions growing to 2040 then stabilizing, resulting in climate change in excess of 3°C by the end of the century. The inclusion of announced policies reduces emissions already from the current decade and results in climate change around 1.8°C (2.6°C only with medium-term targets): the implementation gap. Additional targets and policies are needed to reduce country-level and collective global emissions further, to a level compatible with climate change of 1.5°C: the ambition gap.

The energy system model projections show that a transition to a low-carbon economy is feasible from a technical point of view, with increased investments and costs of energy. Importantly, the general equilibrium model projections show that this transition can be achieved with limited costs to the overall economy. The macroeconomic costs of the transition to a 1.5°C pathway are estimated to be less than 0.5% of global GDP by 2040 (i.e. a drop of 0.02% of annual GDP growth). However, it is important to underline that this global figure hides significant diversity at the level of individual countries.

The transition to a low-carbon economy is one where certain sectors experience degrowth and certain other sectors experience increased growth. A global transition of jobs away from fossil fuels-intensive sectors to low-carbon-oriented sectors takes place. The fossil fuel extraction industry experiences the most significant job losses, while the power generation industry, construction and agriculture experience job increases, due to the deployment of renewables, greater electrification and biomass production; the overall net effect of energy-related jobs is an increase.

Thus, the low-carbon transition is not just a technical challenge, but also a challenge for policy design, for aligning the correct types of investment, for labour training and reconversion, for limiting the negative side-effects of costlier energy on the population overall. The announcements of emissions reductions targets have to be accompanied by concrete plans of their implementation, taking into account their effects on employment at the local regional scale and planning solutions for types of jobs that are at risk while facilitating opportunities for jobs on the rise. This is the concept of Just Transition.

## 5. Hydrogen: an accelerator of the energy transition?

"I want to say one word to you. Just one word."

"Yes, sir."

"Are you listening?"

"Yes, I am."

"Plastics."

"Exactly how do you mean?"

"There's a great future in plastics. Think about it. Will you think about it?"

- "The Graduate" (1967 film, directed by Mike Nichols, USA)

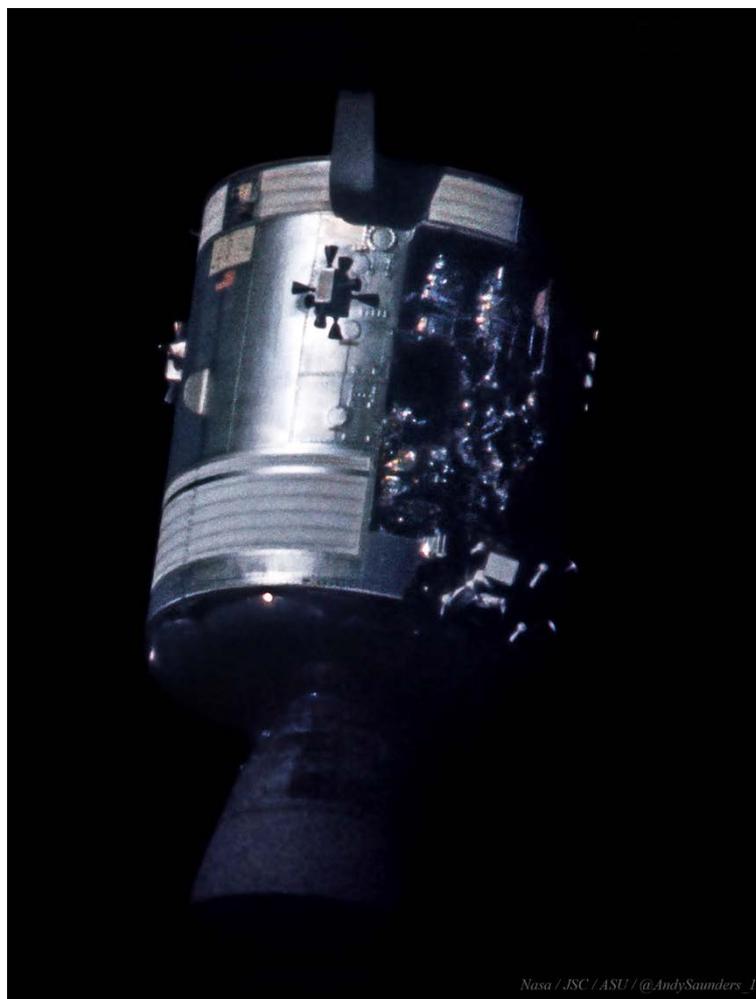


Figure 16: Photo of the Apollo 13 spacecraft

Source: NASA/Andy Saunders<sup>14</sup>. The damage has left the spacecraft's hydrogen fuel cells exposed.

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<sup>14</sup> <https://arstechnica.com/science/2020/04/heres-an-unprecedented-look-at-apollo-13s-damaged-service-module/>

### 5.1. Hydrogen: another energy carrier necessary for decarbonisation?

During the 2010s, technological improvements in batteries and heat pumps seem to point towards electrification being a key enabler for emissions mitigation in certain sectors. Rather than being a solution to fuel the entire economy, hydrogen is being positioned as a key fuel for these specific sectors that are harder to abate. Hard-to-abate sectors share many characteristics that prevent substitution with electricity, the energy carrier that is projected to become low-carbon at relatively low-cost. Heavy transport (trucks, airplanes, ships) require a fuel with high energy density so that they can carry it around with an autonomy over a long distance, which is difficult to achieve given the weight of batteries. Heavy industry with current processes requires high temperatures and optimal heat exchange over a large scale that is difficult to achieve with electricity indirect heating [103]. An alternative could be biomass-based liquid fuels for transport and solid biomass for industry; however, these fuels could have impacts on deforestation, possible biodiversity loss, water use and food prices, and their production in a sustainable way presents many challenges [104].

Hydrogen is another alternative, but it presents its own set of challenges. Hydrogen, the lightest element in the periodic table and the most abundant element in the universe, is rarely found just by itself in the natural environment. Di-hydrogen molecules are very light and escape Earth's gravity into outer space. Hydrogen is usually associated with other elements in heavier molecules, such as hydrocarbons. In order to use it as an energy carrier, hydrogen must first be produced, which itself needs energy inputs. It must be stored and transported, either as a liquid at very high pressure or at very low temperatures; or as a gas, with high rates of leakage. Thus, the development of hydrogen as an energy carrier has faced the double problem of production and storage and transportation, in terms of practicality and cost.

There has been a resurgence in interest in hydrogen in recent years, which would indicate that the time for its wider adoption has come after several decades of false-starts. The EU presented its hydrogen strategy in 2020 [105], the USA in 2023 [106], and Japan updated its hydrogen strategy in 2023 [107], all of them aiming at supporting the development of this industry and significantly ramping up production of low-carbon hydrogen. An important announcement by the private sector was made in 2020, when the world's largest aircraft manufacturer, Airbus, committed to commercialize fully hydrogen-fuelled aircraft for passenger transport by 2035 [108].

Furthermore, hydrogen-derived synthetic fuels are discussed as new energy carriers to enable decarbonisation. These are hydrocarbons that would be produced using CO<sub>2</sub> captured from ambient air and would be able to use the fossil fuel storage, transport and final use infrastructure that is already in place. Importantly, in 2023 the EU voted into law regulations of the ReFuelEU aviation initiative, which include an obligation for a minimum share of synthetic hydrogen-derived fuels in aviation of 1.2% in 2030 and 35% in 2050 [109].

### ***The emergence of a hydrogen economy***

A future of a “hydrogen economy” has been posited for a long time. In the most ambitious of such speculations, hydrogen would rise to become the predominant energy vector used in all human activities, overtaking all other forms of energy (see Figure 17). It has been observed that, since the industrial revolution, global energy consumption patterns have been moving from energy vectors rich in carbon towards those with a higher hydrogen-to-carbon ratio, i.e. from wood to coal, from coal to oil and from oil to gas; hydrogen, with no carbon at all, would then be the natural evolution of this trend [110], [111].

Energy from hydrogen is not a new concept. The physicochemical concepts of water electrolysis to produce hydrogen and hydrogen use in a fuel cell to produce electricity have been known since the first half of the 19<sup>th</sup> century.

Already in 1874, French science fiction writer Jules Verne was envisioning a large use of hydrogen by having his engineer character say in his “Mysterious Island” (1875): “I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.” [112]

The use of surplus renewable electricity to produce hydrogen was first proposed by British polymath scientist and Marxist humanist J.B.S. Haldane in his vision of the future “Daedalus; or, Science and the Future” (1924): “there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen”. [113]

Similar to solar photovoltaics, an early developer of hydrogen technologies was space exploration, where other things than cost are the deciding factors. Soon after their invention by British engineer Francis T. Bacon in 1959, the first power-producing fuel cells were used in the American spacecraft Gemini (1962-1965, acid-based) and Apollo (1967-1972, Bacon’s alkaline cell) that resulted in the first humans landing on the moon [114].

Following the OPEC oil crises in the 1970s, interest in hydrogen applications increased. The following years saw the first hydrogen combustion airplane (Russia, 1988), first solar-powered hydrogen production plant (Germany, 1990), first hydrogen fuel cell car (Germany, 1994). The early 2000s saw an increased interest for hydrogen use in road transport, with the first two commercial fuel cell vehicles in Japan in 2002, a hydrogen fuel initiative in the USA providing \$ 1.2 bn in 2003, a hydrogen highway network of refuelling stations in California in 2004, and several pilot programs for hydrogen fuel cell busses in Europe, Canada, USA and Japan over 1998-2007. Hydrogen fuel cell applications started being proposed for consumer products, such as laptop and telephone chargers [115], [116].

The term “hydrogen economy” was first proposed by South African chemist John Bockris in his 1975 book “Energy: the solar-hydrogen alternative”. In the early 2000s, the term was popularized by economist and writer Jeremy Rifkin in his 2002 book “The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth”; Rifkin was an advisor to the European Commission when the EU launched a \$ 2 bn commitment in hydrogen development in 2002.

However, despite considerable decreases in costs of fuel cell and electrolyzers, the prohibitive costs, the storage and safety issues, and the overall complexity of refuelling infrastructure resulted in the 2000s expectations of a wider adoption of hydrogen not materializing.

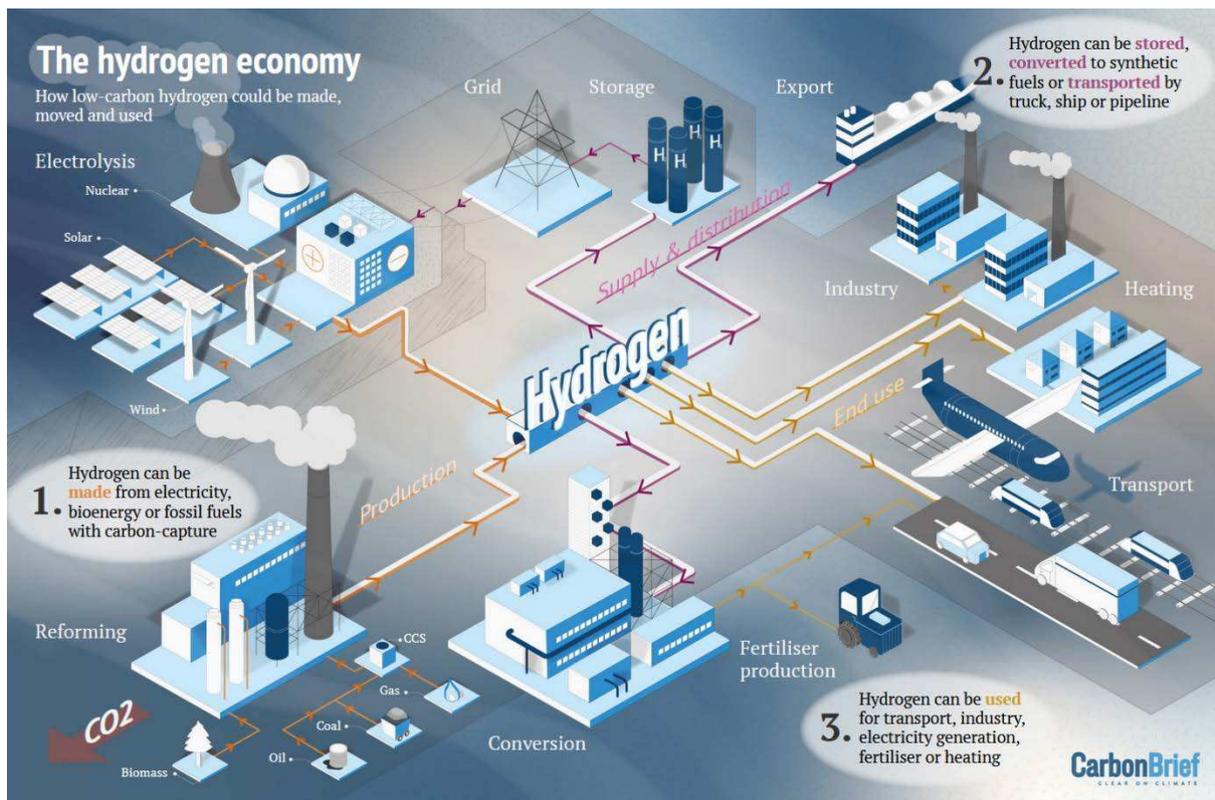


Figure 17: Schematic of the functioning of the hydrogen economy

Source: Carbon Brief [117].

Hydrogen could also facilitate the sector coupling between electricity and buildings, transport and industry. In times of excess intermittent renewables electricity production (wind and solar), the electricity could be used to produce hydrogen; this hydrogen could then be reconverted into electricity at hours of need (acting as buffer electricity storage) or used directly [118].

Given different wind and solar endowments across countries, it has also been proposed that hydrogen could become a way to transport renewable energy over long distances. The terms of trade would be determined by the difference in hydrogen production cost and the hydrogen transport cost; given handling costs, transformation (e.g., liquefaction or conversion into ammonia and reversion into hydrogen) and losses, transport costs could be significant. IRENA expects international hydrogen trade to become significant as early as 2030 and represent a quarter of total hydrogen supply by 2050 [119]; the EU expects to source half of its hydrogen supply by 2030 from imports [120]; the JRC (with the POLES model) estimates that international hydrogen trade will provide at most 10% of hydrogen supply [92].

As a result of this renewed interest, the research, development and deployment (RD&D) expenditure from both public and private actors exceeded its previous peak of the 2000s in 2021 (see Figure 18). Gigawatt-scale electrolyser hydrogen production plants, in particular using solar energy, have been announced; according to the IEA, over 200 MW were installed in 2022, with 170-365 GW in the pipeline by 2030 [121].

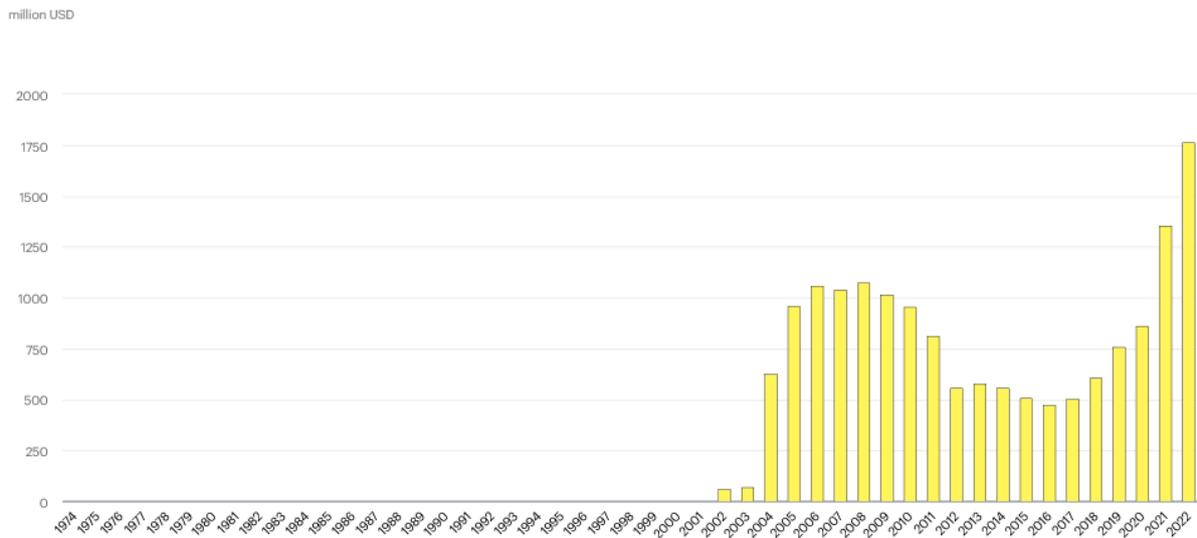


Figure 18: RD&D budget on hydrogen and fuel cells

Source: IEA [122].

This being said, the energy carriers hydrogen and electricity should not be considered as two options in competition but in complementarity with one another. A hydrogen economy is, in fact, one of higher electrification as well. On the one side, green hydrogen is produced with electrolysis, which needs electricity: significantly more electricity will have to be produced in a hydrogen-rich future. On the other side, hydrogen can be used in fuel cells, which, in practice, use hydrogen to run an electric motor: for fuel cells, hydrogen consists in a storage medium and electricity is the final energy vector that is used. Thus, it is possible to speak of hydrogen as a means to enable *indirect* electrification, as opposed to the *direct* electrification from the grid to the end-use – and therefore act as an enabler for the decarbonisation of hard-to-abate sectors.

In the following section, we will see what the drivers are for existing and new uses of hydrogen, and which technologies are likely to play a role in its production. We will examine way with which hydrogen production, currently entirely based on fossil fuels, could become zero-carbon and enable emission reductions in other sectors. These projections will be useful also in the next sections, as hydrogen is an energy vector that can be used in the production of materials such as steel and cement.

## 5.2. What is the business model for green hydrogen?

Currently, hydrogen is one of the most carbon-intensive energy vectors, as its production is mostly based on fossil gas and coal. A shift away from the current mode of production is necessary to turn hydrogen into a low-carbon fuel and enable the decarbonisation of other sectors.

In 2018, global hydrogen production stood at around 70 Mt (see Figure 19) and was responsible for around 830 MtCO<sub>2</sub> of emissions as per the IEA [123] – a considerable amount, representing about 2.5% of world energy and industry CO<sub>2</sub> emissions. As established uses of hydrogen are not as an energy carrier but as an intermediate product in industrial processes, the emissions from hydrogen production are classified in the processes emissions of the chemicals industry.

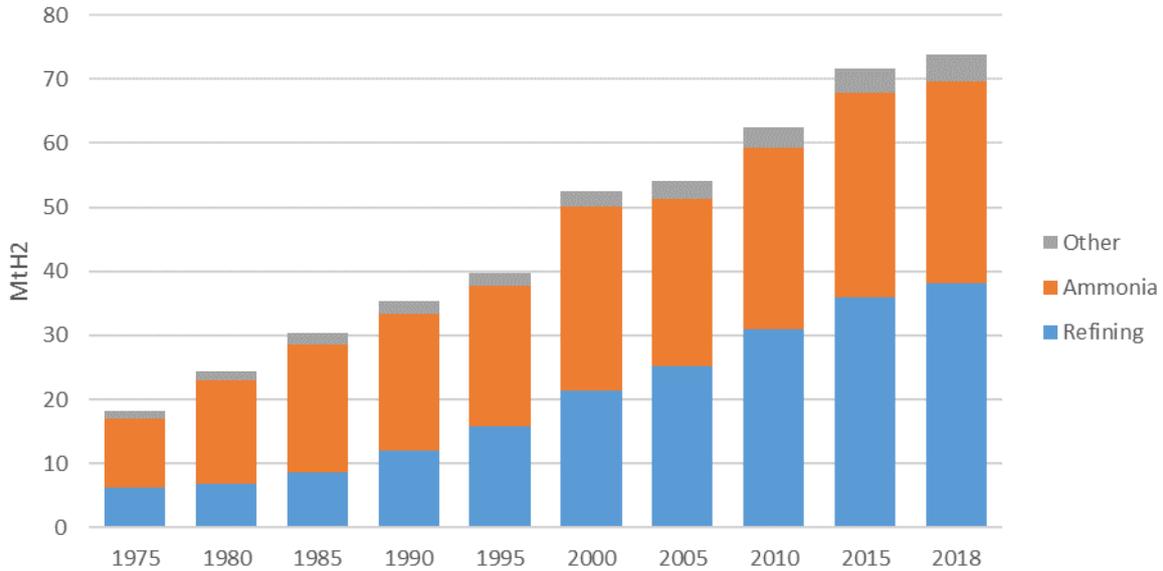


Figure 19: Global demand for pure hydrogen, 1975-2018

Source: IEA [123].

The nascent hydrogen industry faces the challenge of decreasing these emissions while increasing production. This will yield emissions savings both in the chemicals industry and in the various sectors where hydrogen is used as an energy carrier.

In order to assess a wide spread of possible futures with different roles for hydrogen, we present here results from a projected baseline with current energy and climate policies (*Ref*) and a scenario with global climate policies in the form of a carbon price resulting in long-term temperature stabilizing at 1.5°C (*15C\_CCS*). These scenarios are defined more in detail in the scenarios section of the article in section 6.2<sup>15</sup>.

### 5.2.1. Where will green hydrogen be needed?

Historically, hydrogen has been used as a raw material in various industrial processes. Its use as an energy vector is still marginal but is expected to increase.

#### *Established and new uses as an industry feedstock*

Established uses of hydrogen – in fertilizers productions, in oil refineries and in other chemical industries – correspond to demand for industrial processes. They are detailed in Annex iii. A new use of hydrogen not as an energy vector but as part of an industrial process is in steelmaking, where hydrogen could be used in the direct reduction of iron ore into steel (see the article presented in section 6.2).

<sup>15</sup> The work in this section was also used in the JRC Global Energy and Climate Outlook 2022 [92], where this author was the lead author. That report had a specific focus on hydrogen demand and production, as well as on the prospects of inter-continental hydrogen trade.

Hydrogen demand for these uses is projected to be essentially stable in both scenarios, despite the emergence of hydrogen use in steelmaking. Perhaps counter-intuitively, this is due to less use of hydrogen in refineries and fertilizers with climate policies.

Indeed, climate policies usher a decrease of the use of oil products like diesel in transport, with a move towards other fuels (such as electricity or the direct energy use of hydrogen in fuel cells).

Climate policies also force a more targeted and efficient use of fertilizers, thanks to farming management practices like precision agriculture that makes use of IT-enabled technologies (remote sensors, satellite imagery, sampling and machine learning) [124]. This results in global fertilizer demand that grows at a decelerated pace or even decreases compared to the recent past: Figure 20 provides an illustration of the reactivity of fertilizer demand to climate policy (carbon price), according to Frank et al. [91] This shows a large material efficiency potential for fertilizer, and thus for the associated hydrogen.

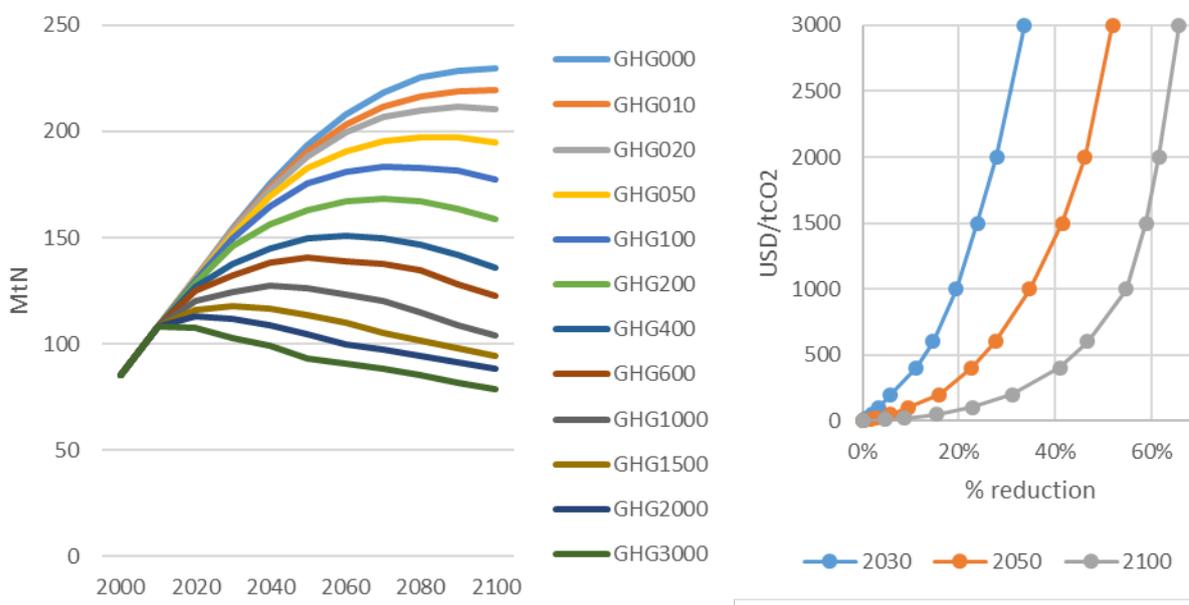


Figure 20: World nitrogen-fertilizer use across different climate policy scenarios (left) and marginal abatement cost curves for select years (right)

Source: Frank et al. (2021) [125] supplementary material, for BASE scenario and biomass price BIO03. GHGxxx denote the underlying assumption for carbon price (in USD/tCO<sub>2</sub>), referring to its value in 2100 with a linear evolution starting from 2020.

Conversely, hydrogen use in steelmaking and in the production of other chemicals is projected to increase.

### New uses as an energy fuel

New uses of hydrogen as an energy vector are several.

It can be used in fuel cells to produce electricity, either in stationary applications (in which case these fuel cells would act as a way to avoid peak electricity prices, and this hydrogen would act as a temporary storage of electricity) or in mobile applications (in electric vehicles using fuel cells and

hydrogen as a way to store the energy chemically, as alternatives to the conventional internal combustion engine and battery-electric vehicles). With the decrease in costs of batteries, prospects for hydrogen fuel cell vehicles have been revised downwards, but hydrogen is still expected to play a role in certain market segments, such as heavy duty vehicles in road transport for long-haul freight.

Hydrogen could also be used directly in combustion, either pure or mixed with fossil gas in the gas distribution network. This could be used to provide heat in buildings and industry. It could also be used in the production of electricity, as a low-carbon alternative to gas-fuelled peaking plants in times of high electricity price [126]. Above a certain mixture level (5-10%), gas pipelines would need to be lined with a protective plastic coating to avoid embrittlement by hydrogen [127]. For the transport of pure hydrogen, existing gas pipelines could be used, however with significant precautions related to limiting leaks, keeping a constant pressure and avoiding possible explosions [128]. The prospects for these uses are that they will be relevant in specific cases and applications, where alternatives are difficult to implement.

Finally, a new and increasingly discussed use of hydrogen is as an input in the production of synthetic methane (Power-to-Gas with the methanation process, see [129]) and liquid hydrocarbons (Power-to-Liquids with the Fischer-Tropsch process, see [130]), which could then be used similarly to fossil gas and oil productions, without the need to adjust distribution infrastructure and end-use equipment. Synthetic fuels production uses CO<sub>2</sub> (itself captured from power plants or industrial facilities combustion, or directly from the air<sup>16</sup>) [131] and low-carbon hydrogen as inputs. Their uptake in the energy system is dependent on many factors that have to align, with carbon capture and transport infrastructure, industrial-scale hydrogen production and integrated plants for the handling and transformation of these chemicals into fuels. The production of such fuels comes at a significant cost premium and their use only makes sense in targeted sectors where reductions are not possible with other ways – in the hard-to-abate sectors discussed in section 1.2, especially in aviation and maritime. Thus, the emergence of such uses is correlated with the ambition of the climate policy; they are not expected to play a large role unless the targets of deep emissions reductions and net-zero are pursued.

### *Projections of hydrogen demand*

Bringing all these uses of hydrogen together, we upgraded the POLES model to build projections of hydrogen demand (see annex iii for more detail). Figure 21 presents projections of hydrogen demand over the coming decades.

Hydrogen demand is projected to increase at a slow pace without climate policies (*Ref* scenario), reaching 120 Mt in 2050 compared to 70 Mt in 2020. The demand increase is significantly accelerated with climate policies (*2C\_CCS*, *15C\_CCS* and *15C\_Elec* scenarios), reaching as much as 400 Mt in 2050. Most of the hydrogen market is driven by climate policies, and its value increases the more stringent

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<sup>16</sup> CO<sub>2</sub> from fossil fuels combustion power plants or industrial facilities result in new emissions; synthetic fuels based on that CO<sub>2</sub> result in that same amount of CO<sub>2</sub> being emitted anew, and in net terms carbon that was in underground fossil deposits is released in the atmosphere. CO<sub>2</sub> from direct air capture (DAC) used in synthetic fuels is emitted anew as well, but in net terms there is no addition of CO<sub>2</sub> in the atmosphere. For this reason DAC is pursued for CO<sub>2</sub>-neutral synthetic fuels, despite its higher cost compared to obtaining the CO<sub>2</sub> from more concentrated flue gases in power plants or industrial facilities.

the scenario is: demand in 2050 increases from 160 Mt in the Reference scenario to 210 Mt in 2C\_CCS to 280 Mt in 15C\_CCS.

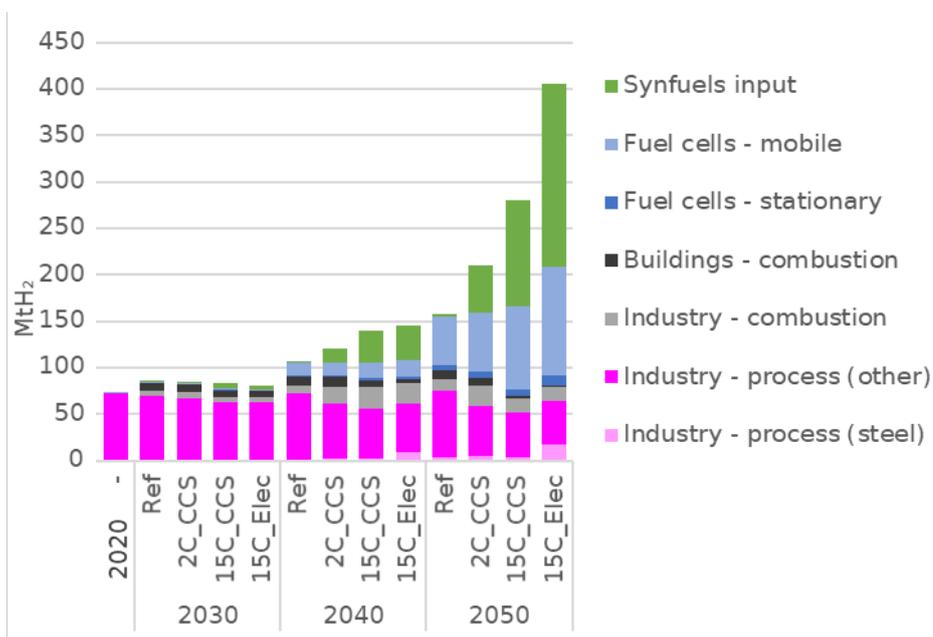


Figure 21: Projections of hydrogen demand by end-use, world, Ref and 1.5°C scenarios

Source: POLES model.

In the 2°C and 1.5°C scenarios, the decrease in hydrogen use as industrial feedstock is more than counter-balanced by the increase in the new uses as an energy vector.

Hydrogen in steelmaking accounts for an overall minor part of total hydrogen demand (as much as 6% throughout 2050).

Hydrogen as a combustion fuel (buildings and industry) consists in hydrogen mixed with fossil gas in the gas distribution network up to a maximum level. It accounts for only 4-7% of total hydrogen demand in 2050. This represents a small market for hydrogen, as other solutions prove to be more cost-efficient and easier to handle (e.g., heat pumps in buildings).

The main part of hydrogen demand arises from transport, either in fuel cells (28-32%) or as input for synthetic fuels production (34-38%). In addition, a minor part of hydrogen is used to produce synthetic methane for industry (6-10%; accounted as synthetic fuels input).

This represents a large market expansion for hydrogen, starting from zero today. However, hydrogen and derived fuels represent a small share of the overall transport energy demand. In the most ambitious scenario for hydrogen (15C\_Elec), hydrogen fuel cell vehicles amount to around 10% of the total vehicle stock in 2050; and hydrogen-derived fuels, which allow to extend the use of internal combustion engines, supply 12% of the energy demand of road transport in 2050. Most of the energy in road transport in low-carbon scenarios is provided by electricity, with niche applications for hydrogen and derived fuels. Hydrogen has a more important role to play in more hard-to-abate sectors and in very deep decarbonisation scenarios: hydrogen and derived fuels reach 22% and 25% of the energy used in international aviation and maritime bunkers in 2050, respectively.

Hydrogen demand in steel and in cement production is examined in the articles presented in sections 6.2 and 7.2, respectively.

The creation of this growing market is dependent on the timely provision of sufficient quantities of hydrogen at competitive prices, along with the creation of the appropriate transport and distribution infrastructure, and, critically, with little to no emissions tied to its production.

### 5.2.2. What are the drivers to make green hydrogen competitive?

#### *Multiple production pathways, few are very low-emissions*

Currently, hydrogen production is based on fossil gas (steam methane reforming process, SMR) or on fossil coal (coal gasification process, mainly in China). Multiple other production pathways exist. The renewed interest in the hydrogen economy has been associated with investments in production capacities of lower-carbon hydrogen; in some cases, these aim to produce blue hydrogen (CCS applied to SMR) but mostly it is to produce green hydrogen (electrolysers powered by renewable electricity, mostly with solar PV).

The processes that were modelled and their techno-economic assumptions are detailed in Annex iii.

A schematic view of the processes modelled in POLES is provided in Figure 22. Conventionally, colour names are assigned to the different types of hydrogen in order to identify them: grey (unabated fossil, from methane or coal); blue (abated fossil, i.e. grey with CCS); turquoise (from pyrolysis); pink (from nuclear); green (from wind and solar).

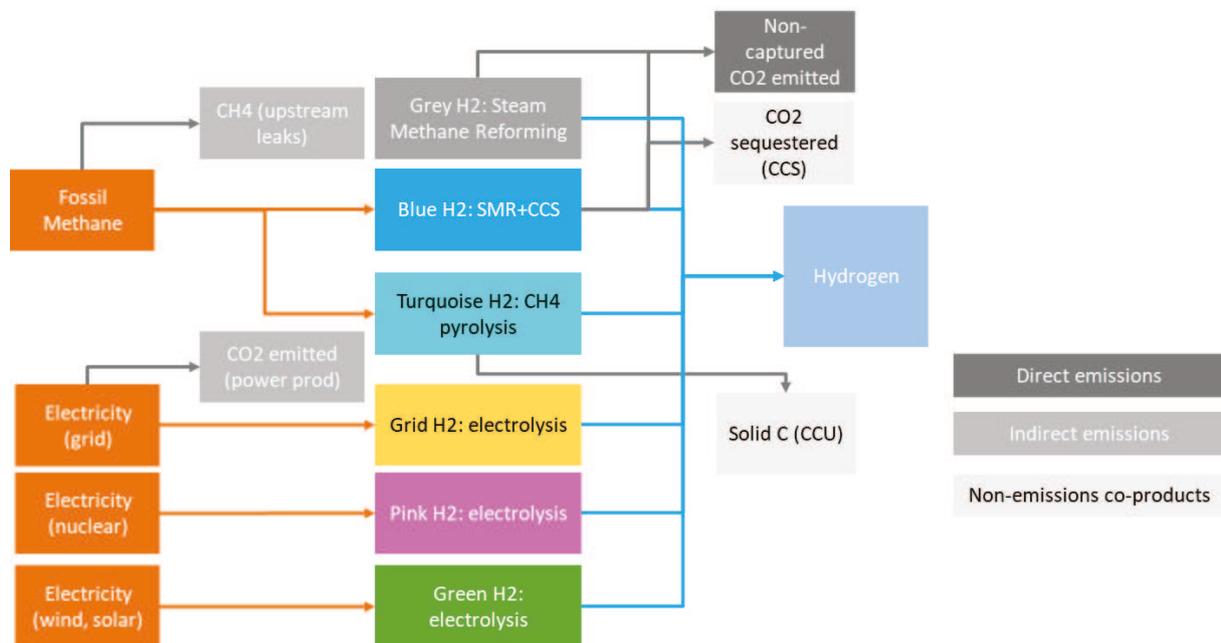


Figure 22: Schematic of the hydrogen production processes modelled in POLES

Source: own work.

Green hydrogen and hydrogen produced using electricity from the grid are produced at zero marginal cost. The cost of production corresponds to the cost of the electrolyser, amortized over the hours of operation. In the case of wind and solar, this corresponds to the load factor of these technologies.

Typically, solar operates 20% of the hours in a year and onshore wind 25% (with large variability across countries and years) and increasing due to optimal site selection and technology improvement [132]. In the case of grid electrolysis, the modelling was set so that its production happens only at times of excess production, when electricity production from intermittent renewables (wind and solar) occurs at times of low electricity demand. This avoids electricity curtailment and maximises the economic value of these renewable capacities. This hydrogen could also be considered as zero-carbon, similar to green hydrogen.

In addition, a cost for buffer storage was added for the green and grid-based hydrogen pathways. This was done so that, despite intermittent operation, they can provide a constant output of hydrogen gas to be transported to the final users. This makes them comparable with other hydrogen production pathways, where operation is continuous throughout nearly the entire year.

In order to properly take into account the emissions content of hydrogen as compared to other fuels, we have to include both direct (emitted upon hydrogen production) and indirect emissions (emitted to produce the inputs in hydrogen production). Only when both of these categories are taken into account can we have a complete picture of the emissions entailed by the use of hydrogen<sup>17</sup>.

An illustration of how these evolve over time in a 1.5°C scenario are provided in Figure 23:

- Direct emissions (consisting in fuel combustion and methane reforming) are mostly captured when CCS is implemented (blue hydrogen, maximum 95% capture rate).
- Fossil indirect emissions (consisting in emissions from the upstream fossil fuels supply chain, at the production site or in transport and distribution) are partly reduced thanks to the effect of climate policy.
- Electricity indirect emissions (consisting in emissions from power production) are greatly reduced thanks to the effect of climate policy, to nearly zero by 2050.

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<sup>17</sup> Another category is that of the emissions of hydrogen itself when leaks occur. Hydrogen is a greenhouse gas that has a 100-year global warming potential estimated at 11.6 [133], which is not negligible (methane has a value of 21-34 [134]). This effect was not quantified here. Further research would be needed to assess whether different production pathways result in different leakage hydrogen rates and thus different CO<sub>2</sub>-equivalent emissions.

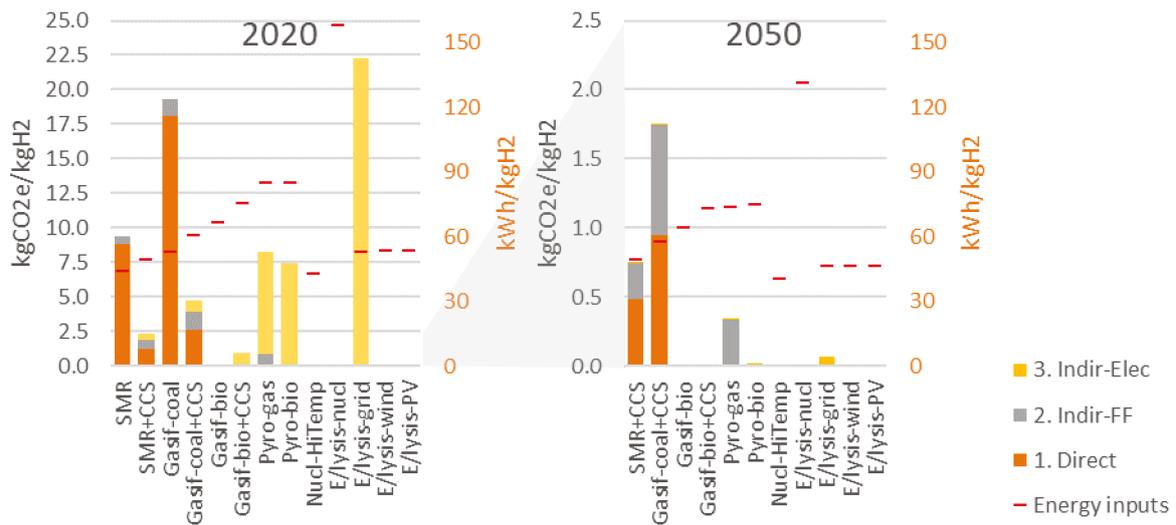


Figure 23: Hydrogen direct and indirect emissions (left-hand axis) and energy inputs (right axis), 1.5°C scenario, USA

Source: POLES model.

As a result, the emissions content of hydrogen, including indirect emissions, decreases over time and becomes lower than that of fossil fuels. In the case of the USA, in 2020 blue hydrogen would have an emissions content three times lower than that of fossil gas (and turquoise hydrogen more or less the same as fossil gas); by 2050, blue hydrogen's emissions content would be nine times lower (and turquoise hydrogen's twenty times lower).

As a consequence, only biomass-based and electrolysis-based hydrogen production pathways have the potential to be truly low-carbon.

### Projections of hydrogen production

We enhanced the existing hydrogen module to take all of the above into account (see annex iii for more detail). Figure 24 provides the resulting production mix for hydrogen, for the scenarios described in section 6.2.

The production mix becomes very diversified with the implementation of a carbon price. Natural gas pyrolysis emerges as a medium-term solution for lowering the emissions of hydrogen production (pyrolysis residue, solid black carbon and ash, are not accounted in (gaseous) CO<sub>2</sub> emissions). Beyond 2030, CCS retrofit and especially electrolysis with PV or wind become the dominant solutions.

An important finding of the projections is that, despite increasing wind and solar production, grid-based hydrogen represents only a small part of total hydrogen production. The volumes of hydrogen that need to be produced require much larger quantities of energy inputs than what power sector curtailment avoidance can provide. The large majority of wind- and solar-based hydrogen is produced with wind and solar capacities that are entirely dedicated to the production of hydrogen.

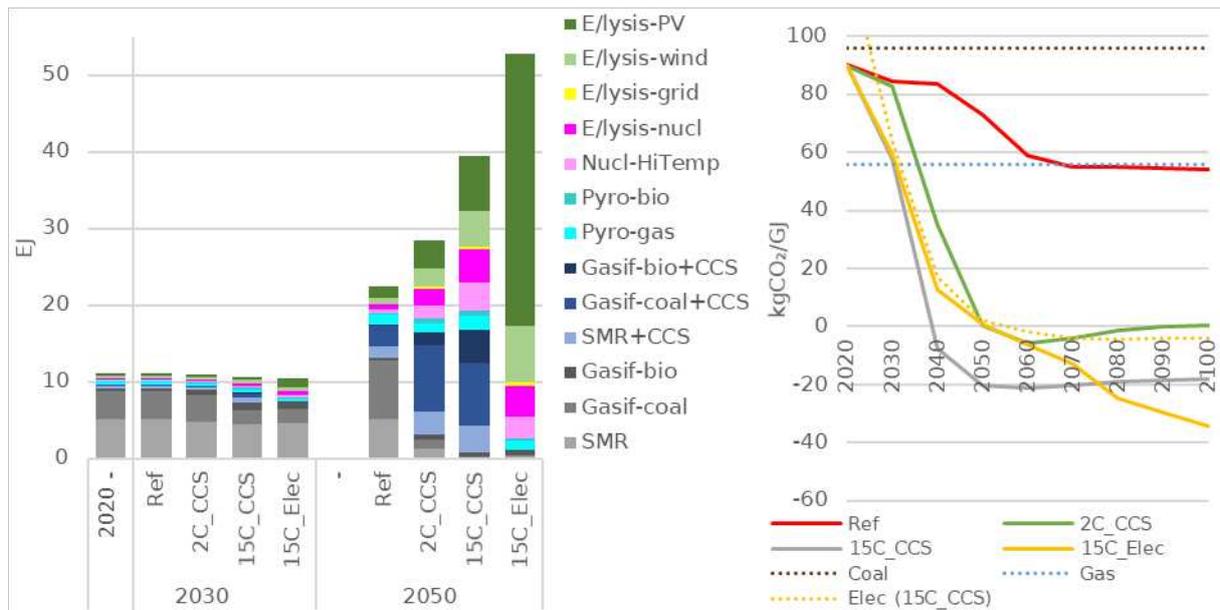


Figure 24: Hydrogen production mix (left) and carbon content of hydrogen produced (right), World

Source: POLES model.

Figure 24 also provides the evolution of the global average carbon content of hydrogen. Its level is currently close to that of coal; it would become lower than that of the cleanest of fossil fuels, gas, only from the mid-2030s onwards and due to the system-wide pressure to decrease emissions in the 1.5°C scenarios. It would closely follow the carbon content of electricity, which would be evolving rapidly itself. The carbon content drops sharply and with the use of biomass and CCS could even become negative; net-zero is reached as soon as 2040 in 15C\_CCS (2055 in 15C\_Elec).

For the coming two decades, we estimate that green hydrogen would reach the market at a considerable price premium compared to grey or blue hydrogen. Figure 25 provides the modelled hydrogen supply costs for several production pathways: SMR, SMR with CCS, electrolysis using dedicated nuclear power and electrolysis using dedicated photovoltaic panels.

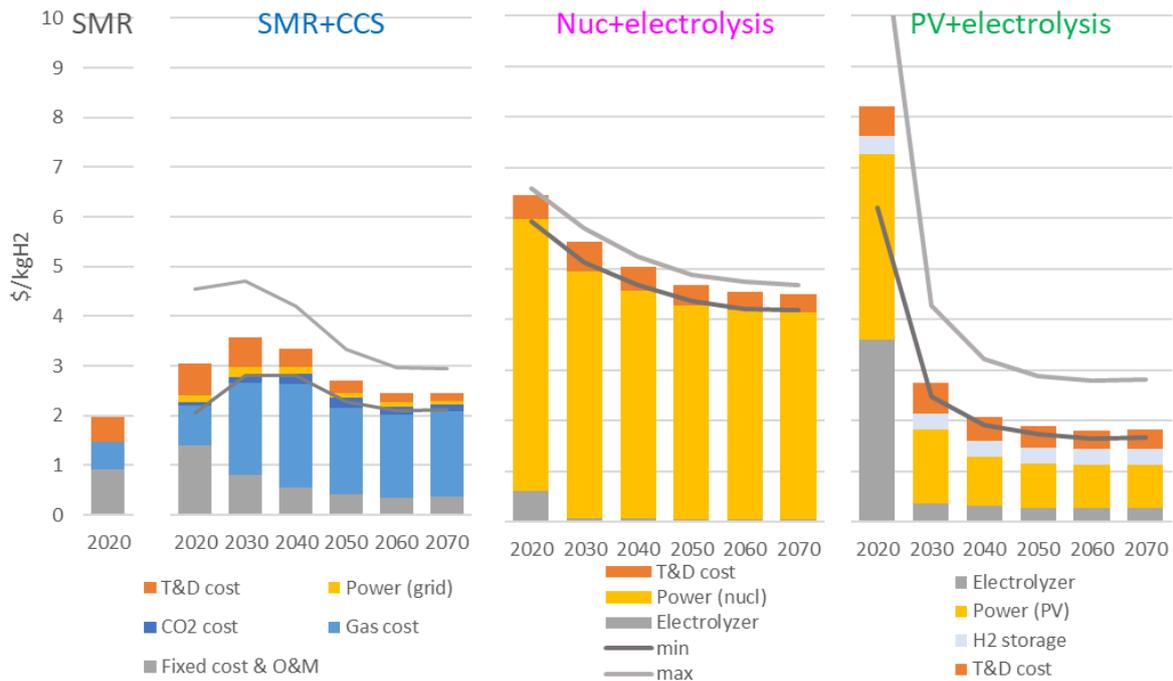


Figure 25: Production costs of select hydrogen production processes

Source: POLES model. Values are averaged over the world, weighted on the regional volume of production for that process. World averages (bars, weighted on the regional volume of production for that process) and regional spread (minimum and maximum noted with lines), 15C\_Opt scenario.

Despite expected cost decreases in the electrolyser and the PV modules, the electrolysis solutions become more competitive than SMR only thanks to the implementation of a CO<sub>2</sub> price. Only after 2030 does hydrogen-PV supply cost become lower than that of SMR excluding CO<sub>2</sub> cost (or lower than that of SMR+CCS). Hydrogen-PV supply costs, including buffer storage cost and transport and distribution cost, reaches 1.9 \$/kgH<sub>2</sub> in 2050 (i.e. 16 \$/GJ). This competitiveness is also highly dependent on the price of gas itself, which has experienced large increase over the 2020-2022 period.

Thus, the supply cost of hydrogen, averaged over the various production pathways, would still be higher than the supply cost of green hydrogen only. Despite the deployment of lower-emissions solutions, the pricing of carbon and the residual emissions still push the average hydrogen price up, from an estimated world average of 12.5 \$/GJ in 2020 to 34 and 22 \$/GJ in 15C\_CCS and 15C\_Elec, respectively. For comparison, the fossil gas price in the USA was 5.5 \$/GJ in 2022 (up from 3.3 \$/GJ in 2019); for hydrogen-PV to be directly competitive with fossil gas in 2050, fossil gas would need to incorporate a carbon price of 185 \$/tCO<sub>2</sub>.

In summary, the nascent hydrogen industry is confronted with the dilemma of fostering demand for a new product while also facing high costs for the provision of a truly low-emissions hydrogen. Investing in comparatively lower-emissions pathways such as blue and turquoise hydrogen might make economic sense as a bridge towards truly low-emissions solutions when they become more cost-competitive. However, urgent action is needed to get the world on track to a 1.5°C-compatible pathway: the need for immediate and deep emissions cuts would be incompatible with these bridge solutions. Moreover, the cost reductions for electrolysers would only happen if sufficient volumes of

hydrogen are produced with this method, in a learning-by-doing effect; and this would only materialize if hydrogen is offered at a low enough price to stimulate demand.

As a result, the business case for large-scale green hydrogen production is still non-existent and this would continue to be the case for at least another decade. An important policy intervention is necessary to jump-start the green hydrogen industry in this intervening period before the hydrogen market can be self-sustaining. This could take the form of financial support (contracts for difference, direct subsidies), green hydrogen purchase obligations, or hydrogen emissions quotas or standards, or a combination of the above [135], [136].

### 5.3. Conclusion: will the hydrogen economy materialize this time?

The development of hydrogen production is undeniably at the centre of discussions in recent years. Substantial budgets of several billions of dollars in public and private funding have been made available for this purpose. However, many uncertainties remain as to the timing and the extent of both hydrogen demand and supply.

Current hydrogen demand is dominated by its non-energy use as an intermediary product in the production of fertilizers. The decarbonisation of hydrogen supply is thus also a means to decarbonise that industry, on top of producing a clean energy vector for new uses.

The majority of hydrogen demand projections are constituted by inputs in synthetic fuels production, for the decarbonisation of hard-to-abate sectors such as aviation and shipping. These projections show the scale with which this new industry has to develop to provide low-carbon fuels to specific segments of the economy. However, several uncertainties surround these projections. Unlike hydrogen, these synthetic fuels are new and the industry does not yet have experience in producing them in large quantities. They also necessitate CO<sub>2</sub> as an input; although availability of CO<sub>2</sub> is not an issue in of itself, its capture and purification does require considerable amounts of energy. Consequently, the emergence of synthetic fuels rests on the prior creation of a CO<sub>2</sub> capture and transport industry, which is not a trivial matter in of itself. The overall business case lies on strong climate policy signals that are pursued consistently over decades, be they obligations to use these fuels instead of their fossil counterparts, or pricing of emissions in order to make the fossil fuels uncompetitive. Policymakers and private actors are called upon to jump-start an industry that is previously entirely non-existent, in anticipation that this industry will be important in the decades to come.

Multiple options exist to supply hydrogen, with pink (nuclear) and green (wind and solar) using electrolysis being the only ones that result in a truly zero-carbon energy vector. However, despite ambitious technology learning, electrolysis-based hydrogen is projected to be costlier than the blue or turquoise equivalents. Blue and turquoise hydrogen could be considered as a “bridge” fuel before hydrogen is in majority green. Nevertheless, the construction of electrolyzers has to occur immediately, in order for the industry to accumulate the proper knowledge and for the expected cost decreases to materialize. It is thus important to support the immediate and mid-term development of pink and green hydrogen, in anticipation of its wider use in the longer term.

The decarbonisation of hydrogen production would directly save some 0.8 GtCO<sub>2</sub> of emissions associated with how it is currently produced, as part of the chemicals industry. In the next sections, we will see how low-carbon hydrogen can become part of the decarbonisation mix in other industry sub-sectors: specifically, steel and cement production.

## 6. Iron & Steel decarbonisation: the promises of innovation and circular economy

“Whereas he saw that the smith had two pairs of bellows, he concluded that these were the winds spoken of, and that the anvil and the hammer were the stroke and the stroke in return, and that the iron which was being wrought was the trouble laid upon trouble, making comparison by the thought that iron has been discovered for the evil of mankind.”

- “*The Histories*” Book 1 ch. 68, Herodotus (circa 430 BCE, Greece/Eastern Mediterranean)<sup>18</sup>

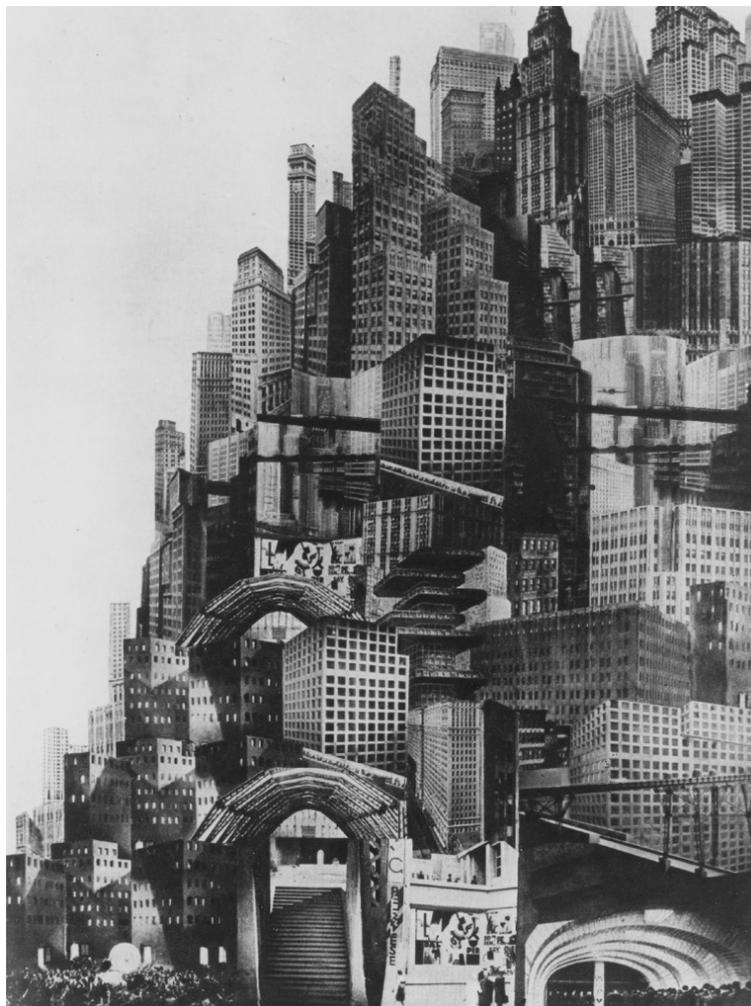


Figure 26: Urban landscape

Source: Montage from “*Metropolis*”, 1927 film, directed by Fritz Lang, Austria/Germany<sup>19</sup>. In the early 20<sup>th</sup> century, United States skyscrapers built from steel and glass impressed foreign visitors and populated visions of the future.

<sup>18</sup> <https://www.gutenberg.org/files/2707/2707-h/2707-h.htm>

<sup>19</sup> [https://pofpa.files.wordpress.com/2010/10/metropolis\\_themes\\_and\\_context.pdf](https://pofpa.files.wordpress.com/2010/10/metropolis_themes_and_context.pdf)

### 6.1. A sector dominated by coal and electricity

Today, steel is ubiquitous in modern economies, from reinforced concrete in basic infrastructure to high-strength steel for specialized applications.

Steel is the most widely used metal today. Over the past century, steel production increased enormously, by a factor of 15 over 1930-2020 (see Figure 27) and stood at close to 1.8 Gt in 2020. The fastest annual growth was observed during the post-war reconstruction period of the 1950s (nearly 8%/year) and 1960s and the period of fast development of China of the 2000s. Production was dominated by the USA and the EU region in the 1930s-1950s (39% each in 1930); today (2020), China is the overwhelmingly dominant producer (57% in 2020). There are around 2700 steel plants globally, with the average and median plant having a 1.1 and 6.0 Mt/year production capacity, respectively [137], [138].

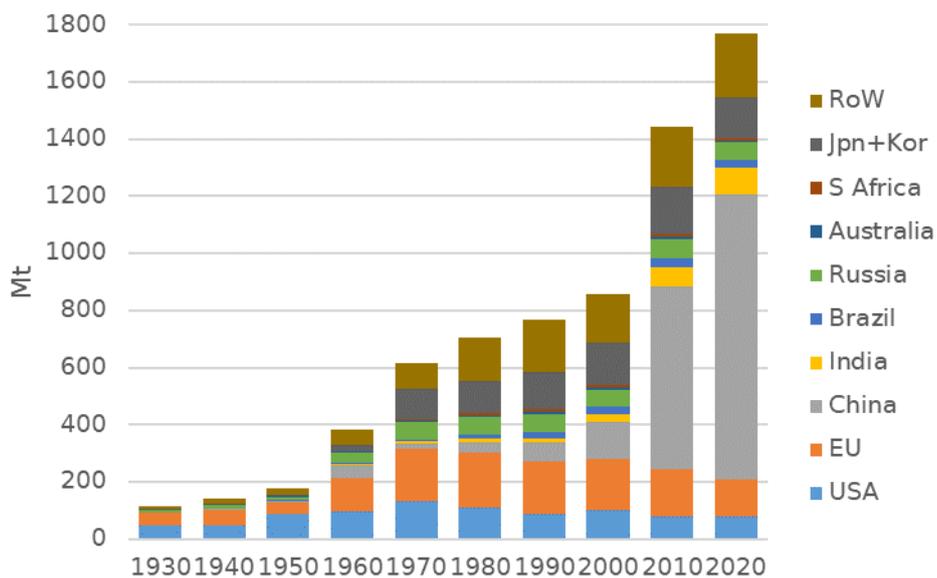


Figure 27: Global steel production, 1930-2020

Source: USGS Iron and Steel statistics [139].

### ***Steel throughout human history***

Throughout the course of human history, the utilization of steel has been a transformative force, shaping societies, industries, and economies across the globe.

The mastering of the technology of smelting iron into tools and weapons was important enough to give its name to an entire epoch of Eurasian prehistory, the last epoch before history proper: the Iron Age – which spans approximately from 1300 BCE to 500 BCE, with great variation depending on the geography and local culture. Among ancient civilizations, iron's remarkable versatility, strength and durability made it an indispensable material, substituting bronze tools and revolutionizing warfare. First appearing in the Eastern Mediterranean, Middle East and West Africa in the 3<sup>rd</sup> millennium BCE, the use of iron expanded quickly in the beginning of the 1<sup>st</sup> millennium BCE.

The history of steelmaking technology is one of trying to achieve ever-higher temperatures and of removing impurities. Early production methods of heating iron ore and charcoal in a furnace resulted in wrought iron (very little carbon content), giving rise to occupations such as the blacksmith. The blast furnace process resulting in cast iron (2-4% carbon content) originated in China around the 5<sup>th</sup> century BCE. Hand-operated and later waterwheel-powered bellows provided additional air to the fuel, raising the temperature in the furnace. The use of fossil coke instead of wood-derived charcoal began in the 18<sup>th</sup> century in England, allowing for the construction of larger furnaces; together with the invention of the steam-powered blowing engine, this jump-started the Industrial Revolution. Introducing air in a controlled way into the pig iron furnace (the Bessemer process, later the Siemens-Martin open hearth process, during the 19<sup>th</sup> century) resulted in an easier evacuation of impurities, greatly improving production speed, labour need and cost. This thereby greatly expanded railway infrastructure, the production of iron-hulled ships and the use of steel frames for tall buildings.

The basic oxygen furnace (using pure oxygen instead of air) further reduced costs and was massively adopted from the 1950s onwards. The development of a power generation industry towards the end of the 19<sup>th</sup> century and the rising availability of steel scrap as a direct result of increased steel use allowed a completely new production pathway to emerge: use of electricity to recycle steel at a large scale.

The electric arc furnace was first used in the early 1900s in mini-mills for specialty products; its use greatly expanded after World War II.

Steel had a critical role in shaping the modern world, and its influence remains a testament to the capacity of scientific and technological advancements to propel societies forward.

Currently, two processes dominate steel production: blast furnace with basic oxygen furnace (BF-BOF, 71% globally in 2019) and electric arc furnace (EAF, 23%). Direct reduction using fossil gas counts for a smaller share (DRI-NG, 6%). The open hearth furnace, historically dominant over the 19<sup>th</sup> and 20<sup>th</sup> centuries, has been phased out (OHF). World production by process for the past four decades is presented in Figure 28.

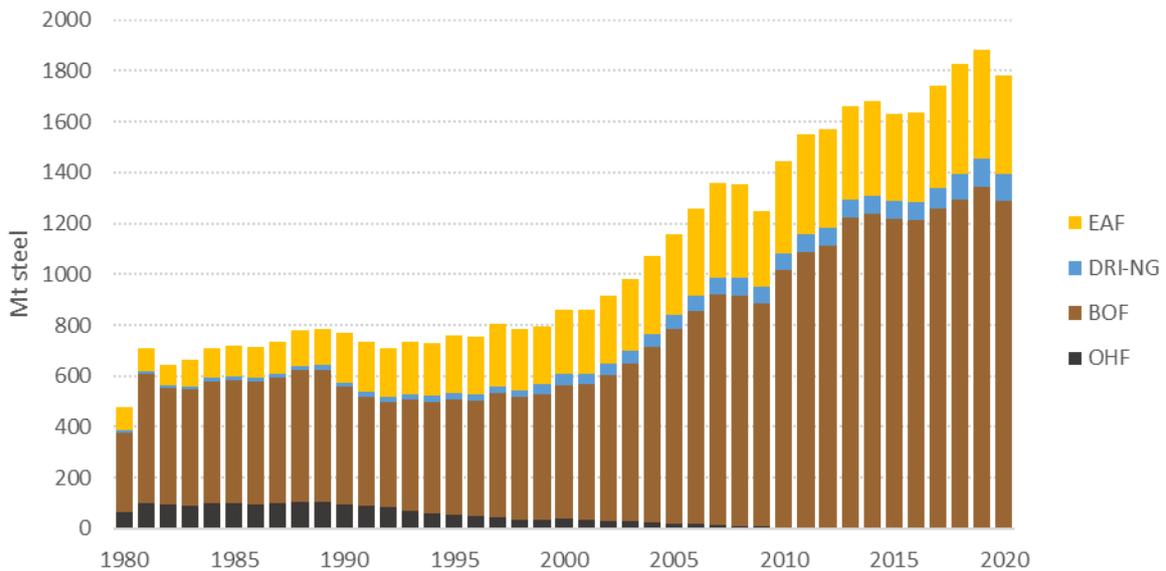
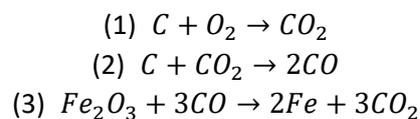


Figure 28: World steel production, by process, 1980-2020

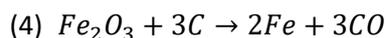
Source: WSA [140], MIDREX [141].

*Primary steel* production converts iron ore into steel products, using energy and a reducing agent. The main chemical reaction taking place is the reduction of the iron oxide (typically hematite, Fe<sub>2</sub>O<sub>3</sub>) into iron metal (Fe).

In the case of a *blast furnace*, which is the most widely used process currently, coke (C) is first burnt with hot air, releasing heat (1); it is then converted into carbon monoxide (CO) (2), which is the reducing agent for the iron oxide (3):



In parts of the furnace, coke can also directly react with iron oxide (4):



The iron ore is pre-processed into porous pellets (sintering process) and coal is pre-processed into coke before introduction in the furnace. In a second step, in the *basic oxygen furnace*, limestone and a variable amount of scrap (up to 30%) are added, which react with the iron and with oxygen blown in the furnace; this is done in order to remove impurities (including undesired carbon atoms), resulting in outputs that are either gases (syngas, reused in the process) or solids (slag, a waste product). The melted iron is also enriched with certain atoms to make a steel material with the desired structural

properties: typically, carbon atoms (0.04%-2.5% in quantity) and atoms of other metals (e.g. nickel and chromium for stainless steel) [142].

In the *direct reduction* process, the reducing agent is fossil gas (mainly methane, which is reformed into carbon monoxide and hydrogen), thereby significantly reducing CO<sub>2</sub> emissions. It produces hot briquetted iron (HBI) that is then converted into steel in an electric arc furnace; HBI can be exported in a different geographical location for the electric arc production step. This process is mostly used in regions that are rich in natural gas; production in Middle East, North Africa, Russia and India amounted to 87% of world direct reduction production in 2020 [141].

*Secondary steel* production consists in recycling scrap in an *electric arc furnace* (Hérault process). Electrodes (three electrodes, in the alternating current process that is most frequently used) are lowered into charged scrap, raising its temperature to the melting point. CO<sub>2</sub> emissions only come from the production of electricity itself, which can be from the grid or on-site for self-consumption.

Due to the energy-intensive nature of steel production and the large production volumes required, steelmaking causes the largest climate change impacts among metals manufacturing, followed by aluminium as a remote second; it is responsible for about a quarter of energy consumed in industry [143] and releases 2.7 GtCO<sub>2</sub> in the atmosphere annually [144].

As one of the main point-source sources of CO<sub>2</sub> emissions, steel has attracted attention as one of the priority sub-sectors of industry to be decarbonised. The production processes are mature and offer little energy efficiency or emissions reduction potential in their current form. Innovation and industry-scale adoption of low- and zero-emissions steelmaking is urgently needed in order to reduce emissions in a significant manner.

In the next section, we will study multiple ways forward for the steel industry to reduce its emissions, looking at several pathways with different assumptions on climate policy, technologies and steel demand patterns.

## 6.2. Opportunities and roadblocks in the decarbonisation of the global steel sector: a demand and production modelling approach

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*I was the main author of all aspects of this manuscript.*

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# Opportunities and roadblocks in the decarbonisation of the global steel sector: a demand and production modelling approach

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## ABSTRACT

The steel sector represents a growing share of global carbon dioxide (CO<sub>2</sub>) emissions and is perceived as a hard-to-abate sector in the drive towards economy-wide decarbonisation. We present a model detailing steel demand and multiple steel production pathways within a larger global multi-regional energy system simulation model, projecting material, energy and emissions flows to 2100. We examine decarbonisation levels and options under different assumptions on climate policy, technologies and steel demand patterns, and study low-carbon options in the production of hydrogen as a steel decarbonisation vector. Global steel demand increases at a decelerated pace compared to the past two decades (+65% in 2050 compared to 2020), driven by substantial increases in the underlying socio-economic conditions. Climate policies lead to a limited positive feedback effect on steel demand (+21% in 2050) due to a faster equipment turnover and higher electrification, which could be overcompensated by energy saving and material efficiency measures. Increased recycling and strong electrification (up to 63% of production in 2050) are projected as key levers towards decreasing emissions, made possible thanks to the increasing availability of steel scrap. Strong climate policies would be needed to push the steel sector to decarbonize fully, with electrification, carbon capture, biomass and hydrogen all contributing. Carbon capture would be necessary to reach net-zero emissions in the second half of the century.

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## KEYWORDS

Iron and steel; climate mitigation; industry decarbonisation; energy system model; integrated assessment model

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## 1. INTRODUCTION

With nearly all states having signed the United Nations international climate treaty of the Paris Agreement since 2016, collective efforts are needed to “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels”[1]. According to literature synthesized by the Intergovernmental Panel for Climate Change’s (IPCC) Special Report on 1.5°C[2], there is high agreement among the scientific community that global anthropogenic emissions of carbon dioxide (CO<sub>2</sub>) need to be reduced to net-zero by around mid-century in order to be consistent with the more ambitious Paris Agreement target. Accordingly, significant efforts to reduce emissions have to be pursued by all world countries and across all sectors of the economy. However, countries and sectors would differentiate their contribution in the overall reduction depending on cost-efficiency and other considerations. Thus, a net-zero global target does not necessarily coincide with a similar target for all sectors. In particular, heavy industry has been identified as a challenging sector to decarbonize, along with aviation, shipping and agriculture[3]; this is due to a combination of sector-specific factors: high projected activity growth, comparatively costlier emissions abatement options and slow capital turnover.

The iron and steel industry is responsible for a sizeable share of the world’s CO<sub>2</sub> emissions: around 7.4% of energy and industry emissions in 2021 with 2.70 GtCO<sub>2</sub>; the volume and share of these emissions grew rapidly over 2000-2015 (from 1.33 and 5.5% to 2.76 GtCO<sub>2</sub> and 8.0%, i.e. +5.0%/year) and remained relatively stable since[4]. This is mainly due to an increase in demand for steel and steel products, from 860 to 1960 Mt over 2000-2021, mainly coming from China and India, while the emissions intensity has decreased slowly (-0.6%/year over 2000-2021). Without additional effort, the

demand for steel and the sector’s emissions are projected to increase, in particular due to economic growth and increasing living standards in developing economies[5], [6].

Historically, higher income levels and well-being have been correlated with an increase in the demand of material goods, and of steel in particular: over 2000-2021, steel demand grew by 3.4%/year while global GDP grew at 3.3%/year. The challenge then becomes to reconcile continued increase in well-being for all (and associated steel demand increase) with the aspirations to decarbonize the world economy. Quantitative tools that are able to create multi-sectoral sectoral decarbonisation pathways are particularly suited for this task.

A number of private sector announcements have placed the objective of net-zero emissions in 2050 or earlier as something achievable for the iron and steel sector but provide little information in the means to achieve this: Baowu[7], POSCO[8], ArcelorMittal[9], TataSteel[10], ThyssenKrupp[11]. Privately-funded think tanks have produced a quantitative basis for the net-zero objective with a techno-economic evaluation of options (see the study of the business coalition Net-Zero Steel Initiative[12]). Other studies have focused on static assessments of options[13], [14].

Techno-economic modelling of steel demand and production is thus a prerequisite for constructing pathways for the future of this sector. Modelling is an important tool in making informed and quantitative estimates of the future needs of the energy sector[15], and has been used by researchers, public planners and private investors alike. Energy system models and integrated assessment models (IAMs) are prominently used to inform the IPCC’s working group on mitigation options. Several of these models represent the iron and steel sector independently of the rest of industry; however, its representation is done in a stylized manner. Several models do not represent the iron and steel sub-sector separately from other industrial sub-sectors[16]; few models represent steel demand by end-use (as opposed to a using a single type of demand[17]), few represent physical production of steel (as opposed to using a single economic activity indicator as a driver[18]) and few represent specific production processes (as opposed to a single value of energy efficiency for the entire sector); see a comparison of several IAMs[19]. Moreover, industrial ecology and material flow models have worked on representing steel stocks and annual steel demand by end-use, as well as estimating scrap made available for recycling, but do not represent the steel production side[20], [21].

The main goal of this study is to chart a way forward for the iron and steel industry in a context of energy transition as required by the regional and global effort of decarbonisation to limit climate change. We propose to tackle these issues of steel demand and supply in an integrated way within an energy system model. The resulting projections of steel flows, energy needs and greenhouse gas emissions are more self-consistent.

We first provide information on the methodology to project steel demand and production; we then describe the scenarios that we assessed (section 2); we present and discuss results for steel demand and trade, for the steel production mix, emissions and investments, and for overall mitigation options (section 3); finally, we conclude on main findings and open issues (section 4).

## **2. METHODS: MODELLING WORLD STEEL DEMAND AND SUPPLY**

### **2.1. The energy system model POLES**

Prospective Outlook for Long-term Energy Systems (POLES) is a global multi-regional energy system model that has been used extensively in global and regional climate policy studies[22]–[24]. POLES is a 66-region multi-sectoral partial equilibrium simulation model with an annual time step, with endogenously calculated energy prices (including electricity and hydrogen prices with multiple production technologies) and lagged adjustments of energy demand. Demand for energy services is derived from existing equipment and macroeconomic indicators; following equipment depreciation, choice across fuels or technologies is made with a logit distribution function using total costs and preference factors. All greenhouse gas emissions are represented.

### **2.2. Steel module overview**

We modified the POLES model by integrating different aspects for decarbonizing steel demand and production. This is a significant evolution of a previous POLES steel module[25], which had not been used since 2003.

The overall scheme of the materials demand and production module enriched and developed in this work is given in Figure 1. A general description is provided below, with more information in the following sections and more detail in supplementary information (SI). See SI section 7 for a comparison of key results with the previous model version.

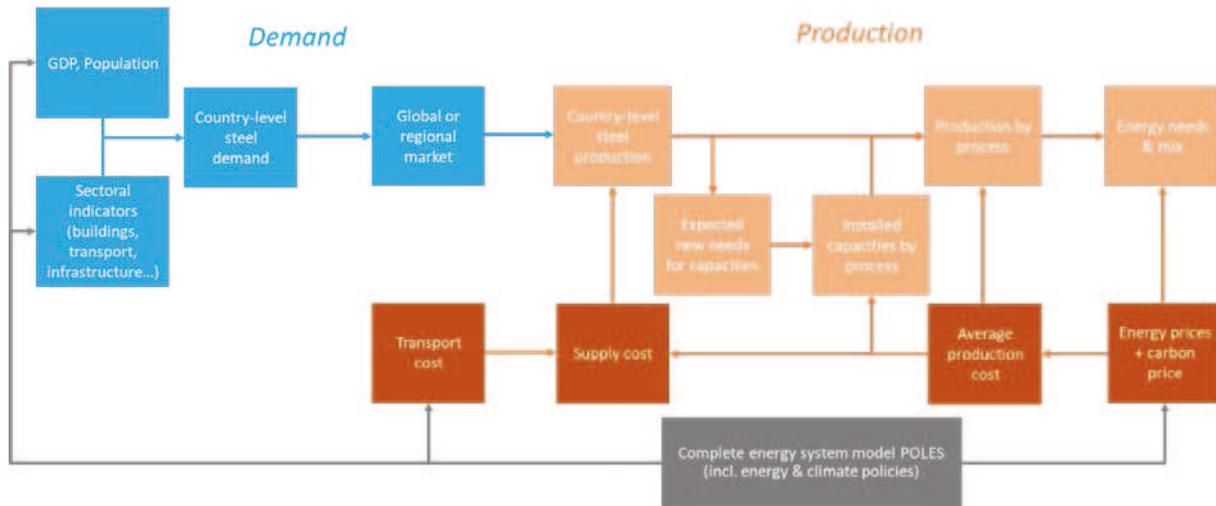


Figure 1: Schematic view of the steel demand and production modules of POLES for this work

Top left: for each region, annual demand for steel is determined based on material intensity per end-use, which are associated to stocks and flows of equipment, ultimately relying on macro-economic development and living standards. For each end-use, steel scrap is released at the end of the lifetime of the associated equipment; a scrap collection rate determines quantities of scrap available for recycling.

Top right: demand is met by production at the global level, with allocation based on production and transport costs and self-sufficiency constraints. Annual production is distributed across several production processes based on their costs and existing capacities; planning for new capacities is based on anticipation of future production needs and on costs. Cost-based competition within each process determines final energy consumption by fuel; energy- and process-related emissions are then calculated.

Bottom: energy and climate policy acts on the prices for energy fuels, including secondary fuels (electricity, hydrogen). Demand for steel can change as a result of the adaptation of the energy services and of the technologies mix to the policy; regional production allocation and the processes mix can change as a result of the policy directly impacting production costs.

### 2.3. Steel demand

Total apparent steel consumption by region was reconstructed from domestic production[26] and net trade[27].

Time series for steel demand by end-use are difficult to obtain. News reports from the industry provide the decomposition of steel demand by end-use for select regions[28]–[31]: construction ranged from 35% (EU) to 68% (China) and automotive from 8% (China) to 26% (USA). However, the sectoral decomposition differs across sources and only select years are available; therefore, a top-down decomposition of total consumption would necessitate many assumptions.

For this work, demand was estimated for certain end-uses in a bottom-up manner (specific material content per sector times an activity indicator), leaving a residual category when compared with annual apparent consumption time series. Three main demand sectors were singled out: buildings construction, road transport and power. See SI sections 4 and 5 for detail.

#### *Buildings construction*

Buildings construction (residential and commercial) is the single largest consuming sector for steel, estimated in this work at 32% of total global steel demand in 2015. Although “construction” is estimated to be the largest end-use by industry reports, it encompasses not only buildings but also other infrastructure; in this modelling, demand for buildings construction is separated from demand for other infrastructure, which is in the residual category.

A specific steel demand per floor area surface is associated with projections of new constructions of floor surfaces. Steel demand per surface were adapted from [20]. No strong correlations were found with macroeconomic indicators (GDP/capita, urbanization rate, population density); differences appear to be related to regional construction practices. They were kept constant in the projections.

#### *Road transport*

The automotive sector is one of the main consuming sectors, estimated in this work at 12% of total global steel demand in 2015, and growing strongly at 10%/year. It encompasses the production of light (private cars, vans) and heavy (trucks, busses) duty vehicles for road transport.

A specific steel demand per vehicle type from [32], [33] is associated with projections of vehicle fleets.

#### *Power sector*

This work estimates that the power sector absorbed 4% of total global steel demand in 2015. Steel demand for power generation and for the power grid were distinguished.

Specific material consumption per power generation technology (kg/kW) was obtained from [34]–[37]. New annual installations per technology are produced by the power sector module of the POLES model endogenously, on the basis of equipment lifetime, total costs and bottom-up electricity demand projections. Power generation capacities lifetimes differ depending on the technology; they range from 20 (wind) to 50 (hydro) years.

Specific steel consumption for the power transport and distribution grid (kg/GWh) was derived from [38]. New needs for the grid arise from the projections of power generation and a grid equipment lifetime. Grid equipment is considered to have a 40 year lifetime.

#### *Infrastructure and other*

The remaining demand pertains to the construction of public works and other infrastructure (roads, rail network, oil and gas and mining extractive industries, manufacturing industries), to machinery and equipment (mechanical engineering, maritime vessels and other transport vehicles, containers and packaging, tubes, domestic appliances, and other uses). This work estimates that in 2015, it corresponded to 52% of global steel demand. Given the diffuse nature of this demand category and the lack of specific drivers to associate it with in the energy system model for a bottom-up estimation, this remaining demand was projected as a constant percentage of total demand. In projections, the aggregate changes in the three bottom-up end-uses above drive the evolution of the residual demand.

## 2.4. Steel production

Currently, three main processes dominate world steel production. The blast furnace followed by a basic oxygen furnace (BF-BOF, 72% of world production in 2020) makes use of coking coal as a reduction agent for the iron oxide in the ore; steel plants can also include facilities to convert mineral coal into coke. The electric arc furnace (EAF, 22% of production) is a form of recycling, it melts scrap metal into new steel items. The direct reduction with EAF process (DRI, 6%) does away with coking coal and uses a mix of hydrogen and carbon monoxide (as syngas derived from methane or coal) as reduction agents, producing sponge iron, which is fed into an EAF to produce steel. Market shares have been mostly stable over the past 30 years, with direct reduction gaining importance at the expense of electric arc.

Production processes considered for the modelling were limited to those with a technology readiness level today that have a reasonable chance to represent a sizable share of production capacities in the time horizon of the study. The Technology Readiness Level (TRL) of production processes were taken from [39]–[42]; technologies with a TRL above 5, i.e. from demonstration level to mature, were selected to be modelled. They were: BF-BOF; EAF; DRI using fossil gas followed by EAF (DRI-NG); DRI using hydrogen directly (DRI-H<sub>2</sub>) followed by EAF; smelting reduction followed by BOF (Smelt); low-temperature electrolysis (electrowinning, E-winn); as well as 3 carbon capture options (BF-BOF+CCS, DRI-NG+CCS, Smelt+CCS). Technologies still

at a research level, such as high-temperature electrolysis, were excluded.

Process efficiency and investment costs for new installations are set exogenously (from [12], [39], [43]–[46], the assumptions are presented in SI section 6). Historical statistics on energy[47] and capacities[48], [49] are used to set up process efficiency and fuel mix for existing equipment. Coke ovens were not accounted in the iron and steel sector but in the energy transformation sector.

Investment in new production capacities is calculated based on the growth of production in past years. The choice among capacities is made using a logit distribution with total costs and preference factors. Total costs consist of capital expenditure (CAPEX) and a number of operational expenditures (OPEX):

- CAPEX: overnight investment costs annualized over the lifetime of the equipment with a discount rate;
- raw material costs: iron ore (driven by international maritime transport cost), steel scrap (availability influences the steel scrap price), coking coal (endogenously calculated), oxygen (constant);
- energy input costs (endogenously calculated, with upstream production costs and trade for fossil fuels and multiple production technologies for electricity and hydrogen, which are purchased by the steel sector);
- CO<sub>2</sub> price (exogenously defined);
- CCS transport and storage cost (constant) and carbon credit from biomass-CCS (determined by the carbon content of biomass and can cover, at most, the energy input costs and CO<sub>2</sub> price);
- revenue from by-products (slag produced in basic oxygen furnaces is sold at a constant price).

CCS technologies include a fixed CO<sub>2</sub> capture rate (BF-BOF: 65%; DRI: 55%; Smelt: 80%, from[39], [50], [51]).

Preference factors represent the factors that influence the choice that are unrelated to pure economics, reflecting country specificities observed on the historical mix such as inertia in choosing existing technologies (the weight of past capacities, its effect is phased out by 2035), or technological availability for new technologies (CCS availability and electrowinning maturity grows over time; a shortage in global scrap curtails investments in new electric arc capacities). In addition, there is the possibility to retrofit certain processes into others (in particular for retrofitting CCS).

The choice among fuels within each process is made using a logit distribution with user costs, including efficiency and carbon pricing and any process-specific constraints (such as a specific reduction agent). Biochar being a less energy dense fuel than coal and traditionally used in smaller furnaces, the use of biochar as a coke substitute was capped at 50% of the energy consumption of furnaces.

Regional allocation of global production is done on the basis of the region’s average production cost and a transport cost

(cost of exporting towards net importers, weighted average over importers' market share in global trade) under the constraint of available capacities per region.

## 2.5. Scenarios

In order to take into consideration several uncertainties in how the energy system as a whole, as well as steel demand and steel production technologies more specifically, might develop, we considered multiple scenarios that were quantified with the POLES model.

The scenarios are driven by macroeconomic projections (GDP, population) that are defined exogenously as model inputs; energy prices, technological development and emissions are calculated endogenously under scenario-specific constraints and parametrization. Scenarios rely on historical statistics for energy demand and steel production, which extend to the year 2020.

We assessed the following contrasted scenarios:

A Reference (*Ref*) scenario: existing policies related to energy supply and demand policies and targets, as well as legislated emissions policies and targets that are backed by supporting energy-sector policies, are enacted. No additional policies are considered compared to what had been legislated as of June 2022 (see Annexes of [52] for the list of policies considered). Accumulated net CO<sub>2</sub> emissions over 2020-2100 amount to 3070 Gt, resulting in a global mean temperature increase at the end of the century of 3.0°C (median probability), as calculated by the online MAGICC tool[53].

Several scenarios compatible with the Paris Agreement goal of limiting climate change to 1.5°C above pre-industrial levels: they differ in several dimensions related to technological availability and maturity, and in the socio-economic implementation of the climate policies necessary to reach the temperature objective. They consist in:

- (i) *15C\_CCS* with an earlier availability of carbon capture across the entire economy, to study a steel sector that might continue its reliance on technologies that involve combustion;
- (ii) *15C\_Elec* with more ambitious technological learning for new direct and indirect electrification technologies, to study a steel sector that might move more towards a new paradigm;
- (iii) *15C\_LD* with lower energy service demand and lower material demand, resulting in fewer emissions to decarbonize on the steel production side, to study a steel sector where sobriety, efficiency and circularity are more important;

- (iv) and *15C\_Opt* which combines elements of all of the above, to study a best-case scenario for the degree of economic effort to obtain a decarbonized steel sector.

The specific levers that were used to parameterize these scenarios are presented in Table 1 and are detailed below.

*Climate policy:* For each 1.5°C scenario, a carbon price is applied to all regions and all sectors of the economy. The carbon price follows a sigmoid curve starting from 2022, with an inflection in 2040 and a saturation level in 2100; it is adapted for each 1.5°C scenario for a peak-temperature budget (i.e., at the year of global net-zero CO<sub>2</sub> emissions) of 650 GtCO<sub>2</sub> from 2020, which is compatible with a 1.5°C global mean temperature increase compared to pre-industrial levels at the end of the century. 2100 prices are 0, 880, 1130, 795 and 750 \$/tCO<sub>2</sub> for the scenarios listed above.

*CCS availability:* availability for installing CCS options and CCS infrastructure is determined by a multiplying factor to the technology's cost, uniformly across all regions, with a duration of 50 years from zero (first-of-a-kind) to one (pure cost-competition); first-of-a-kind from 2020 (default) or from 2050 (delayed).

*Bioenergy availability:* lignocellulosic biomass availability is determined by supply costs; higher costs result in total global bioenergy demand not exceeding 170 EJ/year (conservative) and lower costs result in 200 EJ/year (optimistic). A cap for bioenergy penetration in steelmaking processes was set at 50% (conservative) and 75% (optimistic). As a convention, solid biomass energy use is considered carbon-neutral (compensated by carbon absorbed in the growth of new biomass in a sustainably managed cycle); and biomass with carbon capture and sequestration (BECCS) is considered as carbon net-negative.

*New electricity costs:* investment costs for the electrowinning furnace for steel differ, with optimistic costs a third lower than pessimistic costs. Hydrogen electrolyser costs decrease, reaching 480 \$/kW, as per[54] (pessimistic), and to 98 \$/kW in 2050, as per[55] (optimistic); see SI section 7 for a complete view of hydrogen production pathways and costs. In addition, in the pessimistic case the steel sector is provided by the average hydrogen considering all production pathways plus a transport and distribution duty; the optimistic case sees green hydrogen production taking place close to the steel plant, resulting in a price driven only by wind and solar electrolysis technologies, without a transport and distribution duty.

**Table 1: Parameter matrix for the scenarios in this study**

	<i>Climate policy</i>		<i>CCS availability</i>		<i>Bioenergy availability</i>	<i>New electricity costs</i>	<i>Energy demand adaptation</i>	<i>Steel demand adaptation</i>	<i>Steel plant lifetime</i>
<i>Ref</i>	Current adopted policies		Default		Conservative	Pessimistic	Default	Default	Default
<i>15C_CCS</i>	Global carbon price	carbon	Default		Optimistic	Pessimistic	Default	Default	Reduced
<i>15C_Elec</i>	Global carbon price	carbon	Delayed		Conservative	Optimistic	Default	Default	Reduced
<i>15C_LD</i>	Global carbon price	carbon	Default		Conservative	Pessimistic	Energy conservation measures	Material efficiency measures	Reduced
<i>15C_Opt</i>	Global carbon price	carbon	Default		Optimistic	Optimistic	Energy conservation measures	Material efficiency measures	Reduced

*Energy conservation measures:* building surfaces and vehicle stocks are related to demography, economic growth and occupancy rates. Residential surfaces are capped to a maximum value of 50 m<sup>2</sup>/cap (default: no cap; the region with the highest level, the USA, reaches 108 m<sup>2</sup>/cap in 2100). The car ownership ratio is capped to a maximum of 0.4 car/cap (default: values are capped by 0.6 car/cap); in addition, we assume a modal shift from private transport to public transport and soft modes, maintaining the total passenger mobility compared to the default case.

*Material efficiency measures:* specific material demand per floor surface area for buildings decreases over time (to 67% of its initial value by 2050) and specific material demand per vehicle for road transport decreases over time (to 50% of its initial value by 2050), uniformly across all regions, with 2050 values following the ambitious scenario in[56]. Steel scrap recycling increases to a maximum recovery rate (from an estimated 80% of end-of-lifetime scrap collection rate in 2020, to 90% in 2030, accounting for 10% considered unrecoverable).

*Steel plant lifetime:* the default value (35 years) for renewing the stock of steel production capacities was reduced in the 1.5°C scenarios (23 years) to reflect increased pressure to renew the stock towards more low-carbon processes. See SI sections 6 and 8 for more details.

### 3. RESULTS AND DISCUSSION

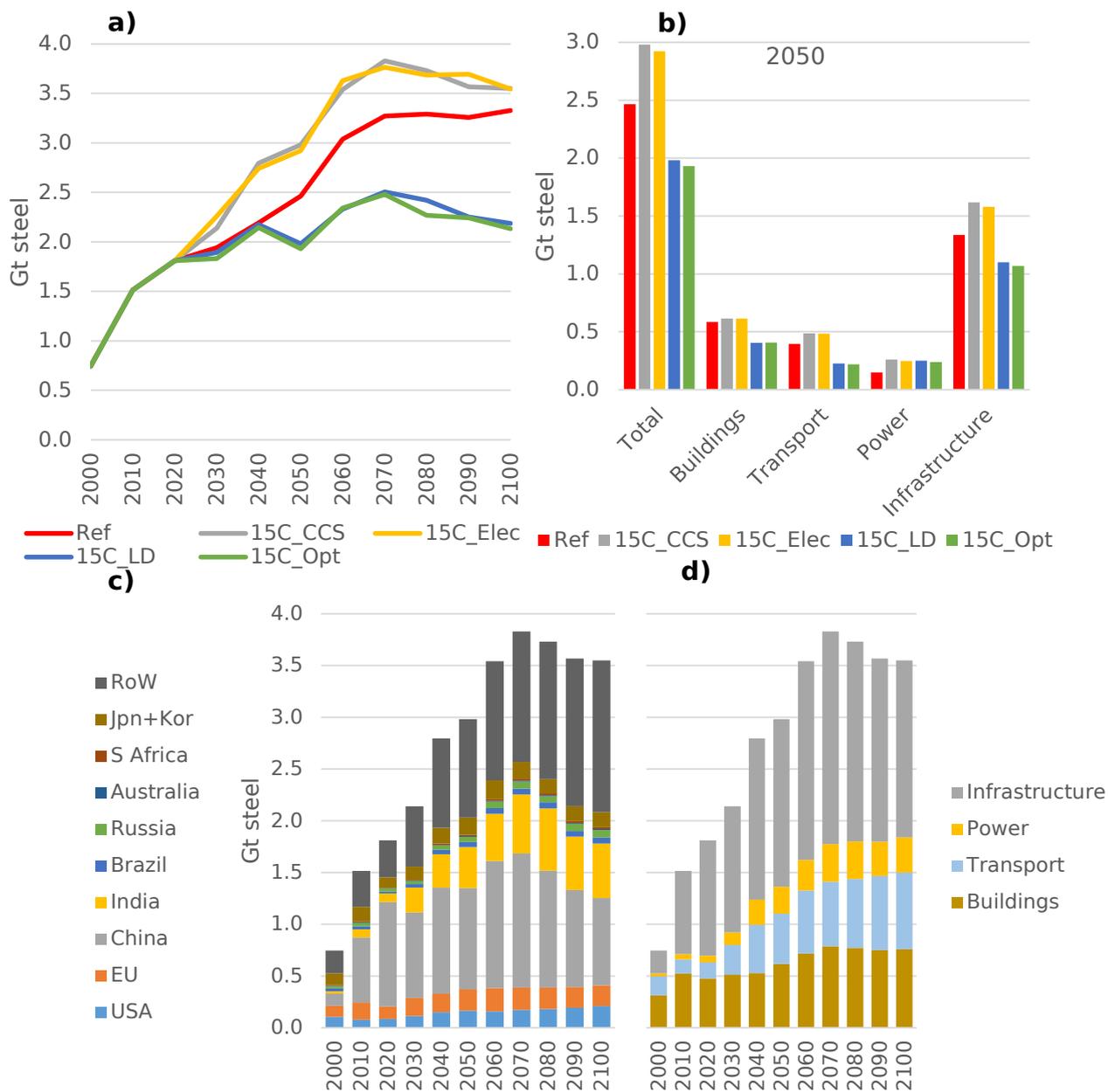
Scenarios were executed to 2100; results are presented for the world and key regional aggregates; more granular results are provided in SI spreadsheets.

#### 3.1. Growth of world steel demand to decelerate

Global steel demand is projected to continue to increase in the coming decades, but at a decreasing rate of growth with a stabilization in the second half of the century (Figure 2). Demand is projected to reach 2.98 Gt in 2050 (65% above the 2020 level) peak in 2070 and reach 3.62 Gt in 2100 (15C\_CCS). Annual demand growth decreases from 4.4%/year over 2000-2020 to 1.7%/year over 2020-2050 and 0.4%/year over 2050-2100. This is driven by a strong demand increase in India and the Rest of the world, while demand in China stabilizes to 2050 and increases again thereafter.

Total steel demand evolution is due to an increase of demand over all uses. In terms of volume, most of the increase to 2050 comes from infrastructure, followed by road vehicles, power and, finally, buildings construction. A second wave of buildings construction in China in the 2070-2090 period, roughly 70 years after the first wave over 2000-2020, results in global steel demand for buildings increasing again, while demand in most other regions increases or stabilizes. Demand for the other uses increase moderately throughout the end of the century.

These increases are driven by the underlying socio-economic conditions. Demand for buildings (+29% over 2020-2050) is driven by an increase in global floor surface area (+66%). Demand for transport (+214% over 2020-2050) is driven by an increase in global passenger (+46%) and goods (+65%) traffic volumes, with corresponding increases in vehicles stocks. Demand for power (+302% over 2020-2050) is driven by an increase in global power production (+180%) (15C\_CCS).



**Figure 2: Global steel demand (a) across scenarios; (b) by end-use sector in 2050, all scenarios (c) by region, 15C\_CCS scenario; (d) by end-use sector, 15C\_CCS scenario**

Source: POLES model. “Jpn+Kor”: Japan and South Korea. “RoW”: Rest of the world.

The implementation of climate policies leads to a positive feedback effect on steel demand. This amounts to 19-21% higher steel demand in 2050 and an additional 16-17% of accumulated demand over 2020-2050 (15C\_CCS and 15C\_Elec compared to Ref). This is brought about by an increase in demand for transport and for power, and to a lesser degree for buildings. This feedback would result in an increase in emissions in order to produce this extra steel; however, in all cases, this increase is smaller than the emissions savings brought about by the new low-carbon equipment and infrastructure built with this extra steel.

In buildings, climate policies accelerate the renovation rate in order to achieve higher buildings shell insulation levels, resulting in more steel needs. Over the 2020-2050 period,

accumulated renovated surfaces are 29-32% higher (15C\_CCS and 15C\_Elec vs Ref), and accumulated steel demand is 4-5% higher compared to Ref. The production-side increase in emissions induced by this higher steel demand (about 0.9-1.0 GtCO<sub>2</sub>, accumulated) are more than compensated by the emissions savings brought about by more energy-efficient buildings and the accompanying switch to low-carbon fuels in buildings energy use (which were at 3.0 GtCO<sub>2</sub>/year in 2020).

In road transport, similarly, climate policies induce a faster stock turnover in order to achieve decarbonisation faster; in addition, climate policies induce a certain reduction of overall passenger mobility as well as a certain modal shift from private cars to busses. These effects combine to result

in 2020-2050 accumulated steel demand 20-23% higher (15C\_CCS and 15C\_Elec) compared to Ref. This considerable increase would result in more emissions from steel production (about 2.3-2.7 GtCO<sub>2</sub>, accumulated); however, they would amount to the equivalent of less than the year 2020's total road transport energy use emissions.

In power, climate policies push towards higher electrification and a shift towards lower-carbon power sources. As the power sector is progressively decarbonised, electricity becomes a lower-carbon energy vector and power demand becomes higher. While low-carbon technologies require less steel than fossil fuel technologies per unit of installed capacity on average, some of them, such as wind and solar, have a low load factor and more units would need to be built to replace the equivalent fossil fuel unit with the same nameplate capacity. Over the 2020-2050 period, the average steel intensity of newly installed capacities is 7% lower in 15C\_CCS compared to Ref (106 kg/kW vs 115 kg/kW) while accumulated installed capacities are 65% higher, resulting in an accumulated steel demand that is 53% higher (55% for 15C\_Elec). Again, this feedback would result in additional emissions in steel production compared to Ref (approximately some accumulated additional 2.4 GtCO<sub>2</sub>); however, these would be much smaller than the emissions saving brought about by the decarbonisation of the power sector (from about 12 GtCO<sub>2</sub>/year in 2020 to net-zero in 2050).

In infrastructure and other uses, resulting from the combined behaviour of the above end-uses, steel demand is also higher than in the Ref (17% accumulated).

As a direct result of the energy and material savings and efficiency measures, the steel demand in 15C\_LD is lower. The climate policies feedback on steel demand could be contained and even overcompensated, resulting in total steel demand that is slightly lower than in Ref (-4% accumulated for 15C\_LD, -5% for 15C\_Opt). The effect is larger in the specific sectors where measures were implemented, buildings (-15%) and road transport (-18-20%). Demand in power is little different to the other 1.5°C scenarios (+44-48%), with differences mostly due to the feedback of lower steel production on electricity demand itself. The difference becomes more pronounced after 2050, when the measures have been fully phased in; total steel demand peaks in 2070 but at a much lower level (2.54 Gt in 15C\_LD compared to 3.80 Gt in 15C\_CCS), a level that is exceeded already in the 2020s in the other 1.5°C scenarios. Thus, these savings and efficiency measures would provide a longer time for the steel production industry to respond to an increasing demand while simultaneously meeting the decarbonisation challenge. Indeed, it could be realistically expected that the higher

costs of producing low-carbon steel would be passed down to the end-users, which would result in a demand level responding accordingly; while a steel price elasticity on demand was not included in this modelling, its effects are here approximated by the adoption of such savings and efficiency measures.

## 3.2. Steel production mix to diversify

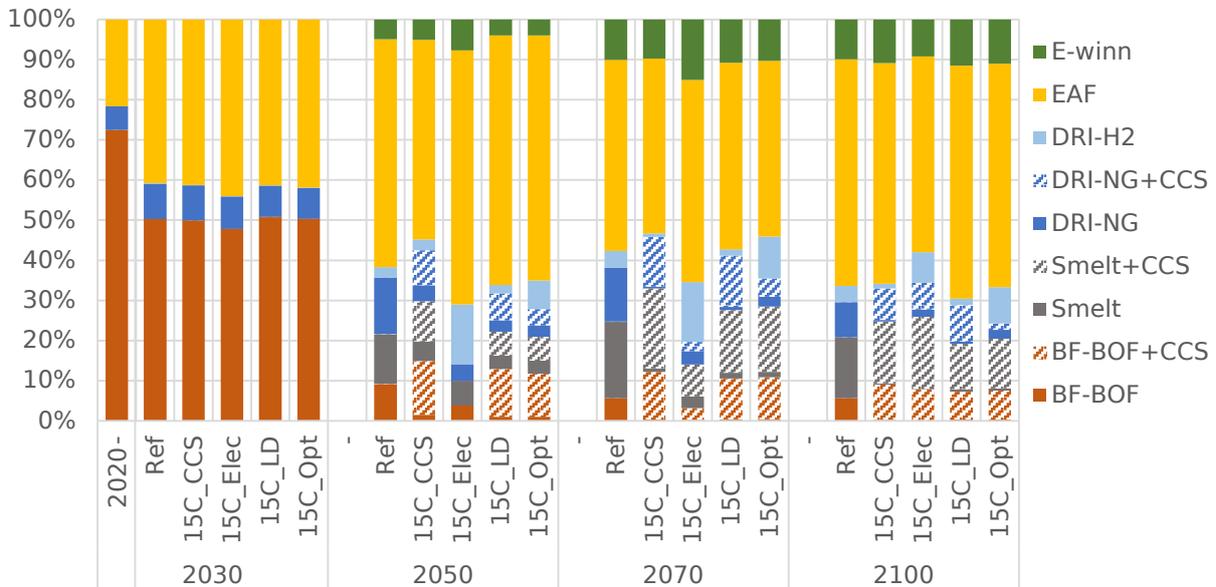
### *Steel production mix*

Recent industrial-scale innovation and investment projects are focusing on DRI-H2 and DRI-NG-CCS solutions[57], which might prove to be decisive for the medium term. We offer here a longer-term view that takes into account a wider range of options that might be available to the sector. The production mix in the projection evolves from the current situation. Figure 3 presents the world production mix, including the substitution process that takes place over part of the stock once older equipment is retired and the effects of retrofitting CCS onto existing capacities.

Without strong climate policies (Ref), there is a strong increase of electrification (EAF) and a progressive penetration of direct reduction and, to a lesser degree, of smelting reduction, at the expense of BF-BOF. EAF covers 57% of production by 2050, up from 22% in 2020. Indeed, the scrap available for recycling (recovered from equipment reaching the end of its lifetime as well as new scrap produced in steel plants) more than doubles over 2020-2050 (+116%), allowing this considerable expansion of secondary steel production. Primary steel makes up 43% of total production, which is sufficient to provide for specialty steel products for which secondary steel is not of high enough quality.

With strong climate policies (15C\_CCS), the mix is much more diversified: CCS technologies emerge (taking up 32% of the market by 2050) and direct reduction decreases (however, direct reduction using hydrogen remains approximately the same at 2-3%). These effects are more noticeable with more optimistic assumptions on electricity (15C\_Elec), where CCS is substituted by more EAF (63%), more hydrogen and more unabated technologies, resulting in higher emissions.

DRI-H2 production over all scenarios increases over time in the first half of the century and reaches 2% (15C\_LD) to 15% (15C\_Elec) share of global steel production of in 2050, the latter amounting to 40 MtH<sub>2</sub>/year. In the second half of the century, the comparatively cheaper CCS options result in that share decreasing. This low share for DRI-H2 is consistent with other studies where this technology was included in economic competition with other production routes[12], [58].



**Figure 3: Global steel production mix**

Source: POLES model.

These changes in production mix are due to several factors. The climate policy effort distorts the competitiveness of different options. Fossil fuel-based technologies without CCS become non-competitive from around 50 \$/tCO<sub>2</sub>. The use of biomass coupled with CCS in BF-BOF and smelting reduction result in carbon credits that decrease OPEX (up to covering all of the expenditure for energy and coke inputs) and decreases net emissions further. Steel production using the smelting reduction and direct reduction processes have the comparative advantage of not needing coking coal and can become more competitive than the BF-BOF process. As the CO<sub>2</sub> price increases, the direct reduction process using hydrogen gains advantage over using natural gas and partly capturing the CO<sub>2</sub> emissions with CCS.

The OPEX of EAF is driven upwards partly due to the impacts of the decarbonisation effort on the electricity price, but also due to the higher price for scrap, due to a higher demand for scrap globally.

The extended use of BF-BOF, Smelt and DRI technologies with CCS at the expense of EAF results in an increase of energy intensity, either after 2050 in 15C\_CCS or after 2070 with the delayed implementation of CCS in 15C\_Elec.

### Steel sector emissions

The resulting CO<sub>2</sub> emissions of the steel sector are presented in Figure 4. Steel sector emissions in 2020 are estimated at 2.4 GtCO<sub>2</sub>. Even without strong climate policies (Ref), emissions peak in the 2020s decade, decrease significantly and stabilize after 2040 to around 1.5 GtCO<sub>2</sub>, with the CO<sub>2</sub> content of steel decreasing from 1.3 tCO<sub>2</sub>/t in 2020 to 0.5 tCO<sub>2</sub>/t in 2050.

With strong climate policies, the steel sector emissions decrease dramatically to around 0.3 GtCO<sub>2</sub> in 2050; the CO<sub>2</sub> content of steel reaches 0.1 tCO<sub>2</sub>/t in 2050 for all 1.5°C scenarios, under an average carbon price in 2050 of 800 \$/tCO<sub>2</sub>. Net-zero emissions are reached in the second half of the century only thanks to the contribution of CCS technologies and biomass (during the 2070s for 15C\_CCS and 15C\_LD, not reached by the end of the century for 15C\_Elec).

As evidenced by the 1.5°C scenarios, the carbon price, CCS availability and plant lifetime are the most important drivers for emission reductions (see also the sensitivity analysis in SI section 8). The shortening of lifetimes in the 1.5°C scenarios to allow a faster turnover is a significant contributing factor to the production mix change and fall in emissions. However, this presents the risk of considerable sunk costs in processes with unabated emissions.

Overall, following the logarithmic mean Divisia index (LMDI) method[59], the main decarbonisation options expressed as a decomposition of emission differences between 2020 and 2050, averaged over the four 1.5°C scenarios, are (Figure 5): electricity (70%), biomass (12%), CCS (10%, most of which with fossil fuels), fossil fuel switch from coal to gas (9%), process efficiency (6%), hydrogen (5%). The increase in tons produced counts as an additional constraining factor for decarbonisation as it would otherwise lead to additional production-side emissions (activity, -17%).

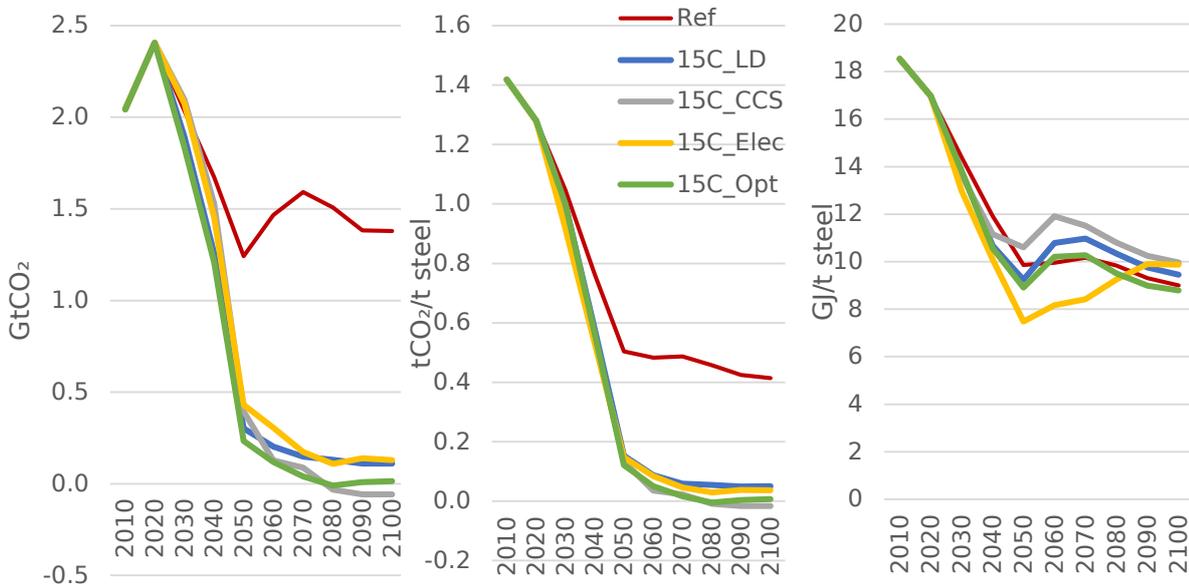


Figure 4: Global steelmaking emissions (left), emissions intensity per ton of output (middle) and energy intensity per ton of output (right)

Source: POLES model.

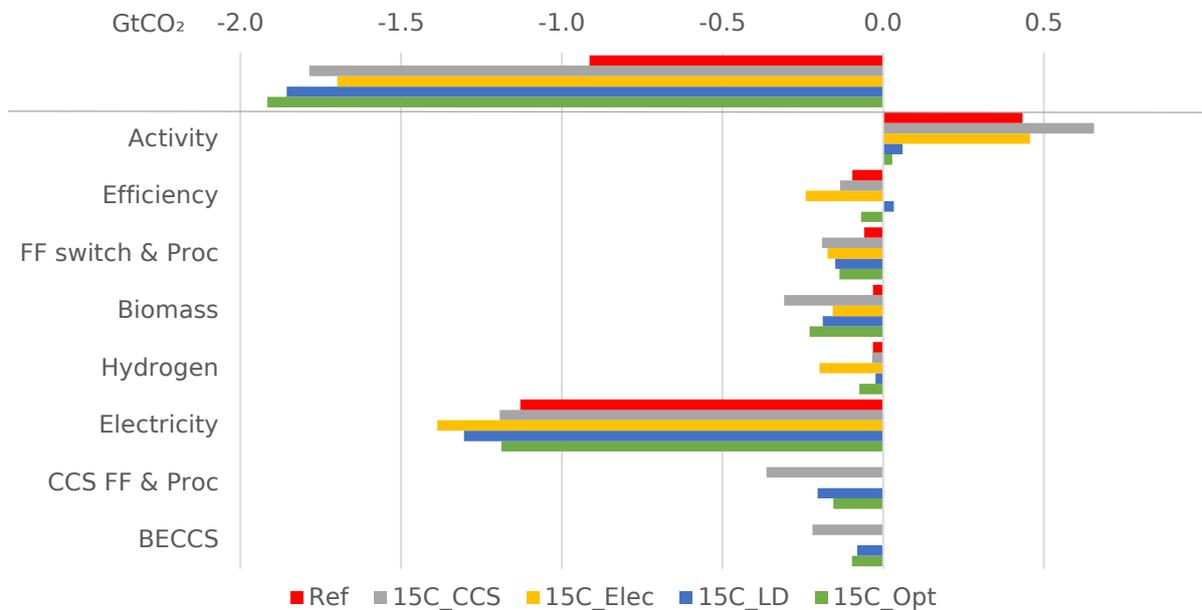


Figure 5: Emissions reductions in 2050 compared to 2020 and distribution of decarbonisation options from 2020 to 2050

Source: POLES model. “Mitig vs 2020” refers to total emissions reductions in 2050 compared to 2020, decomposed in options below. Sector efficiency has been distributed across the “Efficiency” and “Electricity” options, given the large difference in energy use of the EAF process compared to all others. Hydrogen is sourced outside of the steel facility (green hydrogen is not accounted in electricity).

### Steel sector investments and production costs

Investments to support the supply of steel (overnight investment costs of production capacities), both to replace ageing equipment and for greenfield plants, are considerable. They amount to an average of 11 G\$/year over the 2021-2050 period in Ref, which are considerably lower (-54%) than the estimated investments over 2001-2020 of 25 G\$/year as a result of demand growing much slower. Investments are higher in 15C\_CCS (22 G\$/year, +94% compared to Ref), given the costlier technologies chosen, the retrofitting towards CCS, but also the higher capacities installed (+24%) due to an even higher demand. This is

mitigated by demand-side savings and material efficiency measures (15C\_LD and 15C\_Opt), where average investments are lower (14 G\$/year, +19% compared to Ref).

As a result, taking into account the total costs (investment, raw materials, fuels cost, carbon price), the average ton of steel produced in the world becomes costlier. In Ref, the increase is small (+7% over 2020-2050); in 15C\_CCS, steel is more than half as much (+67%) more expensive to produce in 2050 compared to 2020, from about 650 to 1080 \$/t. If these costs were entirely passed down to the final consumer, this would make an average car (using 900 kg of steel) some 390 \$ more expensive (or 1.4% more expensive

considering 28,000 \$/car); this is higher than in [60] (<1%) but consistent with the more ambitious climate target of 1.5°C in this study. This anticipated low-carbon premium can be a limiting factor in the expansion of clean steel production for first movers, and innovative solutions will be needed to decrease the risk for investors (such as rules to access public finance, purchase contracts for low-carbon products, group investments around industrial clusters) [61].

Whether costs would be passed down, especially the costs related to the carbon price, would be a policy-making question related to consumer protection and purchasing power beyond the scope of this study, as well as a matter of climate policy. With rising steel prices, it could be expected that the demand would adjust accordingly: this is indeed reflected in 15C\_LD, which sees a steel demand that is 19% lower than Ref and a steel cost that rises by 61% by 2050 (i.e., 50% higher than Ref in 2050). By comparing Ref and 15C\_LD in 2050, the implicit price elasticity of steel demand is -0.54, which is within the range of values observed for long-term elasticities for energy products[62]. The steel saving measures could, however, be implemented by behaviour change and policy intervention with tools other than just pricing, such as building codes or equipment standards.

Of note, most of the production costs of steel are operating costs rather than fixed costs: the share of operating costs increases from 79% in 2020 to 87% and 90% in 2050 in Ref and 15C\_CCS, respectively.

### *Hydrogen supply for steel*

It then becomes an issue on how to supply the steel sector with sufficient quantities of low-carbon energies in a timely manner. This would be particularly challenging for new fuels that do not yet have a production, transport and distribution infrastructure in place, such as hydrogen.

Hydrogen production would have to move away from the current processes dominated by unabated fossil fuels (steam methane reforming, coal gasification) towards lower-carbon solutions, at a considerable cost (see SI section 7).

Our results show that hydrogen demand for steelmaking is projected to make up a relatively small share of overall hydrogen demand (as much as 6% of total hydrogen demand, in 15C\_Elec in 2040), taking into account non-energy uses such as hydrogen as an intermediate product in nitrogen-based fertilizers, in oil refineries and other chemical processes. Other emerging uses, such as hydrogen fuel cells in transport and the use of hydrogen as an input to the production of synthetic hydrocarbons, consume larger amounts of hydrogen; in decarbonisation scenarios, they are

projected to be the dominant uses of hydrogen worldwide[52], [63]. Thus, the steel sector is likely to not be a driving force in shaping the hydrogen production industry and its market price, and it is likely to be a price taker of hydrogen produced for multiple purposes. For the current most advanced pilot DRI-H2 projects, the same entity will be producing the hydrogen on-site using low-carbon grid electricity specifically, relying on other actors to expand grid capacity[64], [65]. However, DRI-H2 projects' electrolyser capacity is a small share of the overall hydrogen projects underway in Europe[61]. This raises questions as to whether self-production of hydrogen would be the most likely configuration for the steel sector, or whether the business model that would dominate would be hydrogen produced in a variety of ways and transported to the steelmaking site where it would be consumed.

### **3.3. Steel trade patterns to reorganize**

The regional distribution of steel production, dependent on production capacities, production costs and transport costs, remains concentrated around China in the projections (Figure 7). The production over-capacity in certain regions resulting from changing demand patterns redraws the map of potential importers/exporters (Figure 8). In the medium term, with standing capacities and a decreasing domestic demand, China could become a major net exporter. Certain regions change their trade status, from net importers to net exporters (USA, South Africa) at the expense of other exporters that reduce their exports (Russia, Brazil, Australia). The EU moves towards relying massively on imports, while the Rest of the world moves from relying significantly on imports toward self-sufficiency.

In the longer term, the increase in transport costs becomes an important component of traded steel cost: on world average, from 6% to 11% and 15% in 2050 in Ref and 15C\_Opt, respectively, resulting in more self-sufficient supply on average.

The implementation of climate policies usher small changes in the market shares of regions in the world steel production mix compared to Ref: in 15C\_CCS, China +4% market share at the expense of EU, India and the Rest of the world; in 15C\_Elec, China -6% at the benefit of the USA and the Rest of the world (15C\_LD and 15C\_Opt similar to 15C\_CCS). Broadly, countries with a prevalent production mix based on EAF (e.g., USA) are better equipped to reduce emissions if CCS is unavailable and gain market share in 15C\_Elec, while those with a predominantly BF/BOF-based mix (e.g., China) lose market share.

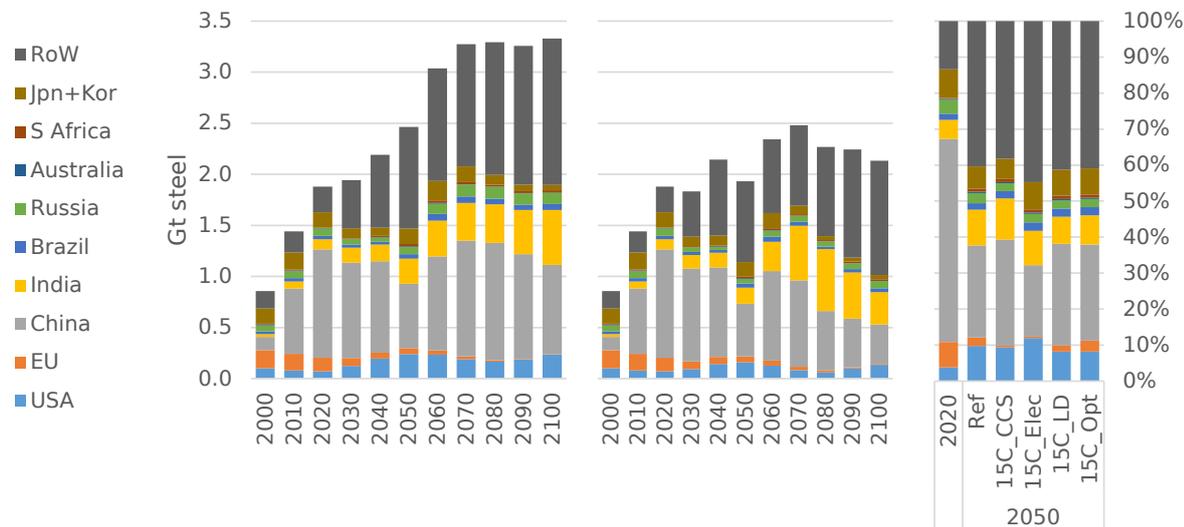


Figure 6: World steel production by region, Ref (left), 15C\_Opt (middle) and 2050 for all scenarios (right)

Source: POLES model.

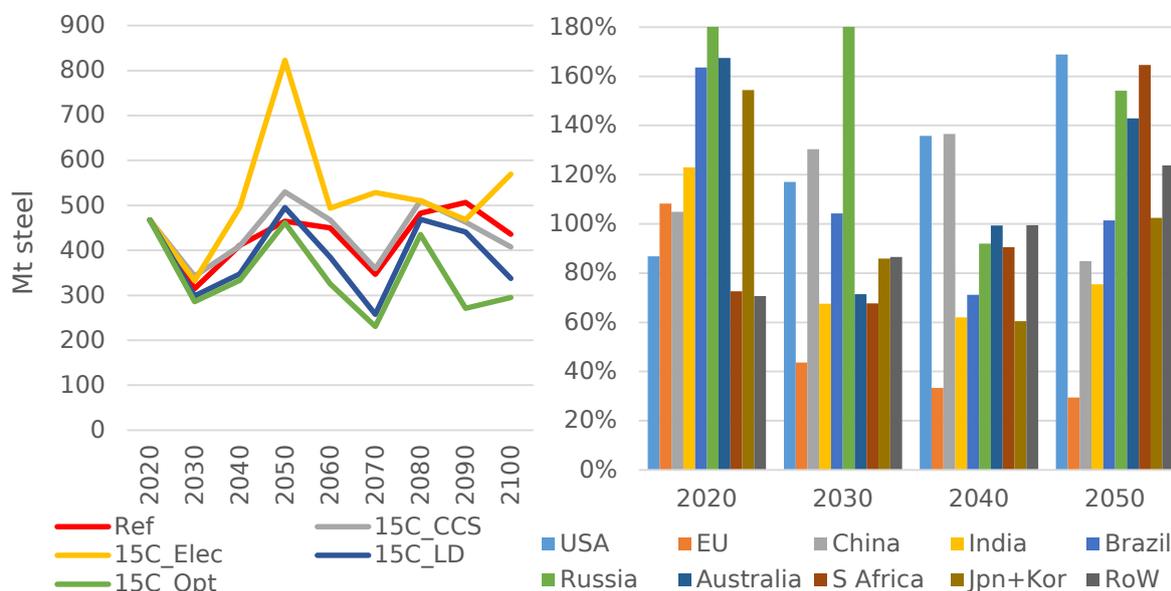


Figure 7: Global steel trade (left) and regional independence rate (right) in the 15C\_Opt scenario

Source: POLES model. Estimated 2020 value for Russia is 240%.

These relatively small changes in market shares are due to the uniform implementation of the carbon price in the 1.5°C scenarios in all regions; a fragmented climate policy with differentiated levels of decarbonisation effort across regions would result in a greater cost diversity and adjusted trade patterns.

As global patterns of demand shift and production capacities adjust, steel trade (global net imports with the model's regional disaggregation) experiences changes in the coming decades, with less trade in the lower steel demand scenarios and overall volumes similar to the recent past (Figure 8). While traded volumes increased over the past decades and reached an all-time high in 2016, exports as a share of total production have actually been decreasing since 2000 (from 39% to 23% in 2020[48]), which is extended and accelerated in the projections (19% and 23% in 2050 in Ref and

15C\_Opt, respectively). 15C\_Elec shows a notable increase in trade by mid-century as the delay of CCS increases residual emissions in BF/BOF-rich countries and changes the regions' ranking of production costs.

These results have to be put in a wider context of country-level industrial policy. Additional non-cost deciding factors might contribute to the decision to relocate production or not. Given the importance of the steel sector in direct and indirect employment, EU policy has regulation to mitigate relocation risk and prevent carbon leakage (EU emissions trading scheme[66], carbon border adjustment mechanism[67]). Other factors include innovation and strategic concerns, as per the EU's proposed Net-Zero Industry Act to maintain or increase domestic production. Conversely, low-carbon steel producers might position themselves as exporters towards leading consumers that

value low-carbon products (e.g., South Africa to EU[68], Emirates to Japan[69]).

Moreover, in addition to new steel trade, the increase in electrification would also be enabled by recycling and large amounts of scrap trade worldwide.

### 3.4. Wider impacts

The supply of energy fuels, including hydrogen, to support the needs of the steel industry come with wider impacts on the energy system and on other sustainability indicators such as land use and water use.

In terms of land use (Figure 9), the low-carbon alternatives come at a significant premium, compared to a 1.6 km<sup>2</sup>/Mt production capacity for a typical BF-BOF steel plant today[70]. A plant supplied entirely by hydrogen produced by electrolysis using solar power would require 20 times more surface (considering a 80 MW/km<sup>2</sup> land use for utility-scale PV[71]); importing the hydrogen by ship would require some 50 deliveries (considering an ammonia tanker carrying 1300 TJ/trip of NH<sub>3</sub> similar to a long range oil tanker of 110,000 deadweight tons [72] and an 74% H<sub>2</sub>-NH<sub>3</sub>-H<sub>2</sub> round-trip efficiency[73], [74]) to 105 deliveries (considering a liquefied hydrogen tanker carrying 500 TJ/trip similar to an 125,000 m<sup>3</sup> LNG tanker[75] and 4% of losses[76]). In addition, a BF-BOF plant that would switch entirely to biochar and biomass would require 460 times more surface (considering 200 GJ/ha of bioenergy crops yield[77]), while a switch to EAF with zero-emissions electricity would require the power grid to install for instance wind capacities occupying the equivalent of 25 times the area of the BF-BOF plant (considering 8 MW/km<sup>2</sup> for onshore wind[78]). Positioning the energy production on a remote site would increase issues of supply logistics and transport losses. Given that steel plants are often located on shorelines to ease the import and export of feedstocks and products, and that steel plants are often in industrial areas where land already has competitive uses, there are significant challenges in low-carbon energy supply to enable low-carbon steel.

In terms of renewables deployment rate, the expansion of low-carbon hydrogen would further burden the power system

to install sufficient capacities of renewables to supply both electricity end-uses and hydrogen electrolyzers. The decarbonisation of electricity poses significant administrative, investment and supply chain challenges already; wind and solar installation rates globally would need to increase by a factor of 11 in the 2040s compared to the 2015-2020 period (from 160 GW/year to 1,800 GW/year). Adding capacities for green hydrogen on top of that, as much as 35% additional by 2050, would raise that factor to around 16 (2,670 GW/year, 15C\_Elec).

In terms of water consumption, if the above maximum of 15% of steel tons produced with the DRI-H<sub>2</sub> process in 2050 are supplied by hydrogen produced with electrolysis, this would require 0.36 Gm<sup>3</sup>/year of water (considering 9 L/kgH<sub>2</sub> stoichiometrically; 2.4 Gm<sup>3</sup>/year for all steel production, 3.8 Gm<sup>3</sup>/year for all hydrogen production). However, these volumes are small when considering the larger consumers of water such as agriculture (2,900 Gm<sup>3</sup>/year in 2019[79]) or withdrawals for energy production mainly for power plant cooling (338 Gm<sup>3</sup>/year in 2016[80]). While volumes are small, regional heterogeneity on water resources could raise local concerns of water scarcity. Furthermore, water could be recuperated from the DRI furnace shaft and recycled to produce hydrogen[40].

In terms of CO<sub>2</sub> flows, the carbon captured in steelmaking and other sectors (hydrogen production, power generation, other) would need to be transported with dedicated infrastructure to the point of sequestration. While the costs are estimated to be low on a per ton basis (around 10 \$/tCO<sub>2</sub>[81]), the infrastructure remains to be built entirely, or use repurposed fossil fuel infrastructure, with few actual projects for country- or continental-scale transport materializing as of 2023[82]. The world average steel plant of 2.3 Mt/year[83] would produce some 4.2 MtCO<sub>2</sub>/year in the case of a BF-BOF plant equipped with carbon capture. This is comparable to the mass transiting through international gas pipelines (e.g., the Algeria-Tunisia-Italy TransMed pipeline capacity of 30.2 Gm<sup>3</sup> of natural gas over two lines, amounting to 11.6 Mt/year[84]), which underlines the scale of the effort required to put this infrastructure in place.

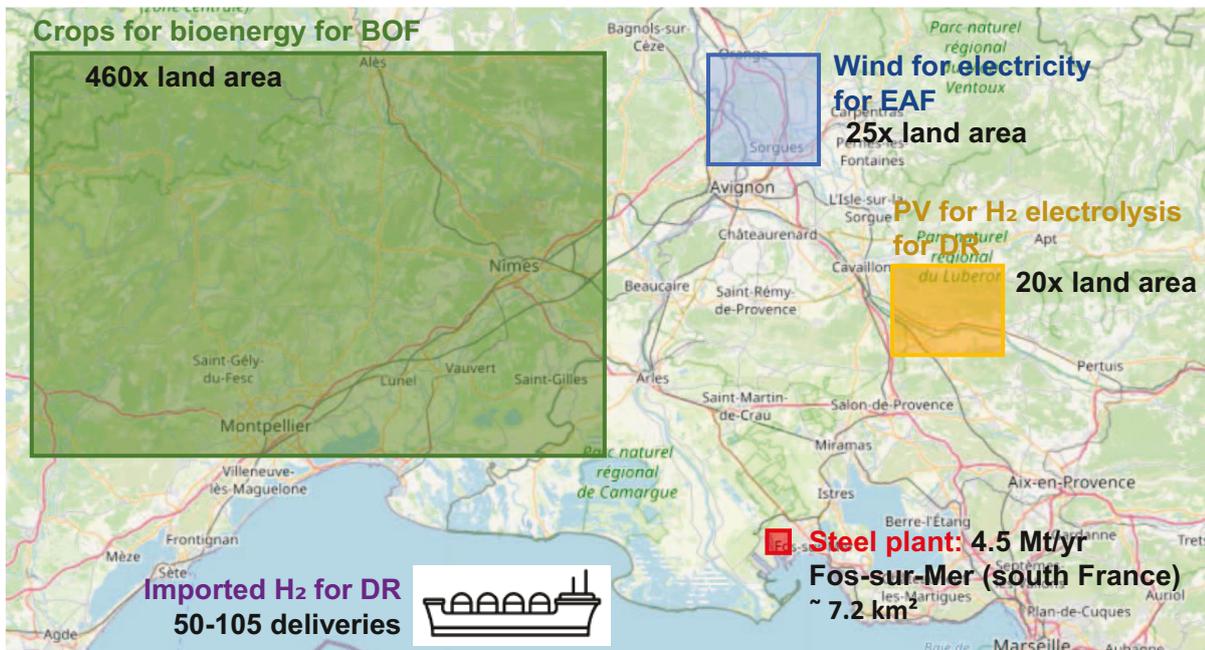


Figure 8: Indirect land requirements for different steel processes options

Map source: *OpenStreetMap.org*

#### 4. CONCLUSION

This paper presents work that gives new quantitative insights in the complex decarbonisation challenge of a sector perceived as “hard-to-abate”[42]. This work enriches the representation of industry sub-sectors in energy system models and consists in the state of the art in the way these issues are captured in energy system models. It provides an explicit picture of steel demand and its drivers, of steel production investment needs and of the effects of policy levers that are of interest to both policymakers and investors.

In this paper, we presented a new model detailing steel demand and multiple steel production pathways within a larger global multi-regional energy system simulation model. In order to assess the decarbonisation potential of the steel sector in interaction with the rest of the economy, we built several scenarios of the future energy system with different sets of assumptions on policies, technologies and steel demand patterns. We examined to what extent and at what pace the iron and steel sector can reduce its emissions and the contribution of each decarbonisation option. Finally, we broadened the scope to some additional challenges in the provision of low-carbon energy to fuel the cleaner production of steel.

This study adds an original set of projections for steel demand to the literature. Without additional climate policies, we project global steel demand to increase at a decelerated pace compared to the past two decades, reaching a plateau from 2070 at nearly double the level of 2020. This is calculated in a bottom-up manner due to substantial increases in buildings floor surfaces, road transport fleet, power production system and infrastructure, all of which are ultimately driven by the underlying socio-economic

conditions, if material used per unit of activity remain the same.

This study differentiates drivers for steel demand increase and savings, with a decomposition of effects that is new to the literature. The implementation of climate policies leads to a positive feedback effect on steel demand due to a faster equipment turnover and higher electrification; however, this increase would result in new low-carbon equipment and infrastructure that would yield large emissions savings. Introducing energy saving and material efficiency measures, which could be expected given the projected increase in steel production costs, would overcompensate this increase. Our demand projections in 2050 range from 2.0 to 3.0 Gt. Overall, these projections are comparable to those of other studies: e.g., for 2050, 2.0-2.6 Gt in [85], 2.0-3.4 Gt in [86], 1.5-2.5 Gt in [87] and 1.7-5.2 Gt in [88].

We provide “what-if” projections of decarbonizing steel supply based on technology availability and production costs, as opposed to normative scenarios of technology substitution[89] or potentials assessments[13]. The CO<sub>2</sub> emissions of the steel production sector are projected to decrease even without strong climate policies: with increased recycling thanks to the higher availability of steel scrap, electrification increases at the expense of the currently dominant blast furnace process and thereby yields important energy efficiency gains. Strong climate policies would be needed to push decarbonisation further. In the context of a full decarbonisation of the economy compatible with a 1.5°C climate change target, steel sector emissions would decrease by nearly 90% in 2050 compared to 2020. This achieved with the use of hydrogen in direct reduction but especially thanks to CCS technologies, increased recycling and electrification and use of biomass. The steel sector could reach net zero as

early as the 2070s; however, a delay in the availability of CCS technologies would make this unfeasible.

The costs of material efficiency measures are difficult to quantify; however, the economic assessment hints at their attractiveness as emission mitigation measures. In all decarbonisation scenarios, the steel production cost is projected to increase by half over 2020-2050, mainly driven by the price of energy inputs (including carbon pricing), thereby providing a strong impetus for the implementation of the savings and efficiency measures as an economically efficient option for decarbonisation.

The geographical distribution of steel production as well as the importer/exporter status of world regions are projected to experience in-depth changes. However, as a result of increasing transport costs, global steel trade volumes are projected to stabilize over time.

Although the hydrogen route has gathered significant investments for electrolysis and steel production in recent years [65], [90], [91], we project it to make up only a small part of the solution for steel due to its high supply cost. Direct reduction using hydrogen is projected to produce, at most, 15% of global steel throughout the century and across all scenarios, with a wide diversity across regions. The above share is reached in an optimistic configuration (green hydrogen produced in proximity to the steel plant, ambitious electrolyser cost decreases). Hydrogen demand for steelmaking is projected to make up a minority share of total hydrogen demand. This would put the steel sector in a position of price taker and raises questions as to which business model is likely to materialize, one of steelmakers purchasing hydrogen on the market or one where hydrogen and steel production is co-located.

Furthermore, the provision of large enough quantities of low-emissions energy to the steel sector would pose significant challenges in many fields. The indirect land use would increase severalfold to provide renewable electricity, green hydrogen or biomass. The pace of installation of renewable electricity capacities would need to increase by as much as 16 times compared to the recent past. The carbon transport and sequestration infrastructure remains to be built.

This study confirms the considerable multi-sectoral challenges related to the decarbonisation of the steel sector. Although policymaking and private sector interest in this issue has increased in recent years, more needs to be done in multiple fronts: adapt climate policy to align investments in clean technologies, mitigate bottlenecks in clean energy supply and CO<sub>2</sub> transport infrastructure and anticipate potential adverse effects in land use, water use and employment.

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### 6.3. Conclusion: prioritizing action to align low-carbon investments

We have seen how an energy system model was applied to produce a set of projections for steel demand and steel production, with the associated energy and emissions flows. Steel demand is projected to continue increasing, however emissions are projected to decrease even without additional policy intervention, largely thanks to increased scrap availability, recycling and electrification.

Additional efforts in the form of policies and investments are required to reduce emissions further to a level compatible with the overall economy's transition towards net-zero emissions. There are multiple pathways forward, all of them with different challenges and trade-offs, and all of them resulting in increasing production costs for steel in the future.

A majority of steelmaking capacities will need relining in the next 20 years; given how this business investment cycle and the urgency to decarbonise are aligned, this opportunity should be seized in order to implement low-carbon processes. We have identified the following actions for steel sector emissions reductions, ranked in order of importance:

#### **1. Pursue material efficiency**

An avoided ton of demand is one less ton that has to be produced. Managing buildings construction so as to limit growth of floor space per capita and revising construction codes in buildings in order to avoid over-specification and encourage innovative designs can all yield significant materials savings. The use of specialised steel can reduce steel demand in the automotive sector. A limited rebound effect on steel demand is projected to come from the low-carbon transition, due to increased use in buildings renovation and electrification.

#### **2. Electrify as much as possible**

The electric arc furnace is a mature and proven technology. Its increased role is expected due to an increasing volume of equipment reaching the end of its lifetime. Enhancing building and products design to facilitate recycling and improving recuperation rates can all help to increase cycling, and thus electrification. Innovative processes like electrowinning for primary steel production could turn out to be significant in a future when renewable electricity is vastly more abundant than today.

#### **3. Develop carbon capture and sequestration infrastructure**

Most emissions reductions can be reached with electrification, but without carbon capture the steel sector is not projected to reach net-zero emissions. CCS technologies can capture only a part of the steelmaking emissions, so they are a partial solution. However, their comparatively low costs mean that they can be applied relatively easily, even be retrofit on existing plants. Despite decades of theoretical studies and of small-scale tests, CCS is still untested at large scale; if it is to be a significant option in the medium term, the associated transport and storage infrastructure should start construction immediately. The business case for CCS would be solved with a high enough price on carbon emissions, however there is still lack of clarity on the business model for constructing the CCS infrastructure, i.e. what entity should engage the investments for the transport and sequestration infrastructure – the steel plant operator, a group of industrial sites clustered together, or a different actor.

#### **4. Use biomass parsimoniously**

Biomass (and biochar) as a substitute to coal (and coke) can result in emissions reductions. This substitution is only partial, as its adoption at high rates in the conventional blast furnace presents challenges in maintaining high yields. Coupled with carbon capture, the net emissions of a steel plant could even be negative, if the biomass is sourced from properly managed areas. Indeed, there could be significant trade-offs with other sustainability indicators given the significant land area needed for biomass (biodiversity, food production, water use). These concerns could create uncertainty and time delays in the provision of sufficient quantities of biomass, and this could limit its adoption by the steel industry.

#### **5. Innovate with green hydrogen**

Recent announcements and investments point to an increase in public and private interest in developing steelmaking using hydrogen in direct reduction. This is projected to be an important though costly option. Significant investments in research and development still need to happen in low-carbon hydrogen production itself to make it competitive compared to today's fossil fuel-based hydrogen; and even so, steel based on H-DRI would be costly. However, H-DRI and the equally power-consuming electrowinning are the only truly low-carbon options. In a context of deep emissions cuts and uncertainty around CCS, investing in H-DRI is justified.

#### **6. Be mindful of the just transition**

For a sector as internationally exposed as steelmaking, the wider social and employment implications of the low-carbon transition have to be considered alongside climate concerns. At the country level, many jobs could be at risk from delocalisation due to ill-planned climate policies. Conversely, countries investing in innovative technologies would like to achieve reindustrialisation by conserving or increasing domestic production, with the aim to supply their own market or export low-carbon steel. International cooperation – in the form of standards of maximum carbon content of steel traded, technology transfer, or carbon pricing of emissions – would be beneficial in terms of global emissions reductions; however this does not address the issue of employment delocalisation.

## 7. Cement decarbonisation: a silver bullet challenge?

“What's nice about concrete is that it looks unfinished.”  
- Zaha Hadid (architect, Iraq/UK, 1950-2016)



*Figure 29: Construction materials, including mortar, arranged like a painter's palette*

*Source: Still from "The Legend of Suram Fortress", 1984 film, directed by Sergei Parajanov, USSR. Cementitious materials have long accompanied human history.*

### 7.1. A sector where CO<sub>2</sub> emissions are inherent to the process

Cement is a material used for its binding properties, binding together other materials. It is mixed with sand to produce mortar and mixed with gravel to produce concrete. It is used in construction: buildings, public works and infrastructure of all kinds. End of lifetime comes when cracks in the binding endanger the structural stability of the object it is part of; it cannot be recycled. There are different standardized types of cement, varying in composition, as well as classifications on the compressive strength it can withstand [145]–[147].

#### ***Cement throughout human history***

The origins of cement can be traced back to ancient Mesopotamia and the Indus Valley civilizations in the 4<sup>th</sup> millennium BCE, where it was first used as a bonding agent in the construction of rudimentary structures. These early civilizations developed simple forms of cement by heating limestone and clay to create quicklime, which was then mixed with water to form a basic mortar.

Over time, the knowledge of cement production spread, with the ancient Egyptians, Greeks, and Romans refining its composition and application. The Romans, in particular, enhanced the strength and durability of cement by adding pozzolanic volcanic ash to the mix; the 1<sup>st</sup> century CE dome of the Pantheon in Rome is the world's largest and oldest unreinforced concrete structure that still stands today.

The most widely used cement worldwide is the ordinary Portland cement (OPC), a hydraulic cement (i.e. hardening after reacting with water) whose manufacturing was standardised in early 19<sup>th</sup> century England.

Cement, either by itself or reinforced with steel beams, is ubiquitous in contemporary architecture and infrastructure.

In terms of volume, cement is one of the most widely used materials today. Since 1950, cement production increased enormously, by a factor of 68 over 1931-2020 (see Figure 30) and stood at 4.2 Gt in 2019. Similar to steel, the fastest annual growth was observed during the post-war reconstruction period of the 1950s (9%/year) and 1960s and the period of fast development of China of the 2000s. Similar to steel as well, production was dominated by the USA and the EU region in the 1930s-1950s (35% and 32% in 1931, respectively) while today China is the overwhelmingly dominant producer (57% in 2020). Chinese cement production reached a peak in 2014, remained in a plateau, and dropped sharply by 10% in 2022, with expectations being that production will continue to decrease now that modern Chinese buildings and infrastructure have largely been constructed; this could have considerable implications for China's macroeconomic indicators and economic stability [148], [149].

World cement production has more than doubled just over the past 20 years. There are around 3600 cement plants globally, with the average and median plant having a 1.7 and 1.4<sup>21</sup> Mt/year production capacity, respectively [150], [151].

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<sup>21</sup> Estimated.

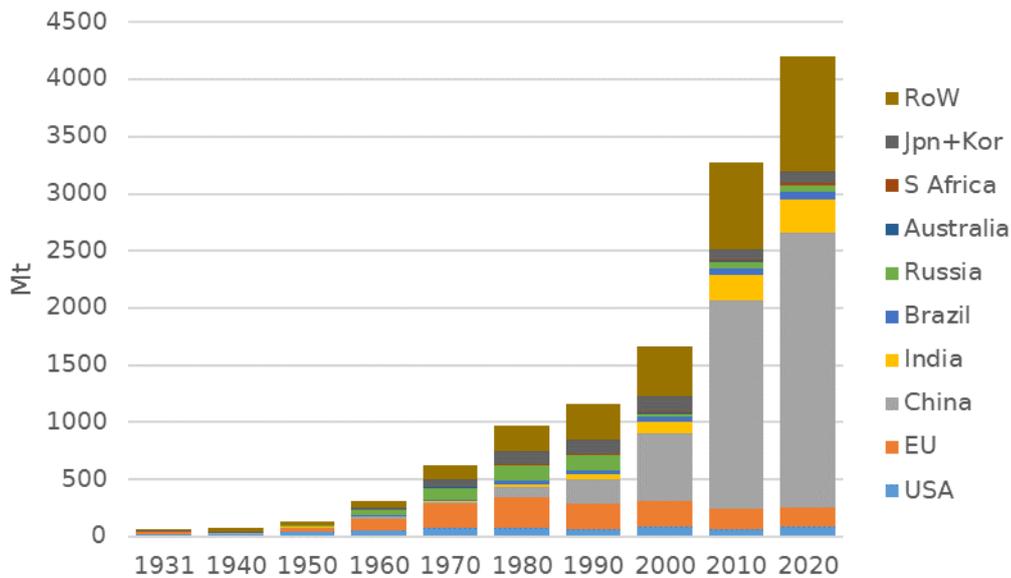


Figure 30: Global cement production, 1950-2020

Source: USGS Cement Statistics and Information [152]. Note: Not all EU countries were available for 1931-1970. Russia for 1931-1980 refers to USSR. Data for 1940 were incomplete.

Cement is a commodity that is produced and consumed locally, in most cases. It is usually delivered to the point of use by road transport, in the form of powder (*ready-mixed cement*, to be mixed with other materials and water to form concrete) or in the form of pre-fabricated concrete blocks (*precast concrete*).

As a consequence of this high cost of transport, most trade flows are short (less than 200 km in Europe [153]) and cross-border trade is limited. There is some international seaborne trade, because of fast regional demand growth in some regions and clinker production overcapacities in others. Recently, China has begun being a net importer. Total trade volumes (cement and clinker combined) have grown over 2012-2019 from 98 to 131 Mt, representing a growing share of global supply (from 2.6% to 3.2%).

Cement production can be broken down into three simple process steps (see Figure 31):

1. grinding of raw material;
2. heating (dehydration, calcination, clinkering, cooling), the product of which is clinker;
3. grinding and mixing (with inert products like gypsum), the product of which is cement.

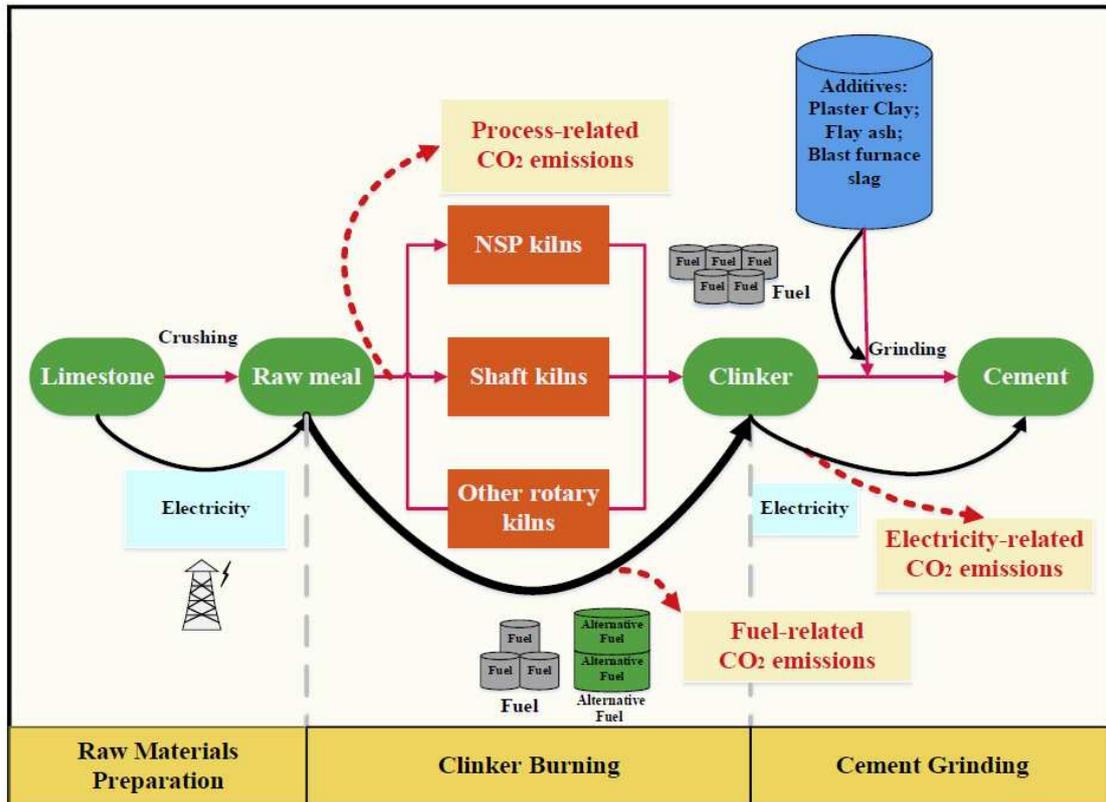
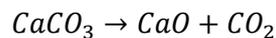


Figure 31: Schematic of the cement production process

Source: Zhang et al. (2018) [154].

The reduced formula for hydraulic cement (the main cement type) is:



Hence, the main source of CO<sub>2</sub> emissions is inherent to production (i.e. *process emissions*), an inevitable part of cement production. The calcination of calcium carbonate into calcium oxide and its compounding with silicates or other metal oxides (clinker) releases CO<sub>2</sub>, about 0.53 tCO<sub>2</sub>/t of clinker produced. The amount of cement produced from clinker can vary with the *clinker-to-cement ratio*, depending on additives and on the type of cement required.

The second source of CO<sub>2</sub> emissions comes from the combustion of fuels to provide heat to drive the process (i.e. *energy emissions*). Temperatures reach up to 1200°C. Usually, lignite, fuel oil and solid waste (plastics, rubber) are used. For the grinding and mixing steps, electricity is mainly used.

Cement is then mixed with water and other inert materials (e.g. gravel) to produce concrete (hydration process). This step absorbs CO<sub>2</sub> over a prolonged period of time (days to years), up to the entirety of the emissions released as part of the clinker production process, i.e. as much as two thirds of the total cement production emissions (carbonation). For reinforced concrete, this has the side-effect of increasing corrosion of steel and thus the material loses its carrying strength [155]. Although the amount of CO<sub>2</sub> absorbed is significant, it is not accounted in emissions balances commonly used in statistics [156], [157].

The type of production process used depends on how recent the cement plant is, as well as the type of raw material that is used. Production processes can be grouped into three groups:

- The *vertical shaft kiln* process has a cheaper investment cost, but it is less efficient and is more environmentally damaging. It has progressively become obsolete in the second half of the 20<sup>th</sup> century, replaced by more recent and centralized technologies.
- The mixed *semi-wet/semi-dry* processes with short rotating kilns are marginally more efficient. The raw materials are mixed with water to obtain a homogeneous slurry, which then has to be dried before introduction in the kiln. They were dominant during the second half of the 20<sup>th</sup> century. It is used where it is relevant for the raw material, when the limestone is rich in clay or chalk.
- The *dry process with a long rotary kiln* is the most energy-efficient process, this became the norm late in the 20<sup>th</sup> century. Certain additional energy efficiency measures have become widespread: the addition of a pre-heater step (waste heat recuperation) and a pre-calcination step (partial calcination of the meal) before feeding into the main kiln. Such plants are presently the most common, also known as new suspension with preheater (NSP).

The lower temperature needed in the pre-calciner (up to 900 °C) makes it accessible for substitution by electricity (indirect heating). The higher temperature needed in the kiln (up to 1400 °C) makes it more adapted to the combustion of thermal fuels.

The main data source for production by process was *Getting the Numbers Right (GNR)*, a website by the Global Cement and Concrete Association of the World Business Council on Sustainable Development [158]. It only covers member companies, i.e. only the partial production of certain countries<sup>22</sup>. China is not covered by GNR. An additional literature review yielded data per production process for China, from [159]–[161]. Clinker production by process for the GNR geographical coverage is given in Figure 32.

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<sup>22</sup> World coverage of cement production is 22% as of 2019. Regional coverage: Africa 31%; Asia & Oceania 17%; CIS 21%; Europe 90%; Latin America 74%; North America 86%; Middle East 14%

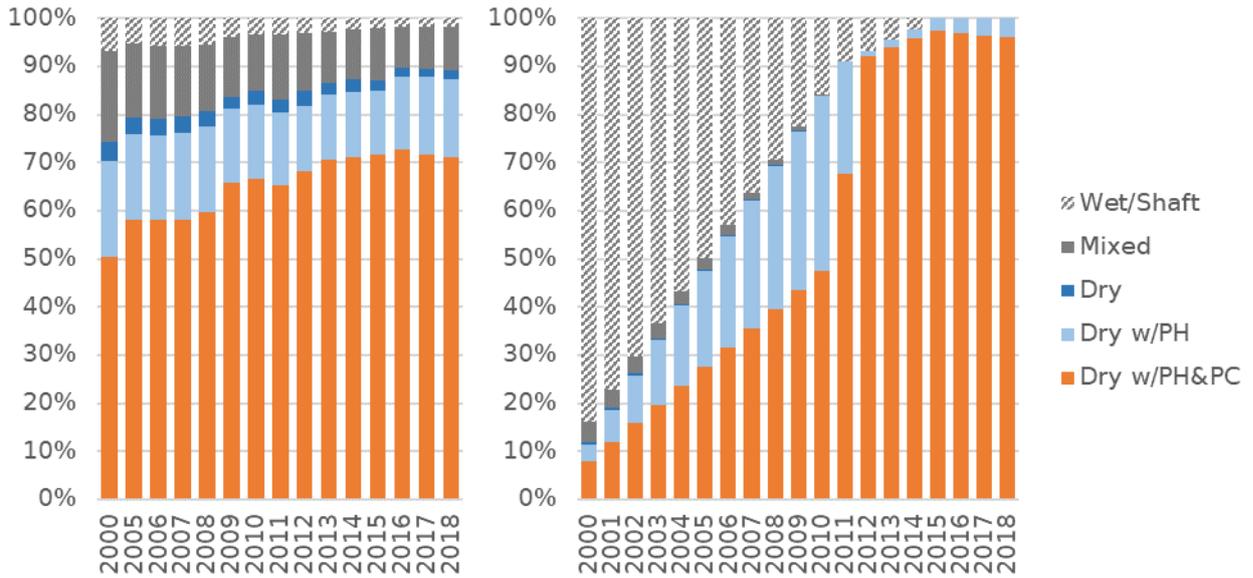


Figure 32: Distribution of clinker production by process (GNR members, left; China, right)

Sources: [158]–[161].

There is a notable evolution towards rotary kiln processes, with pre-heater and pre-calcination.

In China, the deployment of modern kilns with pre-heater and pre-calciner happened very quickly over the years 2006-2015, together with the retirement of older, small and inefficient production capacity. According to the literature, very few dry capacities that are not equipped with both remain.

Due to the energy-intensive nature of cement production, the CO<sub>2</sub> emissions inherent in the production process and the large production volumes required, cement is responsible for about a quarter of CO<sub>2</sub> emissions of industry with about 2.9 GtCO<sub>2</sub> released in the atmosphere annually [162].

As one of the main point-source sources of CO<sub>2</sub> emissions, cement is a priority sub-sector of industry for decarbonisation. Similar to steelmaking, the existing production processes are mature and offer little energy efficiency or emissions reduction potential in their current form. Innovation and industry-scale adoption of new solutions is urgently needed in order to reduce emissions in a significant manner. In the next section, we will study multiple ways forward for the cement industry to reduce its emissions. We will present a model detailing cement demand and multiple cement production pathways, and will examine decarbonisation options under different assumptions on climate policy, technologies and steel demand patterns.

## 7.2. Opportunities and roadblocks in the decarbonisation of the global cement sector: a demand and production modelling approach

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*I was the main author of all aspects of this manuscript.*

# Opportunities and roadblocks in the decarbonisation of the global cement sector: a demand and production modelling approach

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## ABSTRACT

The cement sector represents a growing share of global carbon dioxide (CO<sub>2</sub>) emissions and is perceived as a hard-to-abate sector in the drive towards economy-wide decarbonisation. We present a model detailing cement demand and multiple cement production pathways within a larger global multi-regional energy system simulation model, projecting material, energy and emissions flows to 2100. We examine decarbonisation levels and options under different assumptions on climate policy, technologies and cement demand patterns. Global cement demand, driven by substantial increases in the underlying socio-economic conditions, increases at a decelerated pace compared to the past two decades and stabilizes in 2080. China's decreasing demand and production overcapacity results in increased cement trade in the medium term. Material efficiency measures could significantly limit this demand increase. Strong climate policies would be needed to decrease the cement sector's emissions, with carbon capture being key to decarbonize fully as early as the 2050s, and with electrification, fossil gas and biomass all contributing. Taking into account the carbonation sink would alleviate pressure to mitigate emissions.

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## KEYWORDS

Cement; climate mitigation; industry decarbonisation; energy system model; integrated assessment model

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## 1. INTRODUCTION

With nearly all states having signed the United Nations international climate treaty of the Paris Agreement since 2016, collective efforts are needed

to “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels”[1]. According to literature synthesized by the Intergovernmental Panel for Climate Change's (IPCC) Special Report on 1.5°C[2], there is high agreement among the scientific community that global anthropogenic emissions of carbon dioxide (CO<sub>2</sub>) need to be reduced to net-zero by around mid-century in order to be consistent with the more ambitious Paris Agreement target. Accordingly, significant efforts to reduce emissions have to be pursued by all world countries and across all sectors of the economy depending on cost-efficiency and other considerations. Thus, a net-zero global target does not necessarily coincide with a similar target for all sectors. In particular, heavy industry has been identified as a challenging sector to decarbonize, along with aviation, shipping and agriculture[3]; this is due to a combination of sector-specific factors: high projected activity growth, comparatively costlier emissions abatement options and slow capital turnover.

The cement industry is responsible for a sizeable share of the world's CO<sub>2</sub> emissions: around 8% of energy and industry emissions in 2014[4], with 2.90 GtCO<sub>2</sub>. The emissions are split roughly equally between energy combustion and carbonate oxidation in clinker production as an inherent part of the process. Process emissions grew at a considerable pace since the turn of the century, at 4.2%/year over 2000-2018[5], with an increase in the demand for cement from 1.66 Gt to 4.11 Gt over the same period, mainly coming from China. Without additional effort, the demand for cement and the sector's emissions are projected to increase, in particular due to economic growth and increasing living standards in developing economies[6], [7].

Historically, higher income levels and well-being have been correlated with an increase in the demand of material goods, and of cement in particular: over 2000-2021, cement demand grew by 4.7%/year while global GDP grew at 3.3%/year. The challenge then becomes to reconcile continued increase in well-being for all (and associated cement demand increase) with the aspirations to decarbonize the world economy. International institutions and the private sector have realized this challenge, with several studies aimed at decarbonising cement (International Energy Agency/World Business Council for Sustainable Development[8], European Cement Association[9]).

Quantitative techno-economic tools are particularly suited for creating multi-sectoral decarbonisation pathways. Modelling is an important tool in making informed estimates of the future needs of the energy sector[10], and has been used by researchers, public planners and private investors alike. Energy system models and integrated assessment models (IAMs) are prominently used to inform the IPCC's working group on mitigation options. Several of these models represent the cement sector independently of the rest of industry; however, its representation is done in a stylized manner. Several models do not represent the cement sub-sector separately from other industrial sub-sectors[11]; few models represent cement demand by end-use (as opposed to a using a single type of demand[12]), few represent physical production of cement (as opposed to using a single economic activity indicator as a driver[13]) and few represent specific production processes (as opposed to a single value of energy efficiency for the entire sector); see a comparison of several IAMs[14]. Moreover, industrial ecology and material flow models have worked on representing cement stocks and annual cement demand by end-use; this was often done without a representation of the cement production side[15], [16]; or, with a simplified representation of production with economic trade-offs not taken into consideration[17].

The main goal of this study is to chart a way forward for the cement industry in a context of energy transition as required by the regional and global effort of decarbonisation to limit climate change. We propose to tackle these issues of cement demand and production in an integrated way within an energy system model. The resulting projections of cement flows, energy needs and greenhouse gas emissions are self-consistent.

We first provide information on the methodology to project cement demand and production; we then describe the scenarios that we assessed (section 2); we present and discuss results for cement demand and trade, for the cement production mix, energy, emissions and investments, and for overall mitigation options (section 3); finally, we conclude on main findings and open issues (section 4).

## **2. METHODS: MODELLING WORLD CEMENT DEMAND AND SUPPLY**

### **2.1. The energy system model POLES**

Prospective Outlook for Long-term Energy Systems (POLES) is a global multi-regional energy system model that has been used extensively in global and regional climate policy studies[18]–[20]. POLES is a 66-region multi-sectoral partial equilibrium simulation model with an annual time step, with endogenously calculated energy prices and lagged adjustments of energy demand. Demand for energy services is derived from existing equipment and macroeconomic indicators; following equipment depreciation, choice across fuels or technologies is made with a logit distribution function using total costs and preference factors. All greenhouse gas emissions are represented.

The previously existing non-metallic minerals module consisted in a single production function based on GDP-derived value added, with price-dependent energy efficiencies; no explicit material demand, production pathways or processes were modelled.

### **2.2. Cement module overview**

We modified the POLES model by integrating different aspects for decarbonizing cement demand and production, singling it out from the non-metallic minerals industry subsector. This is a significant evolution of a previous POLES cement module[21], which had not been used since 2006.

The overall scheme of the materials demand and production module enriched and developed in this work is given in Figure 1.



### Power sector

Cement demand for power generation and for the power grid were distinguished. This work estimates that the power sector absorbed just 1% of total global cement demand in 2019.

New annual installations per technology are produced by the power sector module of the POLES model endogenously, on the basis of equipment lifetime, total costs and bottom-up electricity demand projections. Power generation capacities lifetimes differ depending on the technology; they range from 20 (wind) to 50 (hydro) years. Specific material consumption per power generation technology (kg/kW) was obtained from[29]–[32].

New needs for the grid arise from the projections of power generation and a grid equipment lifetime (considered to be 40 years). Specific cement consumption for the power transport and distribution grid (kg/GWh) was derived from [33].

### Infrastructure and other

The remaining demand pertains to the construction of public works and other infrastructure (special use buildings, rail network, oil and gas and mining extractive industries, manufacturing industries). This work estimates that in 2019, it corresponded to 43% of global cement demand. Given the diffuse nature of this demand category and the lack of specific drivers to associate it with in the energy system model for a bottom-up estimation, this remaining demand was projected as a constant percentage of total demand. In projections, the aggregate changes in the three bottom-up end-uses above drive the evolution of the residual demand.

## 2.4. Cement production

### Current status review

Currently, world cement production is dominated by the rotary long dry kiln. This process can be supplemented by a pre-heater of the meal (*Dry-pre-h*) and, additionally, by a pre-calciner step before the main kiln (*Dry+pre-c*); together, these processes made up 85% of global cement production in 2019, up from 37% in 2000. Other processes have been deprecated, such as the shaft kiln (28% in 2000, <1% in 2019), or are specific to local conditions of cement quality desired and of available raw materials despite higher energy needs, such as the semi-wet and semi-dry kilns (*Mixed*, 35% in 2000, 15% in 2019), despite higher emissions of air pollutants[34]. Market shares have shifted significantly since 2000, with the fast construction of capacities in China and their conversion to the most modern and energy-efficient process (*Dry+pre-c*).

Emerging and innovative technologies at various stages of research and development include:

- A fully electric kiln (*Elec-k*): in which resistive electricity heating is applied to the walls of the rotary long dry kiln is being studied. A pilot scale prototype was built in 2022 in the Decarbonate project[35].
- Alternative binding materials: using different chemistries than the currently dominant Portland cement to obtain similar physical properties but emitting less CO<sub>2</sub>. Several laboratory-scale prototypes and start-up companies have studied these[8]; however, among the many solutions proposed not one appears to be emerging as a more promising one or one that is attracting more investments.
- CO<sub>2</sub>-cured precast blocks: cement that, under controlled physico-chemical conditions, absorbs CO<sub>2</sub> when hardening into concrete. CO<sub>2</sub> absorption up to obtaining net-negative concrete has been obtained in laboratory studies[36]–[38]. However, this solution is adapted where precast blocks of concrete can be accommodated instead of pouring concrete at the point of use (ready-mix concrete); with current uses of precast concrete, this maximum potential would correspond to around 30% of total cement demand[39].
- Substitution of clinker with supplementary cementing materials: using by-products of other industries with similar properties as clinker to reduce the reliance on new clinker[40]. Most of these materials used today would have limited availability in the future with economy-wide decarbonisation efforts (fly ash and reduction of coal use in power generation, slag and reduction of blast furnace in steelmaking)[41].

### Modelling setup

Production processes considered for the modelling were limited to those with a technology readiness level (TRL) today that have a reasonable chance to represent a sizable share of production capacities in the time horizon of the study. The *Mixed*, *Dry+pre-h*, *Dry+pre-c* and *Elec-k* process were considered in this study.

Process efficiency and investment costs for new installations are set exogenously[34], [42], [43], assumptions presented in supplementary information. Historical statistics on the energy consumption of the non-metallic minerals sector[44] and clinker production capacities[45]–[49] set the process efficiency and fuel mix for existing equipment. The clinker-to-cement ratio is set exogenously by region.

Investment in new production capacities is calculated based on the growth of production in past years. The choice among processes is made using a logit distribution with total costs and preference factors. Total costs consist of:

- Overnight investment costs annualized with over the lifetime of the equipment (35 years) with a discount rate (8%);
- raw material costs (calcareous material), kept constant;
- energy input costs, which can include a CO<sub>2</sub> price;
- CO<sub>2</sub> price on process-related emissions;
- CO<sub>2</sub> sequestration cost, for the downstream manipulation of CO<sub>2</sub>;
- Carbon credit from biomass-CCS, determined by the carbon content of biomass and can cover, at most, the energy input costs and CO<sub>2</sub> price.

CCS technologies include a fixed post-combustion CO<sub>2</sub> capture rate[50] for an extra investment cost and an electricity demand penalty[51]. Due to the higher CO<sub>2</sub> concentration in its flue gas, the electric kiln has a discount costs[52]. See SI for details..

The preference factors represent what influences process choice that is unrelated to pure economics; they reflect country specificities observed on the historical mix, such as inertia in choosing existing technologies (this effect is phased out by 2035), or technological availability for new technologies (CCS availability and electric kiln maturity grows over time).

In addition, there is the possibility to retrofit certain processes into others, in particular for retrofitting CCS; the choice is made by comparing the extra costs of retrofit with the production costs without.

The choice among fuels within each process is made using a logit distribution with user costs, including efficiency and carbon pricing.

Regional allocation of global production is done on the basis of the region’s average production cost and a transport cost (cost of exporting towards net importers, weighted average over importers’ market share in global trade) under the constraint of available capacities per region.

Finally, the carbonation sink (the reverse process of calcination taking place during the lifetime of concrete products) is estimated using a carbonation profile over time for each vintage of concrete[53] fitted to estimates of the past sink[49] (see SI for detail).

## 2.5. Scenarios

In order to take into consideration several uncertainties in how the energy system as a whole, as well as cement demand and cement production technologies more specifically, might develop, we considered multiple scenarios that were quantified with the POLES model.

The scenarios are driven by macroeconomic projections (GDP, population) that are defined exogenously as model inputs and are common across scenarios; energy prices, technological development and emissions are calculated endogenously under scenario-specific constraints and parametrization. Scenario rely on historical statistics for energy demand and cement production, which extend to the year 2020.

We assessed the following contrasted scenarios:

A Reference (*Ref*) scenario: existing policies related to energy supply and demand policies and targets, as well as legislated emissions policies and targets that are backed by supporting energy-sector policies, are enacted. No additional policies are considered compared to what had been legislated as of June 2022 (see Annexes of [54] for the list of policies considered). Cumulated net CO<sub>2</sub> emissions over 2020-2100 amount to 3070 Gt, resulting in a global mean temperature increase at the end of the century of 3.0°C (median probability), as calculated by the online MAGICC tool[55].

A 2°C scenario (*2C\_CCS*) scenario: represents a case where global climate mitigation effort accelerates compared to the current situation, but not to the extent to reach the 1.5°C goal of the Paris Agreement.

Several scenarios compatible with the Paris Agreement goal of climate change contained to 1.52°C: they differ in several dimensions related to technological availability and maturity, and in the socio-economic implementation of the climate policies necessary to reach the temperature objective. They consist in:

- (i) *15C\_CCS* with an earlier availability of carbon capture across the entire economy, to study a cement sector that might continue its reliance on technologies that involve combustion (similar in setup to *2C\_CCS* but differing on climate policy intensity);
- (ii) *15C\_Elec* with more ambitious technological learning for new direct and indirect electrification technologies, to study a cement sector that might move more towards a new paradigm;
- (iii) *15C\_LD* with lower energy service demand and lower material demand, resulting in fewer emissions to decarbonize on the cement production side, to study a cement sector where sobriety and efficiency are more important.

The specific levers that were used to parameterize these scenarios are presented in Table 1 and are detailed below.

**Table 1: Parameter matrix for the scenarios in this study**

	<i>Climate policy</i>		<i>CCS availability</i>	<i>Bioenergy availability</i>	<i>New electricity costs</i>	<i>Energy demand adaptation</i>	<i>Cement demand adaptation</i>
<i>Ref</i>	Current adopted policies		Default	Conservative	Pessimistic	Default	Default
<i>15C_CCS</i>	Global price	carbon	Default	Optimistic	Pessimistic	Default	Default
<i>15C_Elec</i>	Global price	carbon	Delayed	Conservative	Optimistic	Default	Default
<i>15C_LD</i>	Global price	carbon	Default	Conservative	Pessimistic	Energy conservation measures	Material efficiency measures
<i>15C_Opt</i>	Global price	carbon	Default	Optimistic	Optimistic	Energy conservation measures	Material efficiency measures

*Climate policy:* For each 2°C and 1.5°C scenario, a carbon price is applied to all regions and all sectors of the economy. The carbon price follows a sigmoid curve starting from 2022, with an inflection in 2040 and a saturation level in 2100. The price is adapted for the 2°C scenario so as to have an end-of-century CO<sub>2</sub> budget of 1150 GtCO<sub>2</sub>, and for each 1.5°C scenario for a peak-temperature budget (i.e., at the year of global net-zero CO<sub>2</sub> emissions) of 650 GtCO<sub>2</sub> from 2020. These budgets, counting from 2020, are compatible with a 2°C and 1.5°C global mean temperature increase, respectively, compared to pre-industrial levels at the end of the century. 2100 prices are 0, 209, 880, 1130 and 795 \$/tCO<sub>2</sub> for the scenarios listed above. The carbonation sink is not taken into account in the budget.

*CCS availability:* availability for installing CCS options and CCS infrastructure is determined by a multiplying factor to the technology’s cost, uniformly across all regions, with a duration of 50 years from zero (first-of-a-kind) to one (pure cost-competition); first-of-a-kind from 2020 (default) or from 2050 (delayed).

*Bioenergy availability:* ligno-cellulosic biomass availability is determined by supply costs; higher costs result in total global bioenergy demand not exceeding 170 EJ/year (conservative) and lower costs result in 200 EJ/year (optimistic). As a

convention, solid biomass energy use is considered carbon-neutral (compensated by carbon absorbed in the growth of new biomass in a sustainably managed cycle); and biomass with carbon capture and sequestration (BECCS) is considered as carbon net-negative.

*New electricity costs:* investment costs for electric kiln for cement differ, with optimistic costs a third lower than pessimistic costs.

*Energy conservation measures:* building surfaces and vehicle stocks are related to demography, economic growth and occupancy rates. Residential surfaces are capped to a maximum value of 50 m<sup>2</sup>/cap (default: no cap; the region with the highest level, the USA, reaches 108 m<sup>2</sup>/cap in 2100).

*Material efficiency measures:* specific material demand per floor surface area for buildings decreases over time (to 60% of its initial value by 2050), uniformly across all regions, with 2050 values following the ambitious scenario in [56]. Instead of remaining constant (default), the clinker-to-cement ratio decreases uniformly across all regions by 5 percentage points from 2020 to 2030.

Scenarios were executed to 2100; results are presented for the world and key regional aggregates; more granular results are provided in supplementary information.

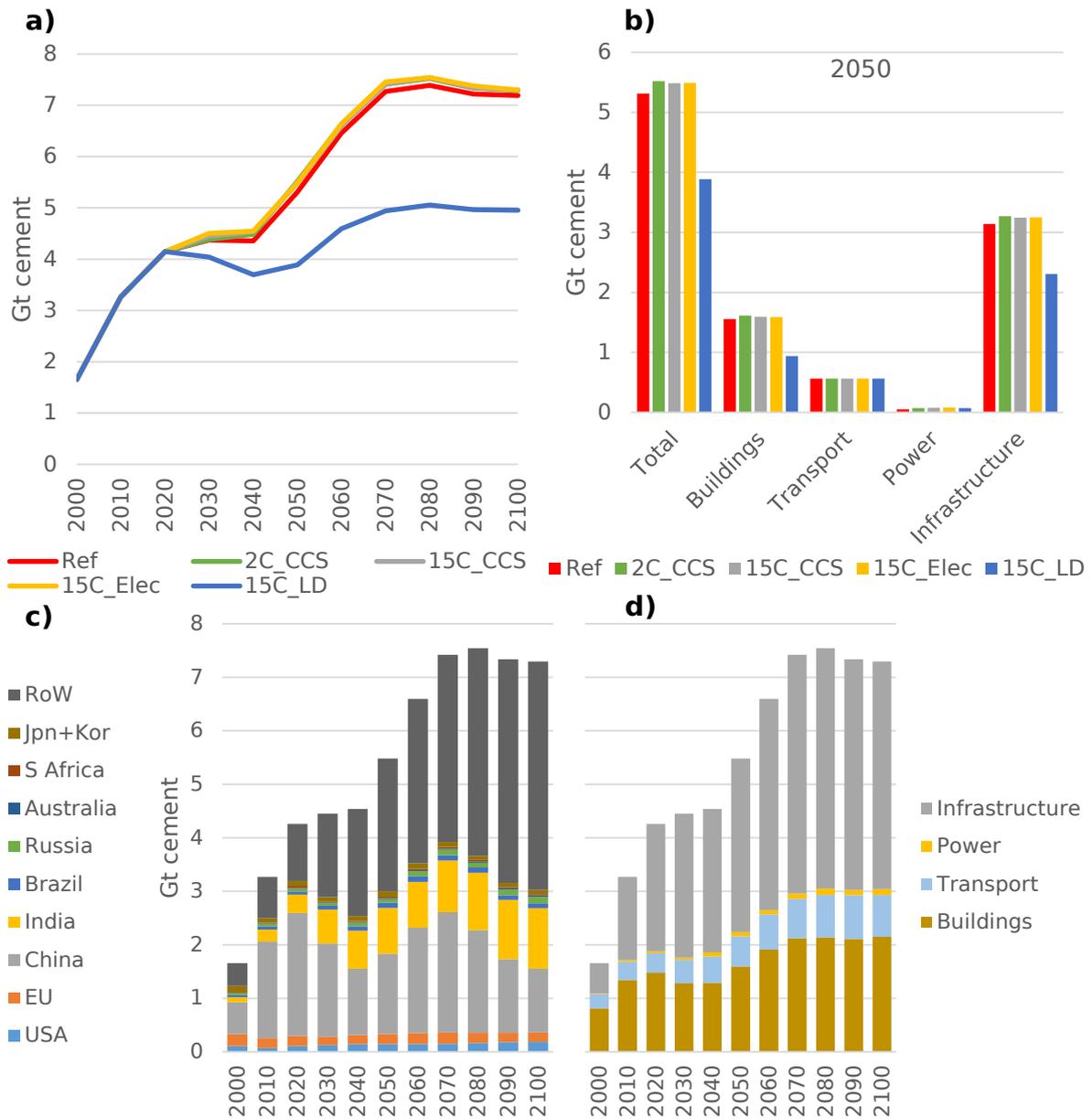


Figure 2: Global cement demand (a) across scenarios; (b) by end-use sector in 2050, all scenarios (c) by region, 15C\_CCS scenario; (d) by end-use sector, 15C\_CCS scenario

Source: POLES model. “Jpn+Kor”: Japan and South Korea. “RoW”: Rest of the world.

### 3. RESULTS AND DISCUSSION

#### 3.1. Growth of world cement demand to decelerate

Global cement demand is projected to continue to increase in the coming decades, but at a decreasing rate of growth with a stabilization in the second half of the century (Figure 2). Demand is projected to reach 5.48 Gt in 2050 (32% above the 2020 level), peak in 2080 and reach 7.30 Gt in 2100 (15C\_CCS). Annual demand growth decreases from 4.7%/year over 2000-2020 to 0.9%/year over 2020-2050 and 0.6%/year over 2050-2100. This is driven by a strong

demand increase in India and the Rest of the world, while demand in China decreases from its historical peak in 2014.

Total cement demand evolution is due to an increase of demand over most uses. In terms of volume, most of the increase to 2050 comes from road transport infrastructure, followed by buildings and power; other infrastructure as a global total also increases. A second wave of buildings construction in China in the 2070-2090 period, to replace the stock that was built roughly 70 years prior with the first wave over 2000-2020, results in cement demand for buildings increasing again, while demand for the other uses increase more moderately throughout the end of the century.

These increases are driven by the underlying socio-economic conditions. Demand for buildings (+8% over 2019-2050) is driven by an increase in global floor surface area (+65%). Demand for transport (+56% over 2019-2050) is driven by an increase in global passenger (+130%) and goods (+52%) traffic volumes, with corresponding increases in length of paved road network (+85%). Demand for power (+96% over 2019-2050) is driven by an increase in global power production (+179%) (15C\_CCS).

The implementation of climate policies leads to a positive feedback effect on cement demand. This amounts to 2-3% higher cement demand in 2050 and an additional 2-3% of accumulated demand over 2020-2050 (15C\_CCS and 15C\_Elec compared to Ref; 2% for 2C\_CCS). This is brought about by an increase in demand for buildings and for power. This feedback would result in an increase in emissions in order to produce this extra cement; however, in all cases, this increase is smaller than the emissions savings brought about by the new low-carbon equipment and infrastructure built with this extra cement.

In buildings, climate policies accelerate the renovation rate in order to achieve higher buildings shell insulation levels, resulting in more cement needs. Over the 2020-2050 period, cumulated renovated surfaces are 29-33% higher (15C\_CCS and 15C\_Elec vs Ref), and cumulated cement demand is 2-3% higher compared to Ref. The production-side increase in emissions induced by this higher cement demand (about 0.5-0.6 GtCO<sub>2</sub>, cumulated) are more than compensated by the emissions savings brought about by more energy-efficient buildings and the accompanying switch to low-carbon fuels in buildings energy use (which were at 3.0 GtCO<sub>2</sub>/year in 2020).

In power, climate policies push towards higher electrification and a shift towards lower-carbon power sources. As the power sector is progressively decarbonised, electricity becomes a lower-carbon energy vector and power demand becomes higher. While low-carbon technologies require less cement than fossil fuel technologies per unit of installed capacity on average, some of them, such as wind and solar, have a low load factor and more units would need to be built to replace the equivalent fossil fuel unit with the same nameplate capacity. Over the 2020-2050 period, the average cement intensity of newly installed capacities is 21% lower in 15C\_CCS compared to Ref (36 kg/kW vs 46 kg/kW) while cumulated installed capacities are 64% higher, resulting in a cumulated cement demand that is 52% higher (60% for 15C\_Elec). Again, this feedback would result in additional emissions in cement production compared to Ref (approximately some cumulated additional 0.2-0.4 GtCO<sub>2</sub>); however, these

would be much smaller than the emissions saving brought about by the decarbonisation of the power sector (from about 12 GtCO<sub>2</sub>/year in 2020 to net-zero in 2050).

In other infrastructure and other uses, resulting from the combined behaviour of the above end-uses, cement demand is also higher than in the Ref (3% cumulated).

With energy and material savings and efficiency measures (implemented in 15\_LD), the climate policies feedback on cement demand could be contained and even overcompensated, resulting in total cement demand that is lower than in Ref (-27% in 2050). The effect is larger in buildings, where measures were implemented (-39%), while demand in power is little different to the other 1.5°C scenarios (+44%). Total cement demand also peaks in 2080 but at a much lower level (5.06 Gt in 15C\_LD compared to 7.39 Gt in 15C\_CCS), a level that is exceeded in the 2040s in the other scenarios. Thus, these savings and efficiency measures would provide a longer time for the cement production industry to respond to an increasing demand while simultaneously meeting the decarbonisation challenge. Indeed, it could be realistically expected that the higher costs of producing low-carbon cement would be passed down to the end-users, which would result in a demand level responding accordingly; while a cement price elasticity on demand was not included in this modelling, its effects are here approximated by the adoption of such savings and efficiency measures.

### 3.2. Cement production mix to diversify

#### *Production mix*

The production mix in the projections gradually evolves from the current situation, with larger changes observed after 2030. Figure 3 presents the world production mix, including the substitution process that takes place over part of the stock once older equipment is retired and the effects of retrofitting CCS onto existing capacities.

Without strong climate policies (Ref), there is a strong increase of electrification (Elec-k) and a more balanced role for the other processes. This is due to the relative small differences in the production cost between the mixed process, the dry process with pre-heater (Dry+pre-h) and the dry process with pre-heater and pre-calciner (Dry+pre-c). The electric kiln process covers 3% of global production by 2050. Given the absence of strong climate policies globally, CCS is not implemented and overall emissions increase, as shown in Figure 4.

The climate policy effort distorts the competitiveness of different options. With strong climate policies (15C\_CCS), the mix is little different, the electric kiln reaches 9% share in 2050 and the main difference comes from the implementation of CCS across all processes. CCS becomes competitive from

around 80 \$/tCO<sub>2</sub>. By 2050, CCS is associated with 74% of total capacities (65% in 2C\_CCS), and between 71% and 78% with each process. The higher rate is CCS associated with the electric kiln, which has lower CCS implementation costs due to the high CO<sub>2</sub> concentration in its flue gas.

With more optimistic assumptions on electricity (15C\_Elec), the electric kiln reaches as much as 43% share in 2070 while the relative lack of CCS results in higher emissions. The assumptions on CCS availability result in a CCS penetration pathway similar to 15C\_CCS but delayed by 30 years, with both scenarios presenting similar levels of CCS by 2090. Although CO<sub>2</sub> capture costs are lower for the electric kiln, this is counterbalanced by higher gross emissions in fossil fuel and biomass kilns, and thus a higher potential for receiving carbon credits; this results in the electric kiln reducing its market share in the long term even in the 15C\_Elec scenario.

In the second half of the century, with the availability of CCS in the 15C\_Elec scenario, the *Dry+pre-c* process progressively switches from mostly electricity (used in the precalciner) to biomass; however, the *Mixed* processes had already adopted biomass to reduce emissions and find themselves in a competitive advantage compared to *Dry+pre-c*. This results in a higher market share of *Mixed* in 15C\_Elec.

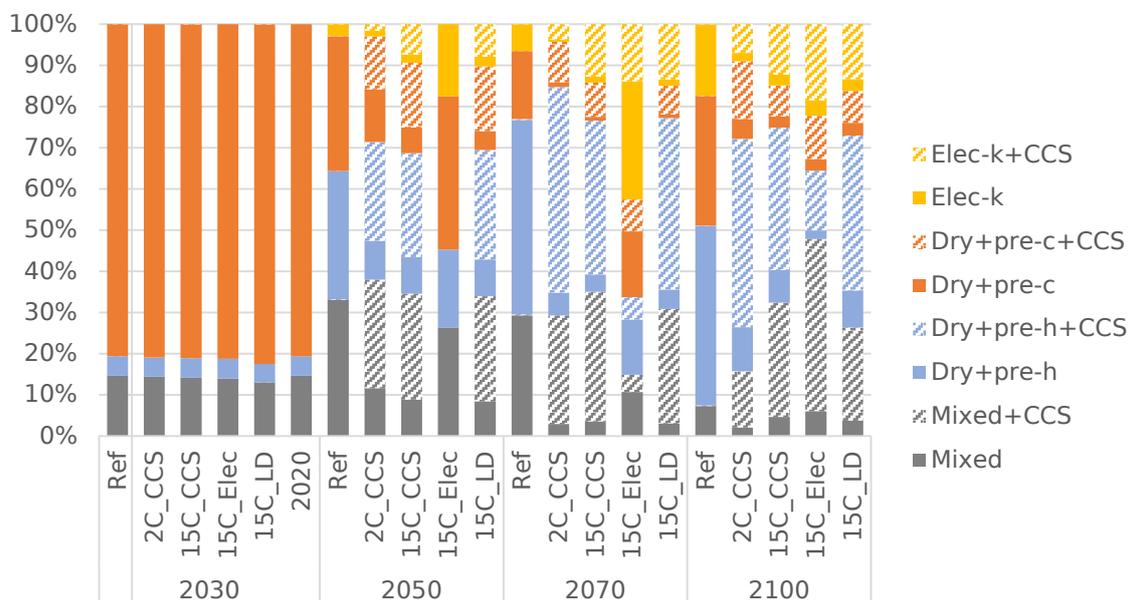


Figure 3: Global cement production mix

Source: POLES model.

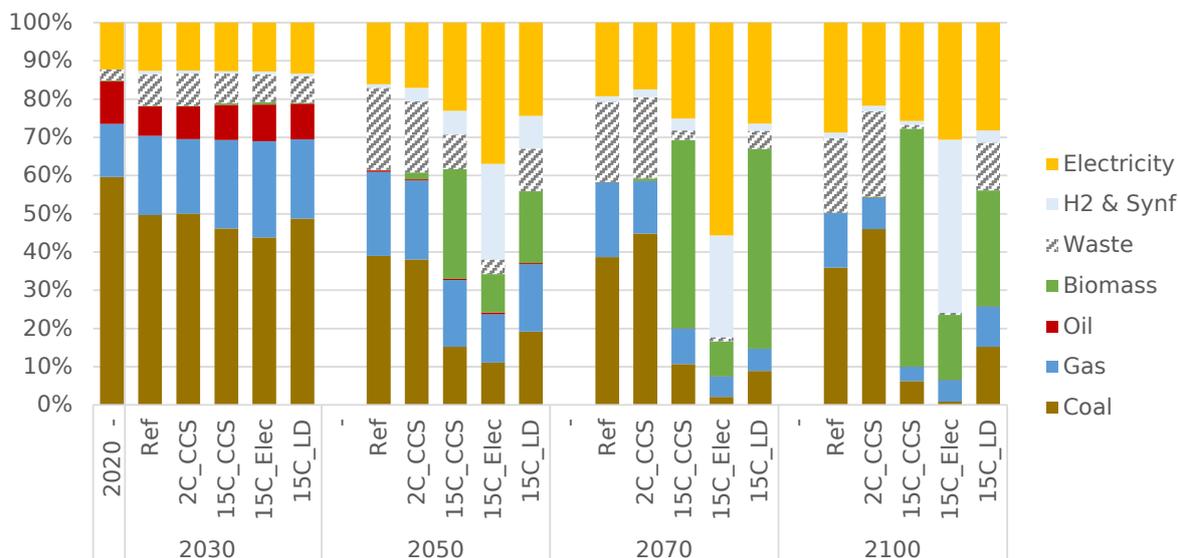


Figure 4: Global cement energy mix

Source: POLES model. Note: "H2 & Synf": hydrogen and hydrogen-derived synthetic methane.

### Energy mix

The energy mix evolves significantly (Figure 4). In the medium term (2030), changes come from increased use of waste and fossil gas at the expense of coal. In the longer term, the sector shifts from the current domination of coal to a more balanced energy mix.

Solid waste demand triples from 2020 to 2030 in all scenarios, up to 0.7-1.0 EJ/year in 2030. In the longer term, the fact that it is a source of CO<sub>2</sub> emissions hampers its adoption and it continues growing only in the Ref scenario.

Considering solid biomass as a carbon-neutral energy vector, the use of biomass coupled with CCS results in carbon credits that decrease operating expenditure (OPEX, up to covering all of the expenditure for energy inputs) and decreases net emissions further. As a lower-carbon substitute to coal, biomass reaches 29% market share in 2050 and 62% in 2100 in 15C\_CCS. The attractiveness of biomass is related to it replacing coal but especially to the carbon credit received by BECCS: 15C\_Elec consumes less than half the biomass that is consumed in 15C\_CCS in 2050.

The lower carbon content of fossil gas allows it to gain market share in the medium term. In the longer term, the adoption of CCS and the extended use of solid fuels comes at the expense of fossil gas and its demand starts shrinking. Demand for clean gases (hydrogen and derived fuels) becomes significant only in the 15C\_Elec scenario as a result of the delayed availability of CCS and the cheaper electrolyser costs to produce these fuels.

The OPEX of the electric kiln is driven upwards partly due to the impacts of the decarbonisation effort on the electricity price, however this decarbonisation increases its competitiveness compared to processes with unabated fossil fuels. By the end of the century, it provides over a quarter of demand across the 1.5°C scenarios.

Another important use of electricity is in the precalciner of the *Dry+pre-c* process, where it reaches as much as 41% of the thermal energy needs of that process (15C\_Elec, 2060; only 9% in 15C\_CCS at the same date).

CCS is among the cheaper mitigation options: indeed, the Ref and 2C\_CCS scenarios present a similar energy mix but with CCS use for 2C\_CCS. While both 2C\_CCS and 15C\_CCS scenarios make extensive use of CCS, reaching the 2°C target implies a continued use of coal and gas (as well as waste); whereas reaching the 1.5°C target implies a complete fossil fuels phase-out. Instead of coal and waste, the 15C\_CCS scenario strongly relies on biomass and electricity.

### Emissions and mitigation options

The resulting CO<sub>2</sub> emissions of the cement sector (without the carbonation sink) are presented in Figure 4. Cement sector emissions in 2020 are estimated at 2.5 GtCO<sub>2</sub>, two thirds of which were process emissions. Without strong climate policies (Ref), emissions continue to increase throughout 2070, following a similar pattern to cement production. The CO<sub>2</sub> content of cement remains at 0.6 tCO<sub>2</sub>/t throughout the projection period.

With strong climate policies, the cement sector emissions decrease dramatically; the CO<sub>2</sub> content of

cement reaches an average 0.2 tCO<sub>2</sub>/t in 2050 for the 1.5°C scenarios, under an average carbon price in 2050 of 810 \$/tCO<sub>2</sub>. Net-zero emissions are reached in the second half of the century only thanks to the contribution of CCS technologies and biomass (during the 2050s for 15C\_CCS and 15C\_LD, end of the century for 15C\_Elec).

The 2C\_CCS scenario reduces its emissions quicker than the 15C\_Elec despite the stronger push to decarbonise the entire economy in the latter

scenario, thus showing the essential role CCS plays in deep mitigation for the cement sector. 2°C climate policies usher significant mitigation (a reduction by more than half in 2050 compared to 2020) but net-zero emissions are only reached with the stronger 1.5°C climate policies.

The lower energy intensity in the 15C\_LD is the direct result of using 5% less clinker per ton of cement produced by 2030.

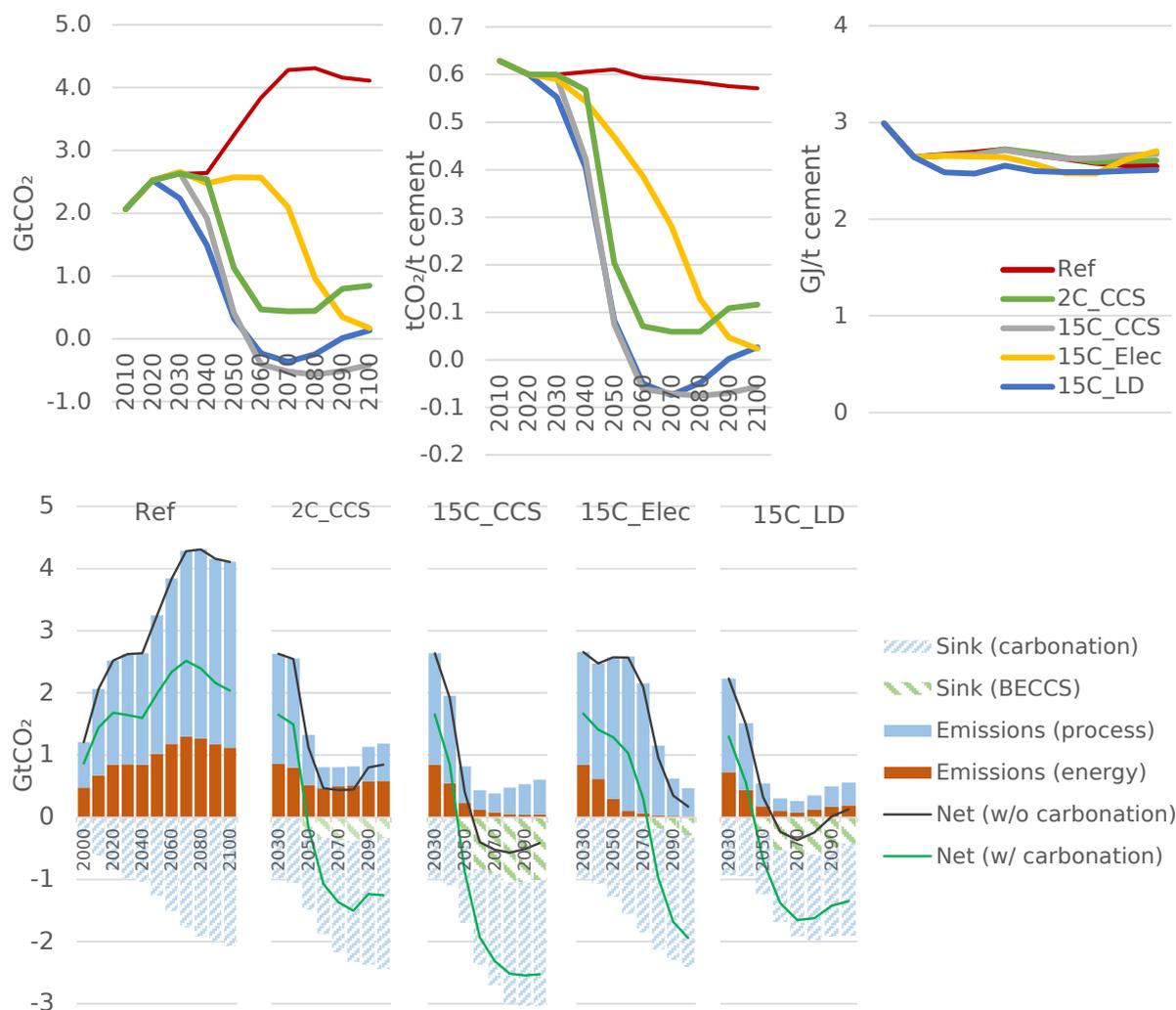
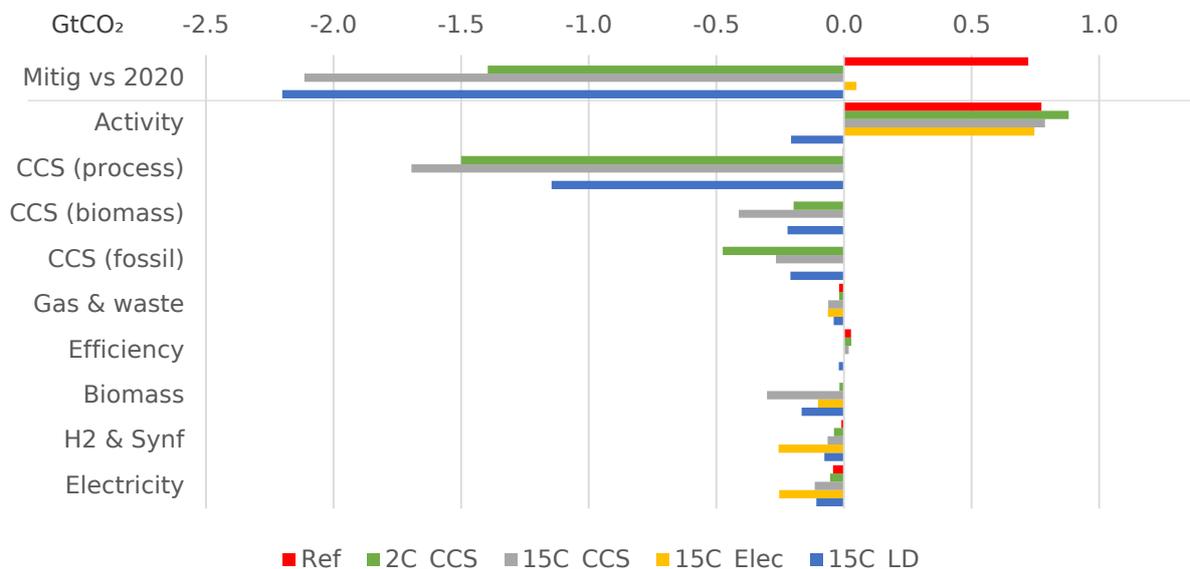


Figure 5: Global cement sector emissions (without carbonation sink, top left), emissions intensity per ton of output (top middle), energy intensity per ton of output (top right) and emissions sources and sinks decomposition

Source: POLES model. Biomass use is considered carbon-neutral. Waste is considered to have the same carbon content as coal.



**Figure 6: Emissions reductions in 2050 compared to 2020 and distribution of decarbonisation options from 2020 to 2050**

Source: POLES model. “Mitig vs 2020” refers to total emissions reductions in 2050 compared to 2020, decomposed in options below. “H2 & Synf”: hydrogen and hydrogen-derived synthetic methane. Carbonation sink not included.

The emissions increase towards the end of the century in all climate scenarios is related to the CCS storage saturation of sub-Saharan Africa, which has increasing demand in cement throughout 2100 but a relatively low geological CO<sub>2</sub> storage potential per capita.

The carbonation sink is projected to increase significantly due to recent and projected cement demand. Taking into account this sink, cement overall could become net-negative as early as in the 2040s (15C\_CCS, 15C\_LD), a full decade earlier, and would be a considerable mitigation option if it were accounted as such.

Overall, following the logarithmic mean Divisia index (LMDI) method[57], the main decarbonisation options expressed as a decomposition of emission differences between 2020 and 2050, averaged over the three 1.5°C scenarios, are (Figure 5): CCS (93%, most of which in process emissions, 67%); biomass (13%); electricity (12%); hydrogen and hydrogen-derived methane (9%); switch from coal to gas and waste (4%); and process efficiency (<1%); as well as the increase in tons produced that counts as an additional constraining factor for decarbonisation as it would otherwise lead to additional production-side emissions (activity, -31%).

### **Investments and production costs**

Investments to support the supply of cement (overnight investment costs of production capacities), both to replace ageing equipment and for greenfield plants, are considerable. They amount to an average of 12 G\$/year over the 2021-2050 period in Ref, which are considerably lower than the

estimated investments over 2001-2020 of 22 G\$/year as a result of stabilizing demand and little retrofit. Investments are higher in 15C\_CCS (16 G\$/year, +33%; +16% in 2C\_CCS), given the costlier technologies installed and retrofitting activity; also, the total capacities installed are higher (+4%) due to an even higher demand. This is mitigated by demand-side savings and efficiency measures (15C\_LD), where average investments are nearly the same as in Ref (12 G\$/year, +2%).

As a result, taking into account the total costs (investment, raw materials, fuels cost, carbon price), the average ton of cement produced in the world becomes costlier. In Ref, the increase is already considerable (+35% over 2020-2050); in 15C\_CCS, cement is nearly twice (+80%) more expensive to produce in 2050 compared to 2020, from an estimated 86 to 155 \$/t. If these costs were entirely passed down to the final consumer, this would make an average 50 m<sup>2</sup> dwelling (using a global average of 166 kg of cement per m<sup>2</sup> of floor space) some 570 \$ more expensive. Using a 40%/60% distribution for materials/labour costs in construction (EU[58]) and a 16% share of cement in construction materials (India[59]) as example figures, this would amount to a 5% increase in total construction costs. As a comparison, the year-on-year increase in construction costs in the US were estimated at 14% for 2022[60]; therefore, the low-carbon cement cost premium is something that could be absorbed by consumers.

Whether costs would be passed down, especially the costs related to the carbon price, would be a policy-making question related to consumer protection and

purchasing power beyond the scope of this study, as well as a matter of climate policy. With rising cement prices, it could be expected that the demand would adjust accordingly: this is indeed reflected in 15C\_LD, which sees a cement demand that is 27% lower than Ref and a cement cost that rises by 66% by 2050 (i.e., 23% higher than Ref in 2050). By comparing Ref and 15C\_LD in 2050, the implicit price elasticity of cement demand is -1.52, which is on the high end of the range of values observed for long-term elasticities for energy products[61]. The cement saving measures could, however, be implemented by behaviour change and policy intervention with tools other than just pricing, such as building codes and construction practices.

Of note, most of the production costs of cement are operating costs rather than fixed costs: the share of operating costs increases from 45% in 2020 to 63% in 2050 in Ref and 15C\_CCS.

It then becomes an issue on how to supply the cement sector with sufficient quantities of low-carbon energies in a timely manner.

### 3.3. Cement production distribution and trade patterns to reorganize

Cement is a commodity that is traded little across international borders (around 2% of total production

was traded in 2010-2020); thus, the geographical distribution of production largely follows the distribution of cement demand. In addition to cement trade, it is also possible to trade clinker; this is not considered here.

The regional distribution of cement production, dependent on production capacities, production costs and transport costs, remains concentrated around China in the medium-term projections, with the Rest of the world emerging as the main consuming region (Figure 7).

The implementation of climate policies usher small changes in the market shares of regions in the world cement production mix: 2050 comparing 15C\_CCS with Ref, Rest of World and EU gain 1-3% market share each, while China and India lose 1-3% market share each. These relatively small changes are due to the uniform implementation of the carbon price in the 1.5°C scenarios in all regions; a fragmented climate policy with differentiated levels of decarbonisation effort across regions would result in a greater cost diversity and adjusted trade patterns.

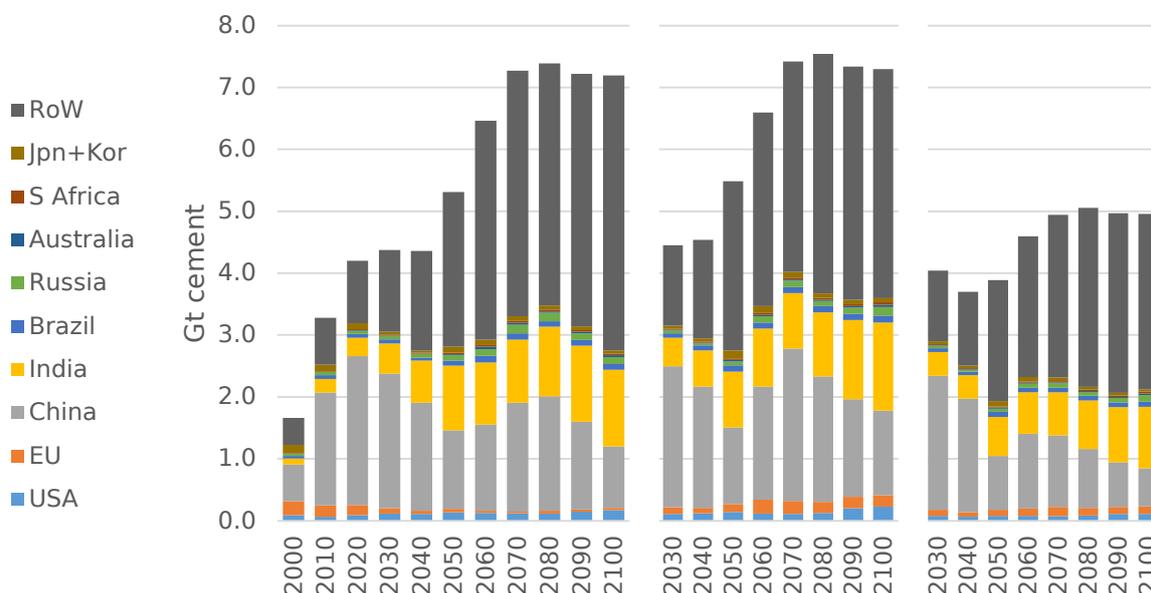


Figure 7: World cement production by region, Ref (left), 15C\_CCS (middle) and 15C\_LD (right)

Source: POLES model.

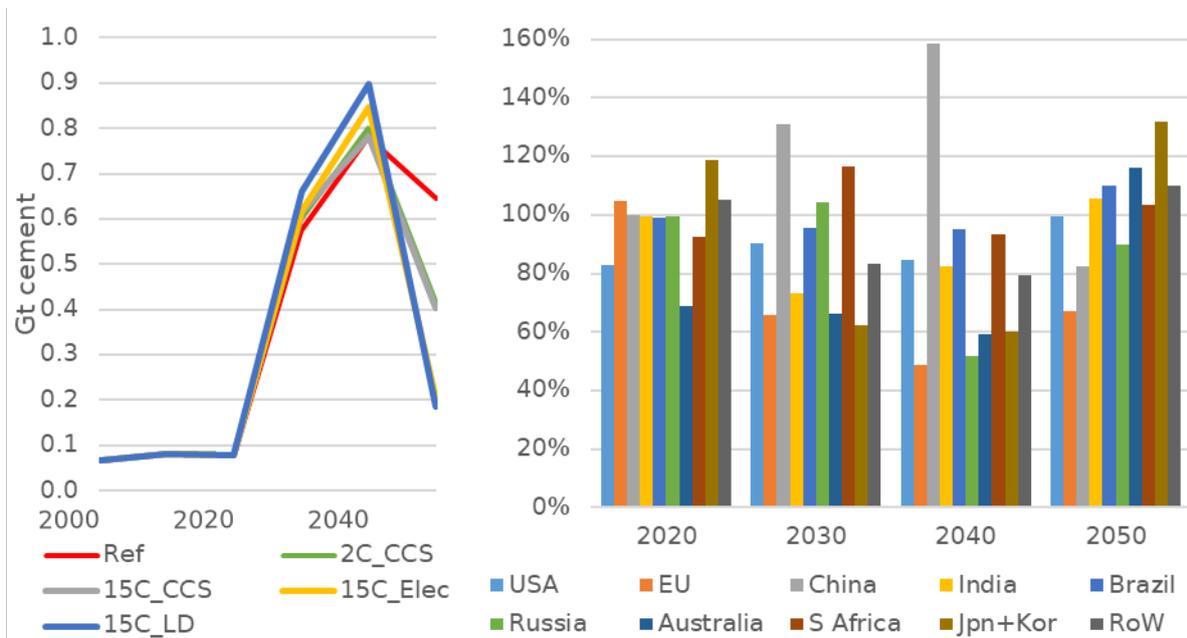


Figure 8: Global cement trade (left) and regional independence rate in the 15C\_CCS scenario (right)

Source: POLES model.

The production over-capacity in certain regions resulting from changing demand patterns redraws the map of potential importers/exporters. As global patterns of demand shift and production capacities adjust, cement trade (global net imports with the model's regional disaggregation) experiences changes in the coming decades, with increasing trade in the medium term, corresponding to a time of over-capacity in China (Figure 8). With standing capacities and a decreasing domestic demand, China could become a major net exporter. Certain regions change their trade status, from self-sufficient to net exporters (India, Russia, South Africa) at the expense of other regions that become importers (EU, Brazil, Australia).

Global trade volumes significantly increase in the medium term; they reach as much as 20% of global production in 2040, before returning to lower levels beyond. Moreover, transport costs per ton of cement traded increase over time. However, in the medium term, the increase in production costs due to the pressure to decarbonise (1.5°C scenarios) is higher yet, resulting in transport costs becoming a relatively lower component in the cost of traded cement.

#### 4. DISCUSSION AND WIDER IMPACTS

The supply of energy fuels and raw materials to support the needs of the cement industry comes with wider impacts on the energy system such as infrastructure development and on other sustainability indicators such as land use.

##### Waste

Solid waste combustion in cement kilns is perceived as a way to increase the circularity of resources and mitigate the use of fossil fuels[8]. However, its development is dependent on how its emissions are accounted and whether waste is

considered as a renewable fuel. In our modelling, waste use in power and cement was capped by a potential (an amount per capita corresponding to EU levels once 2030 policy targets for recycling and waste-to-power are met) and its emissions were accounted with the carbon content of coal. Solid waste is a mix of wood, plastics, and biological material and presents a carbon content as high or higher than fossil coal, as well as emitting other air pollutants potentially hazardous to health. Not accounting it in emissions balances would mean that its combustion is counter-balanced by carbon capture somewhere in its life cycle, similar to IPCC biomass emissions accounting, and considering that this cycle extends to the future at least over the lifetime of the goods that turn into waste. Given that countries adopt increasingly stringent policies in order to reduce the generation of waste and to increase recycling, treating waste as a renewable resource is questionable.

##### Biomass for energy

The cement sector consumes increasing amounts of biomass, from small amounts today to some 4.3 EJ/year in 2050 and 12.1 EJ/year in 2100 in 15C\_CCS. New supply chains would need to be established to provide this new energy vector in sufficient quantities.

However, the cement sector remains a small consumer of biomass in the overall economy in the projections: at most 3% of total bioenergy demand in 2050, 6% in 2100. Indeed, biomass being a limited resource, the model chooses where to use it based on relative costs and emissions abatement potential. More biomass quantities are consumed in the power sector and in hydrogen production (coupled with CCS, resulting in net-negative emissions), as well as feedstock in liquid biofuels production for the transport sector. In the climate mitigation scenarios, biomass demand increases significantly over time, reaching as much as 200

EJ/yr by the end of the century compared to around 62 EJ in 2020. The attainability of such high numbers with regards to food supply, land use change, water availability, biodiversity loss and actual net carbon savings has come into question[62], with limits as high as 300 EJ/yr but also as low as 55 EJ/yr being qualified as sustainable[63] (source).

### ***Biomass as a construction material***

The 15C\_LD scenario assumes that the average building uses 40% less cement. This is technically feasible. Practices could change and building codes could be revised to make a more rational use of concrete by avoiding over-engineering without endangering structural integrity or by using concrete in a more targeted way. Concrete acts both as a steel insulation material and a carrying material for the structural integrity of a building; over-engineering and minimum cement contents in construction standards imply an untapped potential for cement savings[64]–[66]. Concrete could be substituted with other materials such as steel, glass, bricks, stone, and in particular biomass and wood-derived products (such as bamboo and cross-laminated timber).

Indeed, “timber cities” have been proposed as a way to substitute high-emissions materials and stock carbon within the buildings structure[67], at least during the lifetime of these buildings. The feasibility of multi-storey construction using engineered wood products and little to no cement has been proven with a series of prototypes and their use has accelerated over the past twenty years[66].

While this be a solution, its wider adoption depends on the wider availability of wood to be used in a significant share of total construction. 2021 industrial roundwood production stands at 2.02 Gm<sup>3</sup>/yr and used 3.5 Mkm<sup>2</sup> approximately[68], [69]. Assuming that the entirety of the decrease in concrete demand in the 15C\_LD scenario by 2050 would be substituted by wood (1:1 equivalence in volume), this would amount to an additional wood demand of 45.8 Gm<sup>3</sup> to be supplied over 30 years, i.e., 1.53 Gm<sup>3</sup>/yr on average (similar levels to [70]). This corresponds to about 2.5 Mkm<sup>2</sup> of land surface globally dedicated to construction-grade timber plantations (using 6.1 m<sup>3</sup>/ha/yr for average global land productivity[71]): an area equivalent to about half that of the European Union, or to 6.4% of the world’s forests as they stood in 2019. These figures raise important questions as to the sustainability of this solution, with potential important impacts on deforestation and biodiversity loss if this increase of the timber industry is not governed and managed properly[70]. This near-doubling of roundwood production could also come into competition with other uses of land, such as space for food production or space to grow the biomass for energy uses discussed above.

Nevertheless, “timber cities” would provide a scalable option for temporary carbon storage (14.2 GtC stored in engineered structures by 2050 in 15C\_LD) compared to negative emissions derived from using biomass in cement manufacturing (as much as 0.3 GtC of BECCS over the

same period, in 15C\_CCS). This option would be particularly attractive when emissions must be decreased quickly and the temporary temperature overshoot above 1.5°C is to be pursued as much as possible to avoid climate change impacts[72].

### ***CO<sub>2</sub> flows and other materials***

In terms of CO<sub>2</sub> flows, the carbon captured in cement production as well as in other sectors (other industry, power generation, other) would need to be transported with dedicated infrastructure to the point of sequestration. While the costs are estimated to be low on a per ton basis (around 10 \$/tCO<sub>2</sub>[73]), the infrastructure remains to be built entirely, or use repurposed fossil fuel infrastructure, with few actual projects for country- or continental-scale transport materializing as of 2023[74]. The EU has some 200 cement plants with an average capacity of 1 Mt/year; each would produce some 0.7 MtCO<sub>2</sub>/year to be sequestered. These flows are comparable to the mass transiting through international gas pipelines, e.g., the Algeria-Tunisia-Italy TransMed pipeline capacity of 30.2 Gm<sup>3</sup> of natural gas over two lines, amounting to 11.6 Mt/year[75]. This underlines the scale of the effort required to put the CCS infrastructure in place.

Despite the fact that it accounted for about 2% of global fossil fuel emissions in 2021[76], the cement carbonation sink is not accounted for in national inventories of the UNFCCC or in discussions of carbon budgets in the IPCC[77], [78]. The budgets themselves might require adjustment if this sink was not properly accounted for in the climate models underlying IPCC work. Given the stringency of the 2°C and the 1.5°C climate targets, the carbonation sink could be a significant contributor to reaching the global net carbon budget: the cumulated 2020-2100 sink is 123 and 94 GtCO<sub>2</sub> in 15C\_CCS and 15C\_LD, respectively. This is roughly a fifth to a quarter of the difference of the budgets for 2°C and 1.5°C (1150 and 650 GtCO<sub>2</sub>, respectively). This means that by taking it into account, the 2°C scenario would be a 1.9°C-equivalent; or, conversely, the marginal carbon price would be approximately a quarter lower to get to 1.5°C. The sink could even be further increased by systematically applying end-of-life grinding of cement materials to optimize their exposure to the air, similar to mineral enhanced weathering, with potential co-benefits in countering arable land soil acidification[79]–[81]. Integrating this sink might significantly alter sectoral mitigation priorities and the pressure for actively decarbonising cement production, while feasible, might decrease.

Furthermore, the use of cement is associated with sand and gravel as concrete aggregates, and the environmental impact of their extraction is flagged as an increasing concern[82]. This increases pressure to handle end-of-life construction materials in a way as to optimize their reuse as aggregates.

## **5. CONCLUSION**

This paper presents work that enriches the representation of industry sub-sectors, namely that of cement production, and

consists in the state of the art in the way these issues are represented in integrated assessment models; it provides a precise picture of investment needs and the effects of policy levers that are of interest to both policymakers and investors. Given the complexity of economy-wide decarbonisation involving multiple dimensions of material demand, production, trade and energy mix, we used an energy system model to tackle this issue. In this paper, we presented a new model detailing cement demand and multiple cement production pathways within a larger global multi-regional energy system simulation model, to produce long-term projections of material, energy and emissions flows. In order to assess the decarbonisation potential of the cement sector in interaction with the rest of the economy, we built several scenarios of the future energy system with different sets of assumptions on policies, technologies and cement demand patterns. We examined to what extent and at what pace the cement sector can reduce its emissions and the contribution of each decarbonisation option. Finally, we broadened the scope to some additional challenges related to waste, biomass and CO<sub>2</sub> in the cleaner production of cement.

We project global cement demand to increase at a decelerated pace compared to the past two decades, reaching a peak at 7.5 Gt in 2080, up from 4.1 Gt in 2020. This is driven by substantial increases in the underlying socio-economic conditions, in buildings floor surfaces, road transport paved network, power production system and infrastructure. Introducing energy saving and material efficiency measures would greatly temper this increase (peak at 5.1 Gt in 2080), alleviating some of the pressure of the cement production sector to mitigate emissions.

The CO<sub>2</sub> emissions of the cement production sector are projected to increase unless strong climate policies are adopted. With sustained coordinated efforts for decarbonisation and thanks to CCS, the cement sector could reach carbon neutrality by the middle of the century. The energy mix would diversify away from coal. The conventional processes would make use of fossil gas and biomass. The fully electric kiln, currently still at a prototype stage, is projected to produce, at most, 18% of global cement by 2050 and continue expanding in the second half of the century. However, the availability of CCS technologies is crucial for emissions mitigation overall and for reaching the carbon neutrality milestone specifically. Energy savings and material efficiency measures would allow certain savings in cement sector investments (12 G\$/year over 2021-2050 compared to 16 G\$/year without). In all decarbonisation scenarios, the cement production cost is projected to nearly double over 2020-2050, mainly driven by the price of energy inputs (including carbon pricing), thereby providing a strong impetus for the implementation of the savings and efficiency measures as an option for decarbonisation and economic efficiency. As a result of decreasing demand and production over-capacity in China, global cement trade is projected to increase in the medium term.

Furthermore, the provision of large enough quantities of raw materials and low-emissions energy to the cement sector would pose significant challenges in many fields. The indirect land use of using wood products to substitute cement as a construction material could come into competition with land for bioenergy. The carbon transport and sequestration infrastructure to ensure most of the cement sector's mitigation is currently still at a nascent stage and remains to be built.

Overall, cement could be free of the characterization as a material with hard to abate emissions hinging upon the large-scale availability of CCS and the accounting of carbonation as emissions sink.

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### 7.3. Conclusion: prioritizing action among potential disruptive innovations

We have seen how an energy system model was applied to produce a set of projections for cement demand and cement production, with the associated energy and emissions flows. Cement demand and associated emissions are projected to continue increasing at a slower rate. Few changes in the energy mix and the CO<sub>2</sub> content of cement are expected without additional policy intervention.

Additional efforts needed to stabilize and reduce emissions to a level compatible with an economy-wide move towards a 1.5°C- or even a 2°C-compatible trajectory. There are multiple pathways forward, each presenting its own set of challenges and trade-offs; in all pathways, production costs for cement are projected to increase.

We have identified the following actions for cement sector emissions reductions, grouped in medium-term and long-term priorities:

#### 1. Pursue material efficiency

There is significant potential for a more efficient use of cement by revising buildings construction codes to avoid over-engineering; emissions reductions can also be achieved by allowing a lower clinker content where applicable. Significant savings can also be achieved by cement substitution with other construction materials like stone, brick, bamboo and wood products. Substitutability depends on many factors, from technological progress to standard practices and policy push. It is difficult to model material substitution based on costs; in this work they were explored with “what if” scenarios. In addition, a rebound effect on cement demand is projected to come from the low-carbon transition, due to increased use in buildings renovation and power generation, but it is only small.

#### 2. Invest in carbon capture and sequestration

Given that around two thirds of emissions from cement stem from the process itself, deep emission cuts are only possible if carbon capture is applied. Policy clarity and stability is needed in order to attract investment in retrofitting capture technologies on existing cement production capacities and in building the CO<sub>2</sub> transport and sequestration infrastructure. Deep emission reductions and the attainment of net-zero for the sector depends on the speed of deployment of CCS.

#### 3. Address the recarbonation sink

The absorption of CO<sub>2</sub> during the lifetime of cement products (and further absorption if the products are ground at the end of their lifetime) is a process that is unaccounted for in countries’ emissions inventories. This recarbonation sink is projected to more than double during this century and by 2100 be equivalent to the annual emissions of the cement sector of 2010. Taking it into account would change the projections of net emissions, and would radically change the pressure on the cement sector to actively decarbonise. Clarifying the role of recarbonation in emissions statistics would benefit all actors involved, from cement manufacturers to climate modellers.

#### 4. Electrify as much as possible

Part of the existing process (pre-calcination) could be electrified with existing technologies in order to reduce emissions immediately. Further electrification with a fully electric kiln would need more R&D,

but it could have an effect already from the next decade. In the absence of CCS, emissions reductions would be provided at a higher cost by increased electrification.

#### **5. Expand the use of biomass and waste**

Biomass and waste could replace coal without needing to change other parts of the process. Biomass use could come with significant trade-offs on biodiversity loss, so its use should be allocated where it is most needed. Although the cement sector is projected to consume a small share of the overall biomass demand, biomass is an important element of all ambitious mitigation scenarios. However, the climate benefit of both biomass and waste depend on emissions accounting rules that can be put into question. For it to be actually sustainable and beneficial to the climate, great care should be given to where the biomass is sourced from, and ensure that planting and harvesting is managed over a time scale of decades.

#### **6. Consider green hydrogen and hydrogen-derived fuels**

Hydrogen and synthetic fuels combustion can provide an option for providing low-carbon heat, however their potential is limited by their high supply costs. They could become important in a context where CCS does not develop at a quick pace.

#### **7. Investigate new chemistries**

Options with currently low readiness level, such as prefabricated concrete blocks cured with CO<sub>2</sub> or new chemical formulas for binders, could have an effect in the longer term. Although a plethora of initiatives and prototypes exist, their large-scale implementation has to be tested in real conditions in order to assess their cost-competitiveness and practicality.

## 8. General conclusion

Limiting climate change while at the same time striving for a form of development that is sustainable and increasing well-being poses multifaceted challenges to all aspects of human activities. Historically, higher income levels and well-being have been correlated with an increase in the demand of material goods, and more specifically of goods that are energy-intensive and CO<sub>2</sub>-intensive in their production. The demand of such materials is expected to increase. However, the future increase in quality of life and well-being should not be prevented by efforts to transition to a low-carbon/low-GHG economy. Hence, global and regional pathways towards the decarbonisation of the energy system and the wider economy should cover both sides of materials demand and materials production.

### 8.1. Summary of findings

This work tackled the issues of demand and supply in an integrated way within an energy system model, combining outstanding expertise in materials science, economic research and environmental and resource economics. We focused on three materials, hydrogen, steel and cement, whose combined production processes release over 60% of the CO<sub>2</sub> emissions of the industry sector and about 18% of total CO<sub>2</sub> emissions<sup>23</sup>. A particular attention was given to the production of low-carbon hydrogen as a possible enabler for the decarbonisation of steel and cement, while also avoiding emissions in the chemicals industry. This work also entailed a fine calibration of the model to represent currently adopted country policies as well as the enrichment of the representation of mitigation options.

This work enriches the representation of industry sub-sectors with the inclusion of the most recent developments and technologies and pushes the state of the art in the way that these issues are captured in integrated assessment models<sup>24</sup>. We modified the global multi-regional energy system simulation model POLES to represent detailed bottom-up estimations of materials demand and multiple material production pathways. The new model was used to produce long-term scenarios, with different sets of assumptions on policies, technologies and material demand patterns, projecting material, energy and emissions flows to 2100.

Demand for all three materials studied – hydrogen, steel and cement – was found to increase in the coming decades (+300-470% for hydrogen, +11-65% for steel, +0-32% for cement, in scenarios compatible with 1.5°C climate change, in 2050 compared to 2020), with a saturation in the second half of the century for steel and cement.

Multiple mitigation options for the emissions of these three materials were identified in this work. These show that, although challenging in terms of investments, technology innovation, supply chain of low-carbon energy and material efficiency regulation, the reduction of emissions from these so-called hard-to-abate sectors to as low as net-zero is possible and feasible. It provides a wide picture

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<sup>23</sup> CO<sub>2</sub> from energy and industry, i.e. excluding agriculture and land use.

<sup>24</sup> This work was carried out alongside similar work in the enrichment of other energy system and integrated assessment models in the context of the NAVIGATE project. Results from this work were used in the forthcoming publication: Bauer et al. (forthcoming), *Integrated strategies minimize hard-to-abate industry sector CO<sub>2</sub> emissions in low-emission scenarios*.

of mitigation options, investment needs and the effects of policy levers that are of interest to both policymakers and investors.

The steel and cement sub-sectors offer different mixes of mitigation options. Reducing demand or demand increase by material efficiency measures is paramount in order to minimise the challenges faced by the industry to produce these materials. Steel presents a high potential for circular economy, in that a large amount of steel scrap is projected to be available for recycling, thus enabling higher electrification levels; carbon capture, biomass and hydrogen complete the picture of mitigation options. Cement production can be fuelled further by electricity and biomass, however the bulk of mitigation can only happen using carbon capture; moreover, cement generates a considerable carbonation sink that is not taken into account in current country statistics and which could alleviate some pressure from the cement sector to actively decarbonise. The wider impacts on land use of the additional renewable energy production induced by low-carbon materials production were discussed.

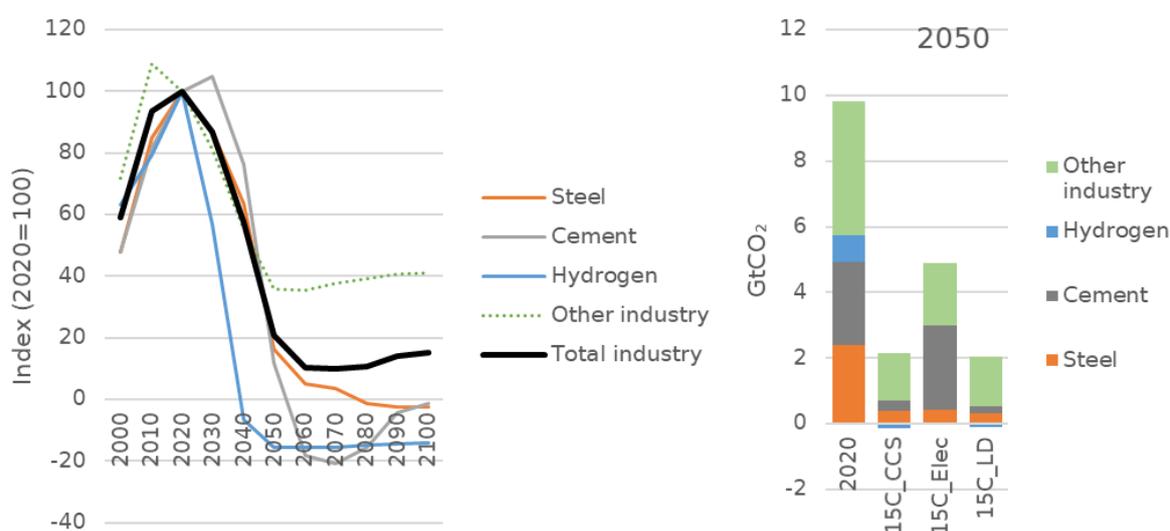


Figure 33: Global emissions by industry sub-sector, over time for 15C\_CCS scenario (left) and in 2050 (right)

Source: POLES model. Hydrogen here refers to hydrogen used as industrial feedstock, not as energy vector.

The total emissions mitigation that can be achieved is considerable (see Figure 33), with different paces of reduction across the sub-sectors that were studied. Thanks to a climate policy signal sustained over time, it is possible to substantially reduce CO<sub>2</sub> emissions in the production of these materials (to net-zero for hydrogen, -82-87% for steel, -0-91% for cement, in 1.5°C-compatible scenarios in 2050 compared to 2020).

Along with efforts in the rest of industry, the three sub-sectors studied in this work contribute for between half and two-thirds (55-67%) of the mitigation of the overall industry (1.5°C-compatible scenarios in 2050). This puts total industry on a path of deep mitigation, with 80% reductions achieved in 2050 compared to 2020 levels in the 15C\_CCS and 15C\_LD scenarios; and 50% reductions in the 15C\_Elec scenario, mainly due to a delay of CCS availability. With such results, the characterization of industry as “hard-to-abate” can be put into question.

In order to reduce emissions to the extent necessary to limit climate change to the Paris Agreement objective of 1.5°C, **an unwavering policy signal that is sustained over decades is needed**. Ambitious policies are required to align industry investments towards low-carbon solutions, with wider interactions with other sectors such as power generation, hydrogen production, biomass production and carbon capture infrastructure. While possible, achieving this is not a trivial matter. This transition presents important challenges and offers opportunities to several stakeholders.

Additional figures for drivers, demand and stock are provided in annex vi.

## 8.2. Discussion and limitations

This work shows that it is **technologically and economically possible** to satisfy the global demand for these materials while at the same time decarbonising their production process. This demonstration was done using a techno-economic model of the world energy system. Such models are useful quantitative tools for long-term energy planning and include sufficient complexity to make them fit for that purpose. However, such tools have been criticised from multiple standpoints; in turn, integrated assessment modellers have attempted to develop their models to partly address such criticism, in a positive feedback loop [41]. Inevitably, this work relies on modelling that presents certain simplifications, biases and uncertainties. Some of these are discussed in the following paragraphs.

In this work, we have mostly focused on global results and trends. While the modelling represents country-level pathways, its granularity and techno-economic focus excludes some dimensions of the transition; for instance, employment effects and innovation policies. Exploring these might reveal additional roadblocks and enablers that could change the dynamics of how decarbonisation might happen in individual countries and, in turn, change the global picture of emissions.

**Supply chains and employment:** The geographical distribution of demand and production for materials is set to change. Certain regions, in particular developing economies, face strong demand increases and will have to plan ahead on how to supply this demand, by investing in domestic production capacities or in infrastructure to import these materials from elsewhere. Certain other regions, China in particular, face a decreasing demand, which means that their domestic production facilities have to reorient towards exports or be shut down. This redrawing of the map and the change of the terms of trade will have severe consequences in terms of employment imbalances, with jobs increases and losses in different countries.

**Innovation challenges and opportunities:** The drive to decrease global emissions presents a technological challenge that will be felt very differently across countries. Richer countries generally concentrate on activities with higher added value instead of basic industrial activities, and are usually at the forefront of technological innovations that eventually diffuse to other parts of the world. Richer countries will be more likely to foster innovation with research policies or by providing financial support to companies that bear the extra cost of being the first ones adopting a new, costlier technology. By developing new technologies they will gain a competitive advantage and then they will be able to export these technologies elsewhere. Furthermore, richer consumers might be willing and able to pay a premium for a product with specific characteristics like something that is innovative or greener. Conversely, poorer countries have fewer capabilities to invest in expensive technologies.

Governments and companies have little fiscal margin to invest or cover the green premium for low-carbon products, as they often face higher costs of capital, higher risk premiums, and struggle to respond to an increasing demand for products and services. As a consequence, while the 1.5°C scenarios presented in this work assume a coordinated push towards decarbonisation across all countries, the actual implementation is likely to be much more fragmented. Here, partnerships between countries for technology transfer or for financial assistance for the decarbonisation transition can be very helpful in maximising emissions reductions with optimised costs allocation. There are many opportunities for companies working in innovative technologies. Industrial production might move closer to where renewable energy is cheaper and abundant, possibly closer to the equator to exploit solar resource. New business models might emerge where hydrogen and semi-finished goods are produced in the Global South and are then consumed domestically or exported to the Global North. Again, governments would need to give great care to the potential jobs losses due to the shift away from high-carbon industries.

**Technology coverage and deeper electrification:** This work has focused on technologies that are currently available, as well as on the current understanding of the cost and availability of new technologies. Over the time horizon of this study, the entirety of the 21<sup>st</sup> century, it is possible – likely – that knowledge will evolve and that newer technologies might emerge. In this work, we attempted to include certain technologies that are still marginal today but have enough policy, research and investment momentum to play a significant role in the coming decades – such as electrolyser for hydrogen, iron ore reduction with hydrogen and with electricity, electric kiln for cement, and CCS. Other technologies still at the laboratory scale might prove to be scalable and competitive and emerge faster – such as CO<sub>2</sub> curing of concrete blocks or deeper electrification technologies (via plasma, microwave, or other concept).

A main driver of results in this work is the electricity price, and how it might evolve as simultaneously decarbonisation of the power sector is pursued. Over the 20<sup>th</sup> century, fossil fuels have been widely and cheaply available while electricity, a secondary fuel that was mostly based on fossil fuels combustion, has been a more expensive fuel. The transition to a low-carbon economy might turn the tables and result in electricity that is more competitive. In our modelling, electricity is projected to become costlier, despite technological learning, due to the need to install storage and flexibility means to accommodate variable renewables, to costly peaking plants with fossil gas and to market mechanisms that are based on marginal cost pricing. Recent trends -- in large-scale storage costs and in market redesign towards capacity markets and contracts for difference -- point towards low-carbon electricity prices that might not necessarily follow an increasing trend.

**Technology dynamics and speed of transition:** Energy system models can be validated on the basis of their ability to project a rate of change that is within the range of what has been observed in the past [163], [164]. However, that could mean that the possible rate of change towards new, low-carbon solutions might be underestimated. The modelling in this work included certain assumptions on the future evolution of technology costs and on technology preferences, which serve to mimic past investment behaviour. These factors might evolve faster (or slower) than assumed in this work.

As an example, many important models close to policy-makers, such as the one underlying the International Energy Agency's World Energy Outlook, have systematically underestimated the deployment of renewable energy technologies [165]. While models do include dynamic effects such

as technological learning rates, this underestimation implies the existence of non-economic parameters (such as consumer preference) that are evolving fast over time in favour of these technologies. It would seem that the deployment of electric vehicles is also happening much faster than predicted by many models, given sales observed in 2019-2023, which could result in a radical tipping of the road transport system from one technology to another in a single business cycle.

**Socio-economic model and the “uncertainty space”:** At its core, the model used in this work is very determined by the socio-economic assumptions used as input, namely GDP growth and population, and in the way that they are used as drivers. Relationships observed in past statistics are held as true in the future and universally applicable. Indeed, GDP is used as a stand-in for many concepts: not just economic growth, but also welfare, development, well-being or prosperity. Many indicators beyond just GDP have been proposed to measure “things that matter” [166] and indeed developing different metrics to measure development is a target of the sustainable development goals<sup>25</sup>. However, no single metric has been adopted wide enough to supplant the use of GDP.

The integrated assessment modelling community has developed several narratives on future development, the Shared Socio-economic Pathways (SSPs) [167], and their quantification for population, GDP, energy and emissions [168], as well as for certain materials [169]. This work uses assumptions on long-term economic growth derived from one of these (SSP2, the “middle of the road” pathway). These pathways offer certain contrasted views on many dimensions – demographics, human development, economy, institutions, technology – and attempt to distil the uncertainty about the future down to five narratives. This was a considerable endeavour. Yet, it is possible to imagine futures quite different from those, with different projections for emissions and their underlying drivers.

As an example of an alternative development pathway, China engaged in a program of buildings construction to provide modern dwelling space to its population and lift it out of poverty, in a “voluntarist” approach [170]; this resulted in a construction boom and a very high materials demand compared to what would otherwise have been expected from its level of income per capita compared to other countries. It is possible to imagine other countries acting similarly, with all world regions reaching a decent standard of living of over 40 m<sup>2</sup>/cap sooner than projected in the scenarios in this work [171].

The development pathway concept could be expanded further. In this work, material and energy services demand projections are determined by income per capita almost exclusively, to the omission of other explanatory variables beyond the economic and hard sciences realms. Such variables and concepts encompass ideology and societal values, beliefs and behaviour change, institutional efficiency and institutional sclerosis, social organisation and alternative development theories, and more. Many of these are difficult to model dynamically, which could implicitly explain why they are rarely examined in energy-economy models<sup>26</sup>.

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<sup>25</sup> SDG 17 “Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development”; Target 19: “By 2030, build on existing initiatives to develop measurements of progress on sustainable development that complement gross domestic product, and support statistical capacity-building in developing countries”, [https://sdgs.un.org/goals/goal17#targets\\_and\\_indicators](https://sdgs.un.org/goals/goal17#targets_and_indicators)

<sup>26</sup> See “An Artist’s Guide on How to do Integrated Assessment Modelling Differently” on non-modellers’ views on modellers’ blind spots, <https://futuremodelsmanual.com/>

The question is to what extent these dimensions not made explicit in the modelling would have an impact on the outputs. Certain studies have attempted to address several of these dimensions. Taking into account structural change across economic sectors in the macroeconomic parameters of energy models could provide more insights on decoupling economic growth from energy use, and potentially provide basis for deeper decarbonisation [172]. Other modelling architectures than the one used in this work, such as Dynamic Stochastic General Equilibrium (DSGE) models and agent-based models (ABMs), capture certain dimensions of consumer behaviour and uncertainty analysis [173]; however they have not yet been applied to study economy-wide energy transitions. The Low Demand scenario in this work integrates some elements of behavioural and demand-side changes of energy and materials; other modellers have also created Low Energy Demand scenarios to assess such impacts [174]. The case of dietary shifts has been used to try to represent behaviour change and changing social norms in a dynamic modelling framework integrated with environmental impacts assessment [175]. Finally, studies on the feasibility of low-carbon scenarios attempt to characterise scenarios by looking at historical analogues of transformation, typically looking at technological feasibility as mentioned above; more recent work also looks at the political, institutional and economic feasibility of different rates of change [176]<sup>27</sup>.

Moreover, uncertainties exist also in the economics and hard sciences realm and certain feedbacks could be underestimated: underappreciated geophysical constraints to energy availability [177], [178], underappreciated effect of energy abundance and scarcity as an enabler or inhibitor of economic growth and monetary inflation [179], physical limits to technological miniaturisation and innovation which could prevent innovation-based economic growth [180], macroeconomic vulnerability to low-carbon transition when taking into account the finance sector and debt [181]–[183]. Such considerations could re-contextualize our expectations of increasing complexity and of an ever-growing economy de-correlated from the material world that underpins it. As a response to such possibilities, future scenarios that look “beyond GDP” have been developed, with such concepts of voluntary de-growth, a-growth or steady-state economy [184]; however, these have not been implemented fully as drivers in energy-economy models.

A full assessment of how all of this could impact energy-emissions-materials modelling is beyond the scope of this work. Suffice to say, addressing these uncertainties is at the forefront of much research.

**Multi-dimensional policy-making:** This work focused on how materials and energy supply can be aligned with the global ambition to limit climate change. Climate policy was a defining driver in the scenarios in this work. It is important to note that climate mitigation is only one element that will shape the societies and economies of tomorrow, and that policy-makers will have to balance many priorities simultaneously.

Other topics are just as important, and they all feed back into how we all conceive and discuss and prioritize the types of solutions on how to tackle the climate change issue: other sustainable development goals, shifts in employment, industrial policy, financial and fiscal stability, the role of the individual in decision-making processes, the value we place in wilderness over altering the landscape.

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<sup>27</sup> See also: Bertram et al., *Feasibility of peak temperature targets in light of institutional constraints* (forthcoming).

A coherent and comprehensive strategy of development should attempt to capture all of the above, as challenging as it may be.

**Ultimately**, while a model and a limited number of scenarios cannot capture everything, work like what has been presented here retains value and policy relevance. It reveals certain key drivers, influencing factors and bottlenecks in the demand and production of materials, and in assessing the emissions gap that needs to be closed to limit catastrophic climate change. The choice of drivers, technologies and assumptions and how these influence the modelling results provide important insights, even if the modelling scope is not comprehensive. In this work, an attempt was made to go beyond the usual domain of application of an energy system model and address additional organisational and sustainability concerns, such as affordability, rate of productive capacity expansion and land use.

Despite all of the caveats listed above, it could be said that models are the best tools at our disposal for planning a way out of the climate crisis, given the alternative of planning it without them.

### 8.3. Research outlook

Closing this work and looking ahead, there are multiple perspectives for further research. This can take many directions, either to deepen the detail of the topics mentioned above or to widen the application of the above methodology to additional aspects.

**Sensitivity analyses:** Many input parameters regarding the future are inherently uncertain. The different scenarios created for this work, along with some sensitivity analyses in the annexes, gave a range of possible outcomes and tested the solidity of the results. Further scenarios could be built with contrasted assumptions on some of the main drivers. In particular, only a single set of GDP and population projections were used in the scenarios presented in this work. Even if we accept the classical economics principles underlying the model's equations, a single set of assumptions on something as uncertain is reductive. Different views on the development of income per capita could be tested, starting from the five sets of projections of the Shared Socio-economic Pathways (SSPs).

**Macroeconomic feedbacks:** This work presented the results of a partial equilibrium model, wherein the costs of the effort to reduce emissions are an output that does not impact overall economic activity. A general equilibrium model quantifies these macroeconomic costs at the sectoral and country levels and result in revised growth prospects. These costs could be used as input in the energy system model; several iterations would converge in a stable set of outputs. The inter-linked models would provide a harmonized set of projections that take this additional form of feedback into account, increasing their accuracy.

**Further detail in materials demand:** For steel and cement, a non-negligible part of the historical demand was not explained by the bottom-up analysis. This important residual demand could be examined more closely, by detailing more bottom-up uses or by finding more adapted drivers to project its evolution. This could change the projections of the total demand levels; and would also result in different quantities available for steel recycling.

**Further socio-economic metabolism analysis:** With a more detailed representation of materials demand, it is possible to explore the potential for different ways in how society uses materials and

builds up stock. It is possible to explore under what assumptions an economy could shift from a regime with a high in-use stock to a lower one, with implications on the annual flows (i.e., annual demand of materials).

**Materials substitution analysis:** In this work, material substitution was treated in a simple way, only by assuming a lower demand per unit of output for the materials studied. The technical potential for substitution could be further explored, alongside the other options to lower materials demand such as avoiding over-engineering and extending lifetime. Also, the substitution problem could be addressed more in-depth in economic terms, where the costs of both options determine the adoption of either option. For example, the economic trade-off of substituting cement with biomass as a construction material would be determined by the production cost of cement produced by the energy model and the production cost of timber products produced by an agriculture and forestry model.

**Additional technologies assessment:** Certain technologies were excluded from the analysis because they are still nascent or appear to offer little decarbonisation potential. They could be integrated in the production processes to be better assessed, if they can be properly techno-economically described. Examples for hydrogen are white hydrogen (naturally-occurring hydrogen that could be extracted from the underground, like fossil gas). Examples for cement are new binder chemistries and prefabricated blocks with CO<sub>2</sub> curing.

**Expand to more materials:** The methodology developed in this work could be applied to other materials. Working with the selection criteria discussed in the introduction, other relevant materials that are energy-intensive and important in terms of volume and emissions are: non-ferrous metals such as aluminium and copper; glass and ceramics; or base chemicals. In addition, many of the model outputs can be directly used to calculate the demand for several critical raw materials associated to new low-carbon technologies, such as lithium and rare earths.

**Expand to the primary supply of materials:** The mining of iron ore and limestone was not covered in this work, as it represents a small part of energy use and emissions. This can be included in the modelling, for example with cost curves that relate production capacities' rate of use and geological scarcity with energy use and production cost. This would add more detail in the projections of production costs and resulting materials prices.

**Materials terms of trade:** The modelling presented in this work could be used to study materials trade projections under different conditions. This could address a wide range of issues, such as: carbon leakage; regional trade blocks with carbon border taxes; opportunities for prospective exporters; or the on-shoring of supply chains and trade-offs between the exports of feedstock and the finished products themselves (such as importing hydrogen for steelmaking versus producing steel where hydrogen is cheaper and importing steel).

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## Annexes

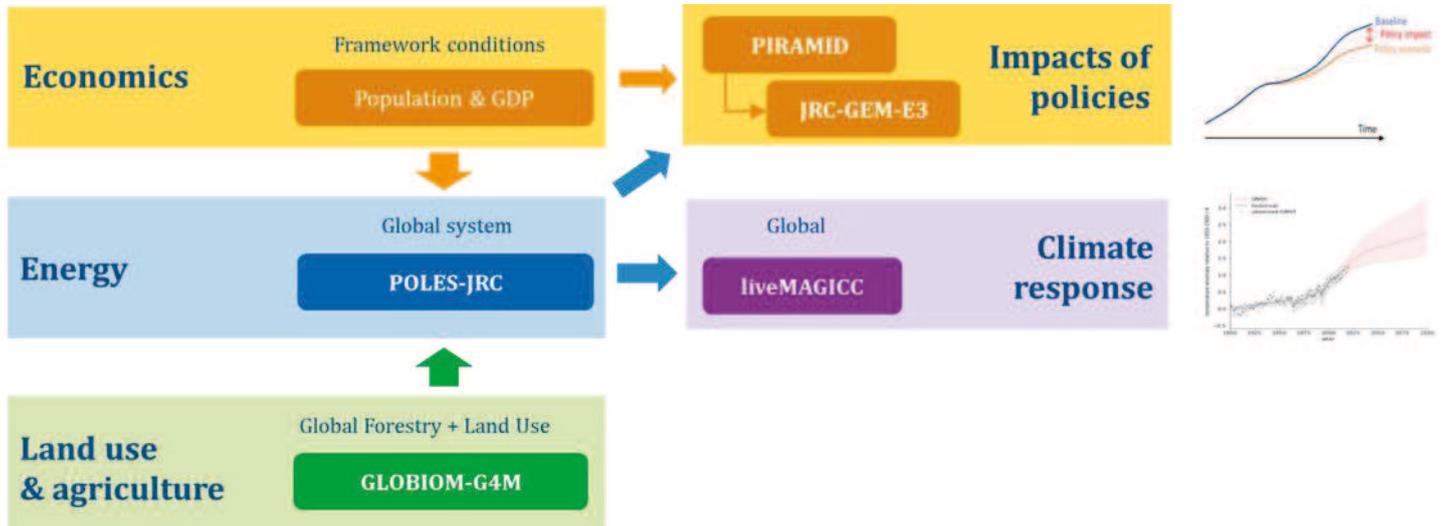
### i. Outreach activities

During this time period, I participated in the following outreach activities to present this work:

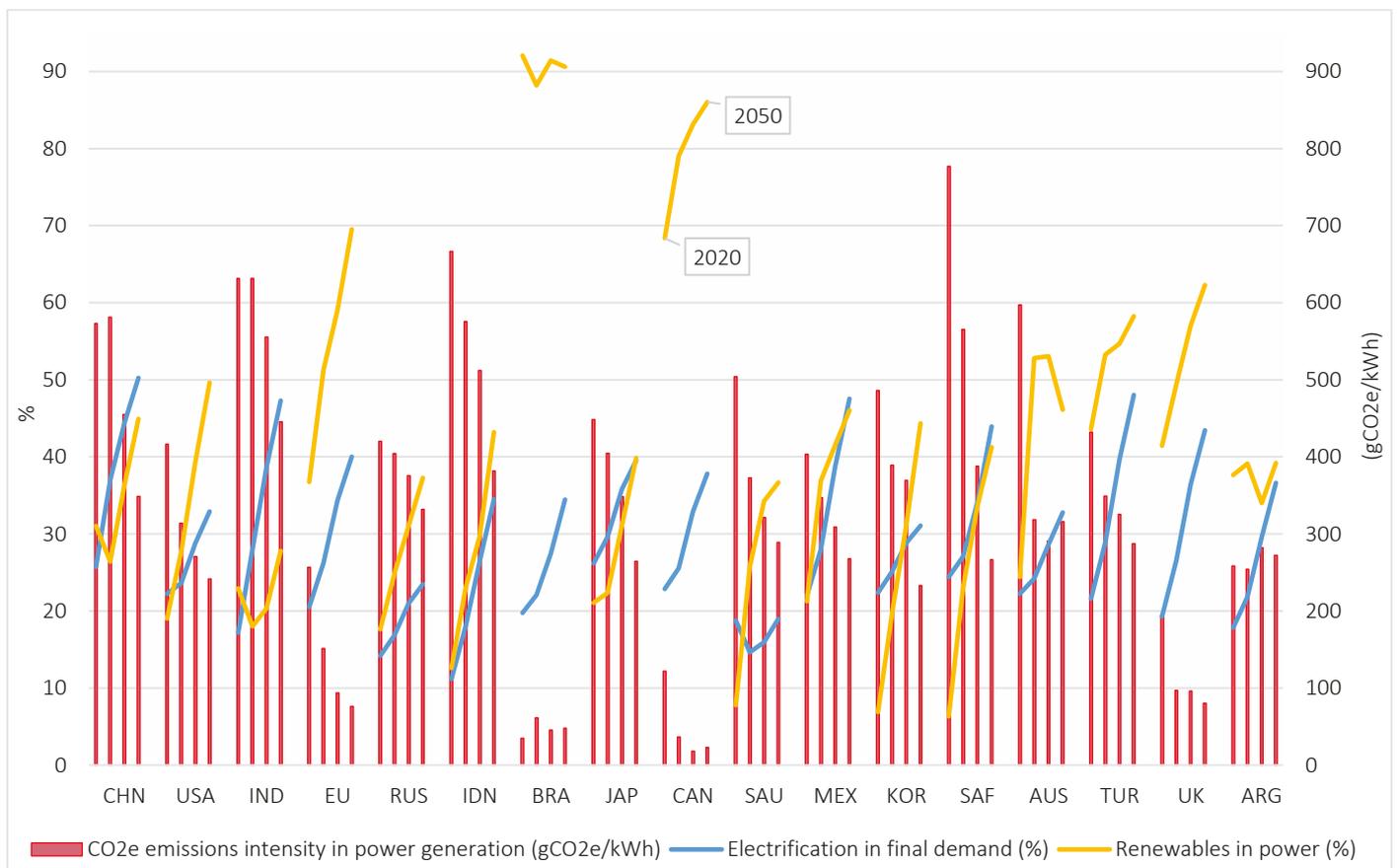
1. Poster presentation at the Integrated Assessment Modelling Consortium (IAMC) 2020 online conference, 4 December 2020. Title: *“Improving the climate footprint of energy-intensive materials: a modelling-based approach integrating demand and supply”*.
2. Oral presentation at the Society and Materials (SAM) 15 online conference, 11 May 2021. Title: *“Improving the climate footprint of cement: a modelling-based approach integrating demand and supply”*.
3. Oral presentation to colleagues of the Economics of Climate Change, Energy and Transport unit at the Joint Research Centre of the European Commission, 13 May 2021.
4. Oral presentation at the UGA GAEL doctoral seminar, 28 May 2021.
5. Oral presentation at the International Association for Energy Economics (IAEE) 2021 online conference, 7 June 2021. Title: *“Pathways towards a net-zero carbon emissions cement: a modelling-based approach integrating demand and supply”*.
6. Poster presentation at the Integrated Assessment Modelling Consortium (IAMC) 2021 online conference, 2 December 2021. Title: *“Materials industry modelling in net-zero emissions scenarios: the case of steel”*. **Laureate of the Best Poster Award**. 14th conference of the Integrated Assessment Modelling Consortium (IAMC), December 2021, online. See: <https://www.iamconsortium.org/event/fourteenth-iamc-annual-meeting-2021/>
7. Oral presentation at the 40<sup>th</sup> International Energy Workshop (IEW), 27 May 2022, Freiburg, Germany. Title: *“Materials industry modelling in net-zero emissions scenarios: hydrogen contribution to low-carbon steel”*.
8. Poster presentation at the Scenarios Forum 2022 at IIASA (Laxenburg), Austria, 20-22 June 2022. Title: *“Estimation approaches for materials demand, recycling and substitution using the POLES model”*.
9. Poster presentation at the Integrated Assessment Modelling Consortium (IAMC) 2022 online conference, 29 November 2022. Title: *“Blue and turquoise hydrogen: bridge options or mirage?”*.
10. IMAGINE project online modelling workshop, 7 December 2022. Title: *“Evaluating production processes and hydrogen supply routes for zero-emissions steelmaking in the EU”*.
11. Oral presentation at the Society and Materials (SAM) 17 conference, Karlsruhe, Germany, 9 May 2023. Title: *“The role of hydrogen, carbon capture, electrification and material efficiency in the decarbonization of the global steel sector”*.

- ii. Supplementary information to article 1: Energy and employment transition implied by climate policy pledges: informing the global stocktake of the Paris Agreement

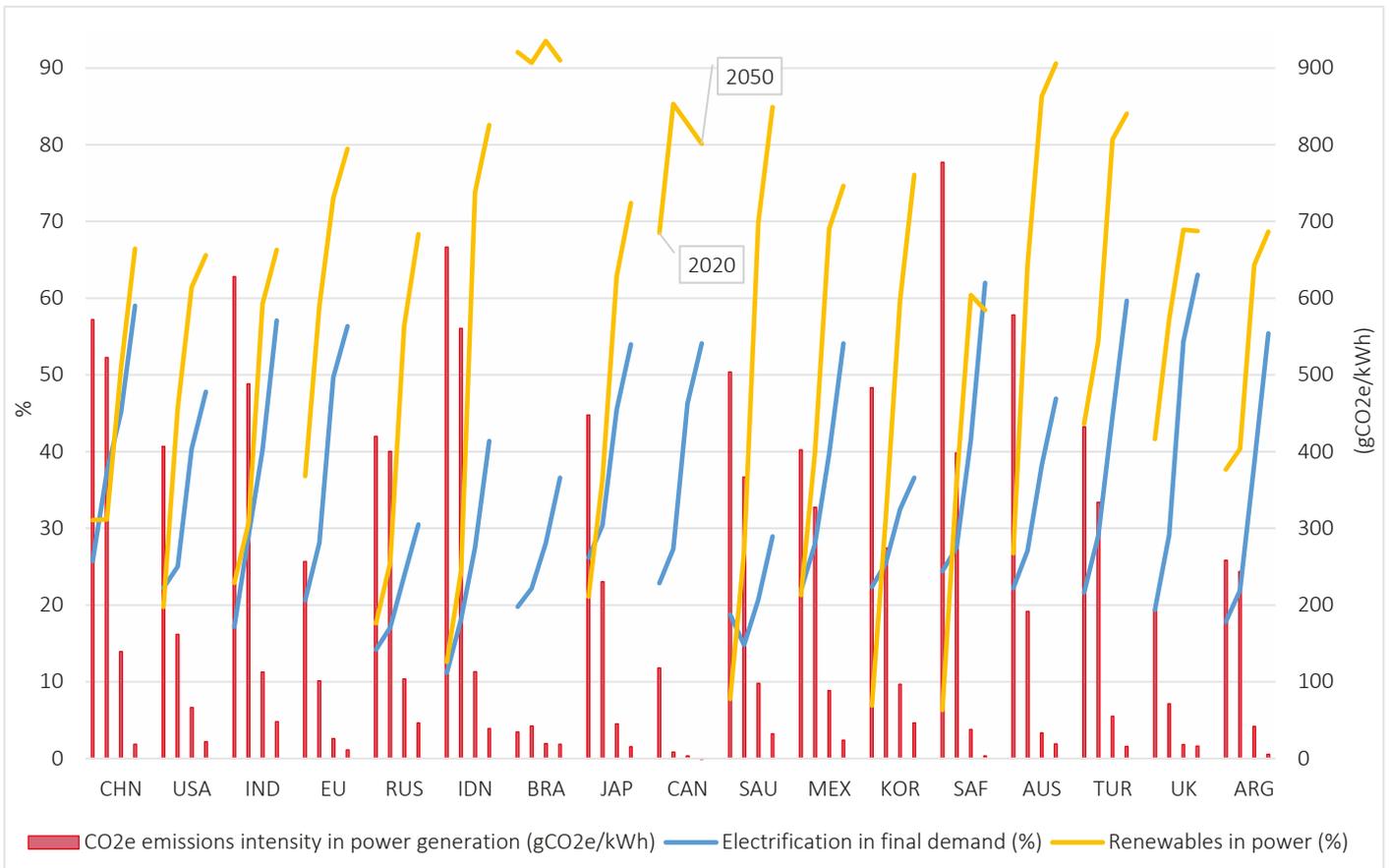
Supplemental Figures



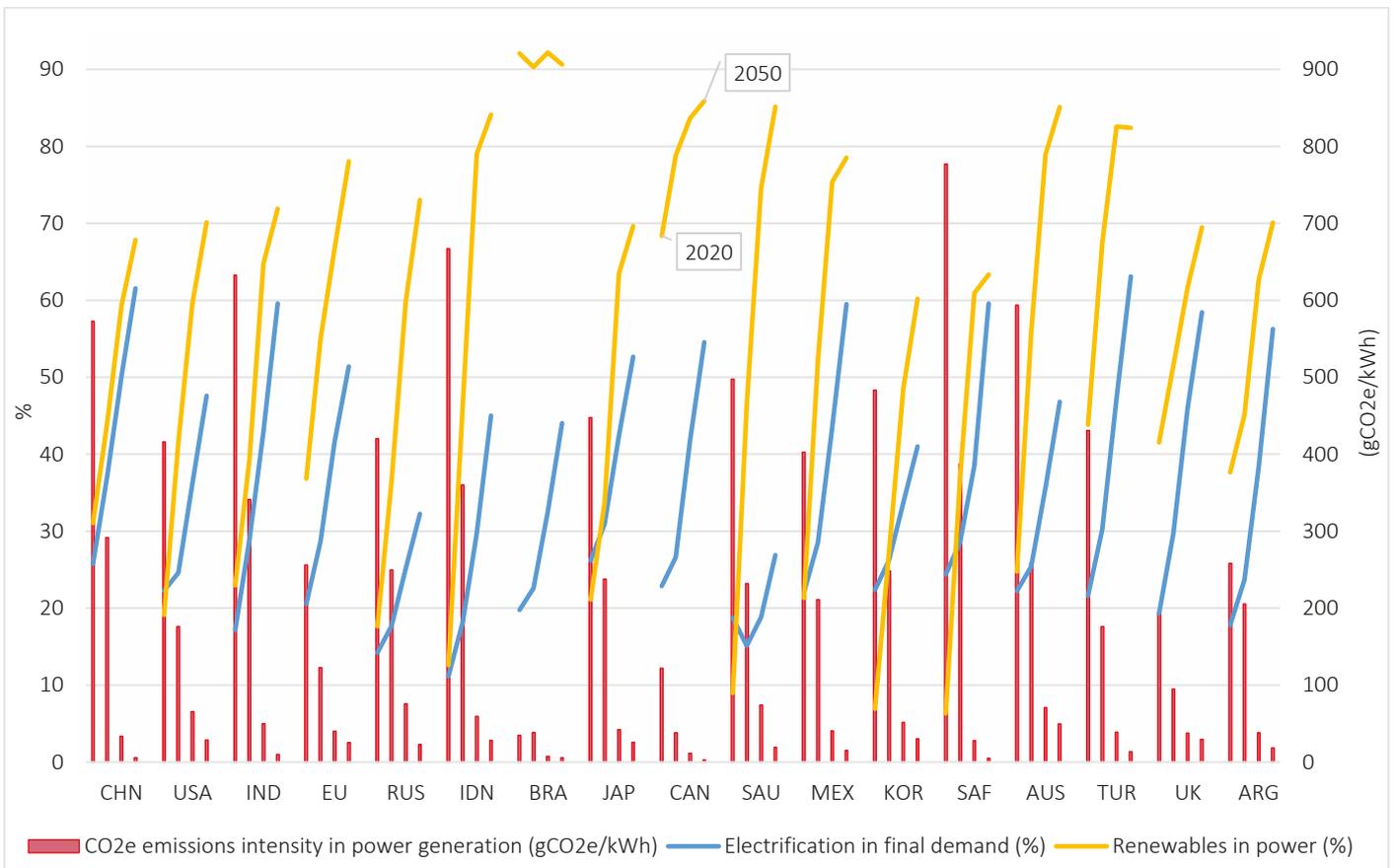
**Figure S1.** Modelling toolbox. Bottom-up energy system and top-down global economic modelling combined. Exogenous population and GDP projections are common to the POLES-JRC and JRC-GEM-E3 models. Satellite data for energy and emissions from POLES-JRC is reconciled into the JRC-GEM-E3 model through the PIRAMID tool. Exogenous inputs from land-use and agriculture are taken from GLOBIOM-C4M model, while GHG emissions from POLES-JRC are used to simulate the climate response projections in the liveMAGICC model.



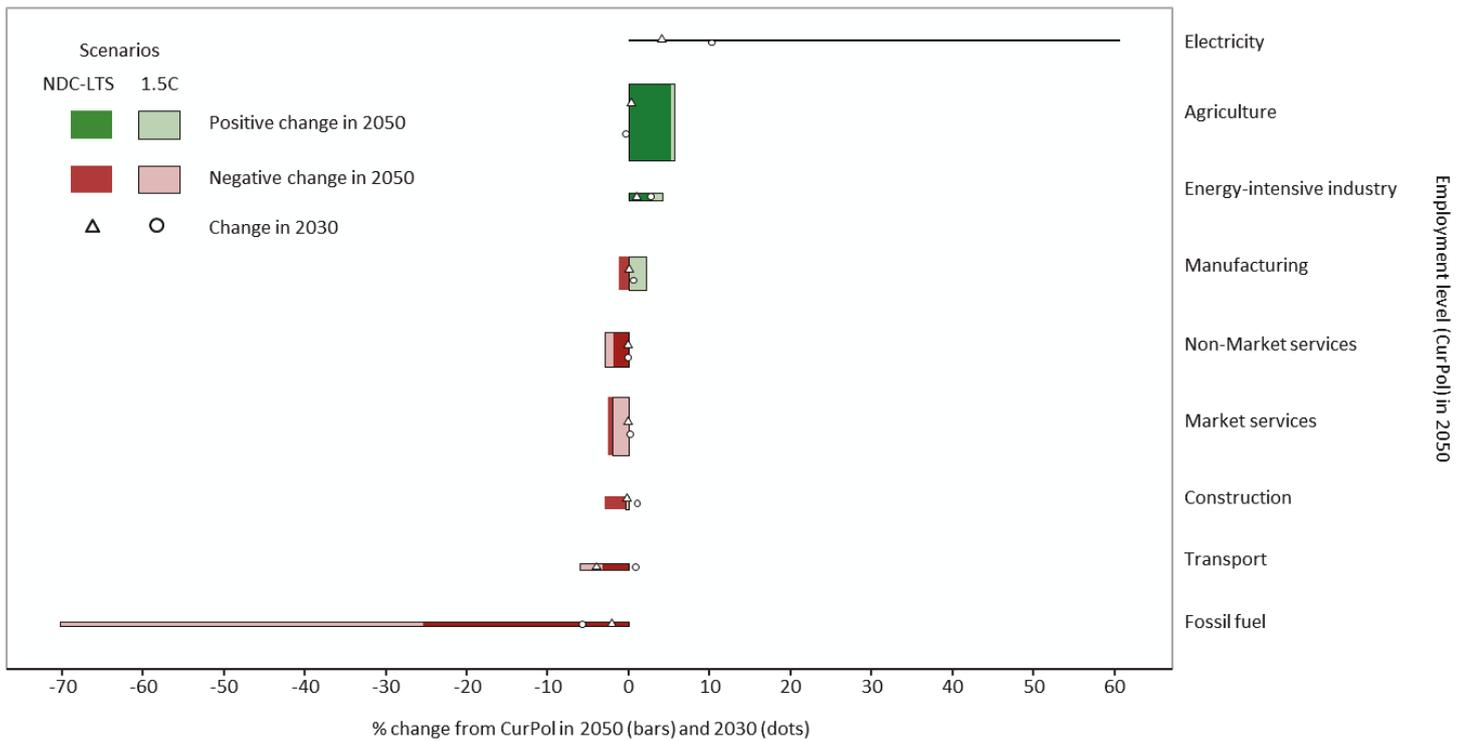
**Figure S2.** CO<sub>2</sub>e emissions intensity (gCO<sub>2</sub>e/kWh), share of electrification in final demand and share of renewables in power generation (%) in selected countries/regions under the CurPol scenario. Contribution from renewables to the decarbonisation of the power sector as electrification in final demand grows over the period 2020-2050.



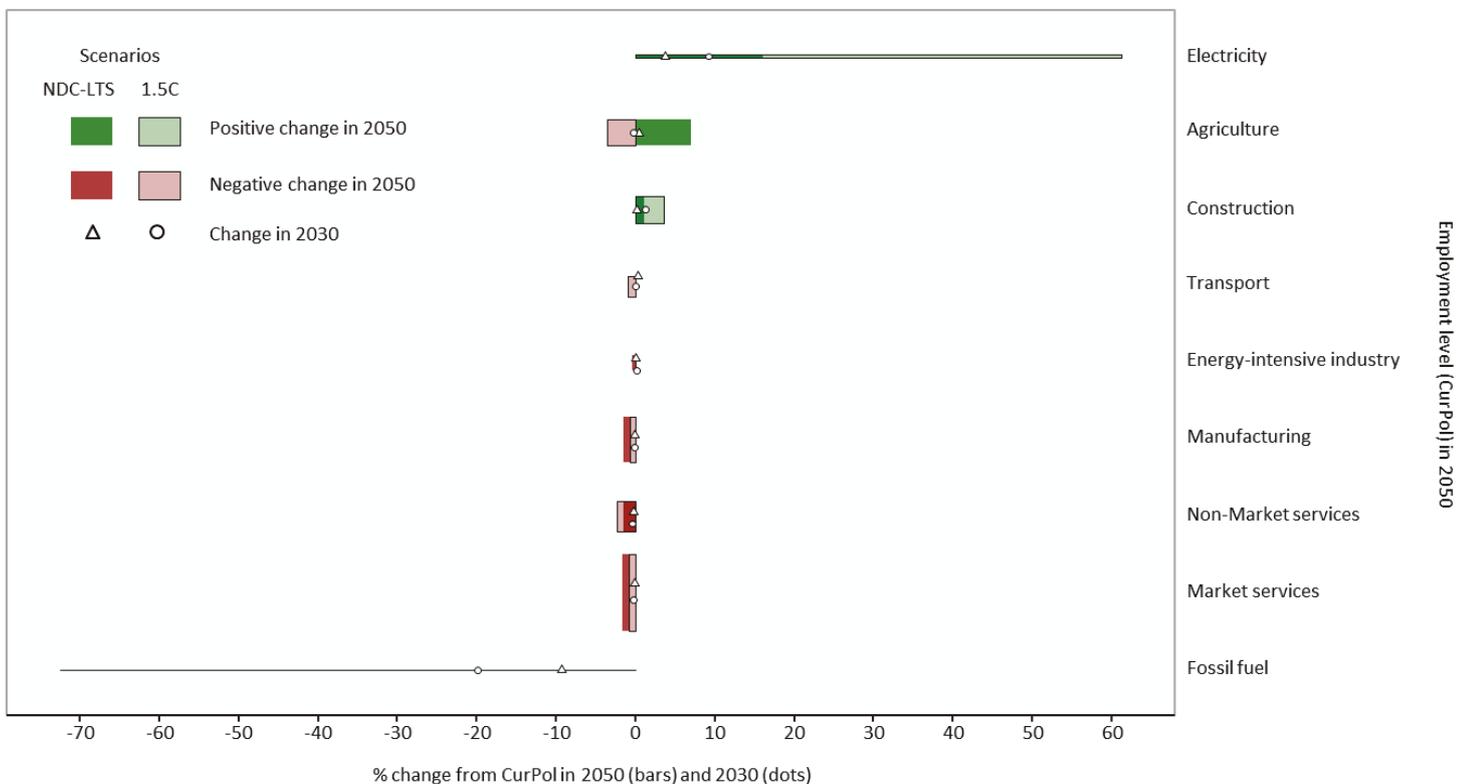
**Figure S3.** CO<sub>2</sub>e emissions intensity (gCO<sub>2</sub>e/kWh), share of electrification in final demand and share of renewables in power generation (%) in selected countries/regions under the NDC-LTS scenario. Contribution from renewables to the decarbonisation of the power sector as electrification in final demand grows over the period 2020-2050.



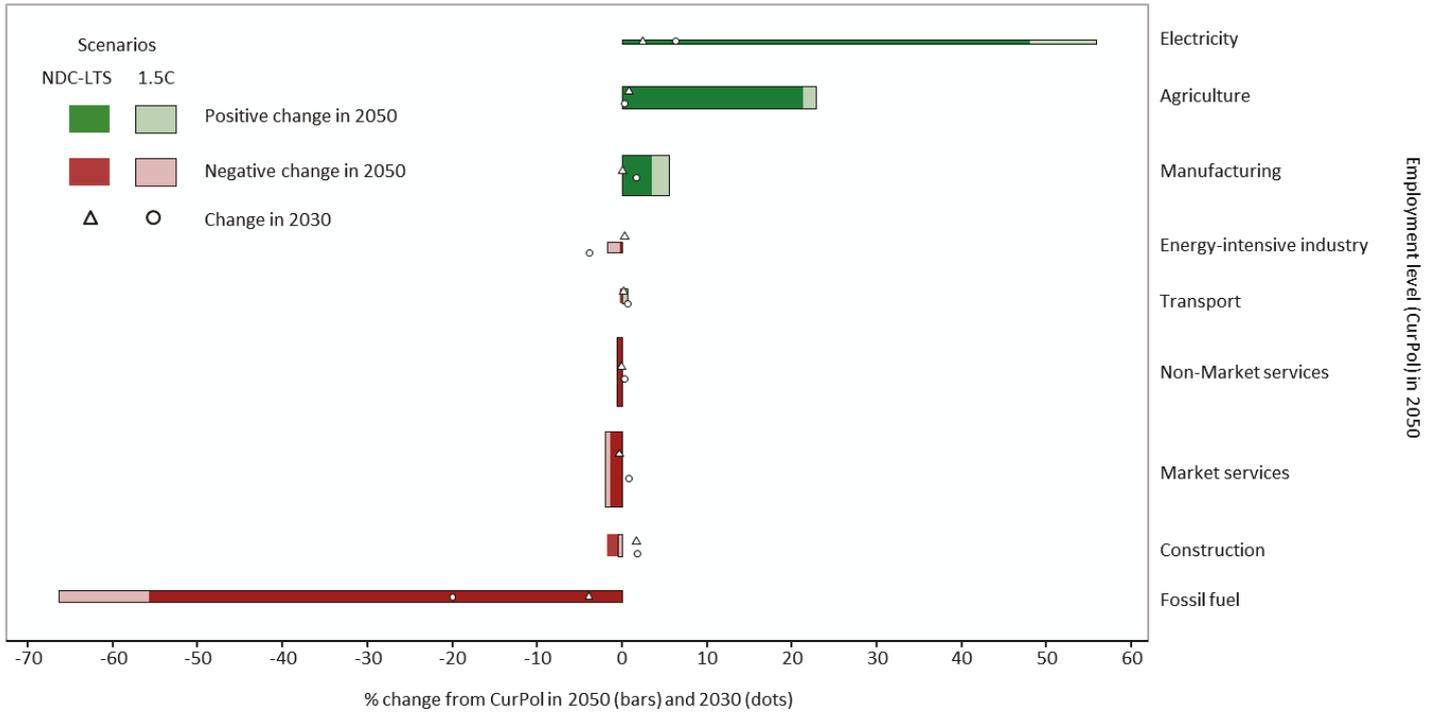
**Figure S4.** CO<sub>2</sub>e emissions intensity (gCO<sub>2</sub>e/kWh), share of electrification in final demand and share of renewables in power generation (%) in selected countries/regions under the 1.5C scenario. Contribution from renewables to the decarbonisation of the power sector as electrification in final demand grows over the period 2020-2050.



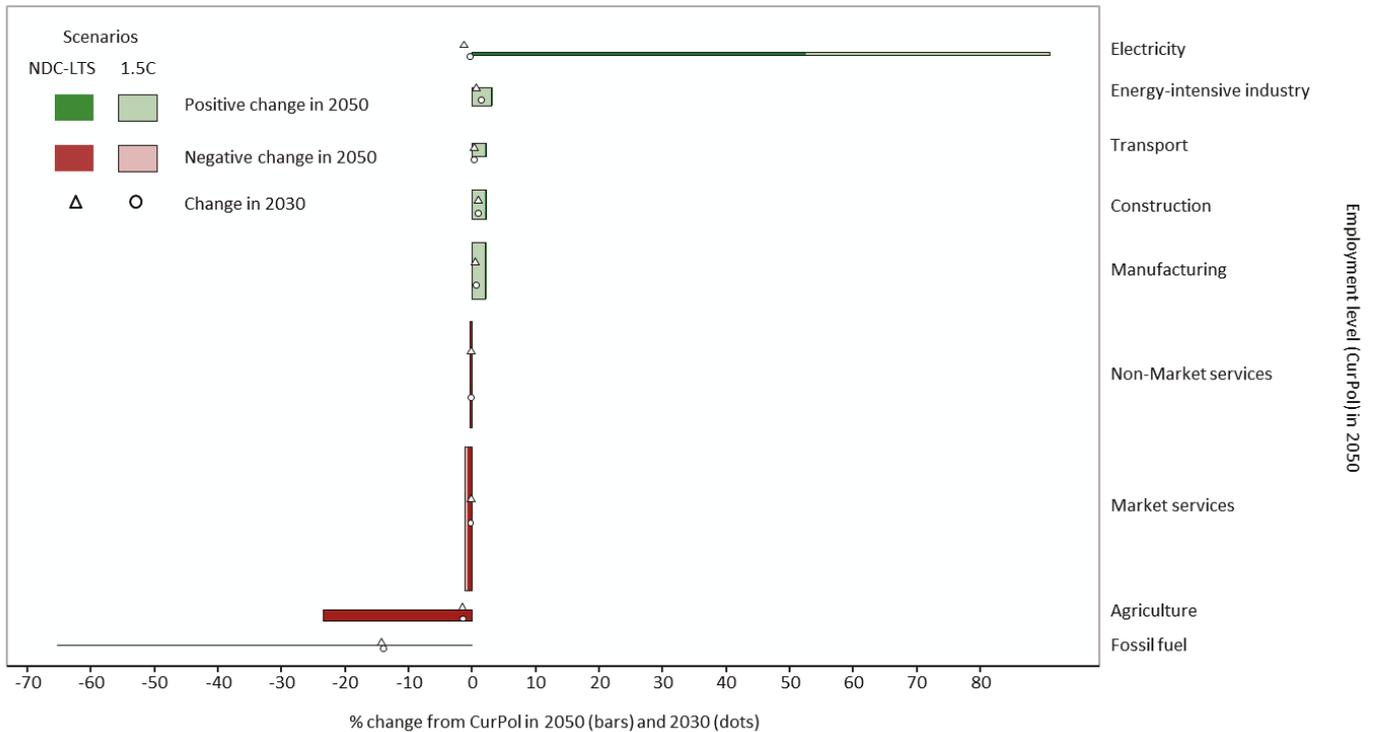
**Figure S5.** Africa – transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenario. Change in sectoral employment relative to the CurPol scenario (x-axis) and level of employment under the CurPol scenario in year 2050 (y-axis). The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.



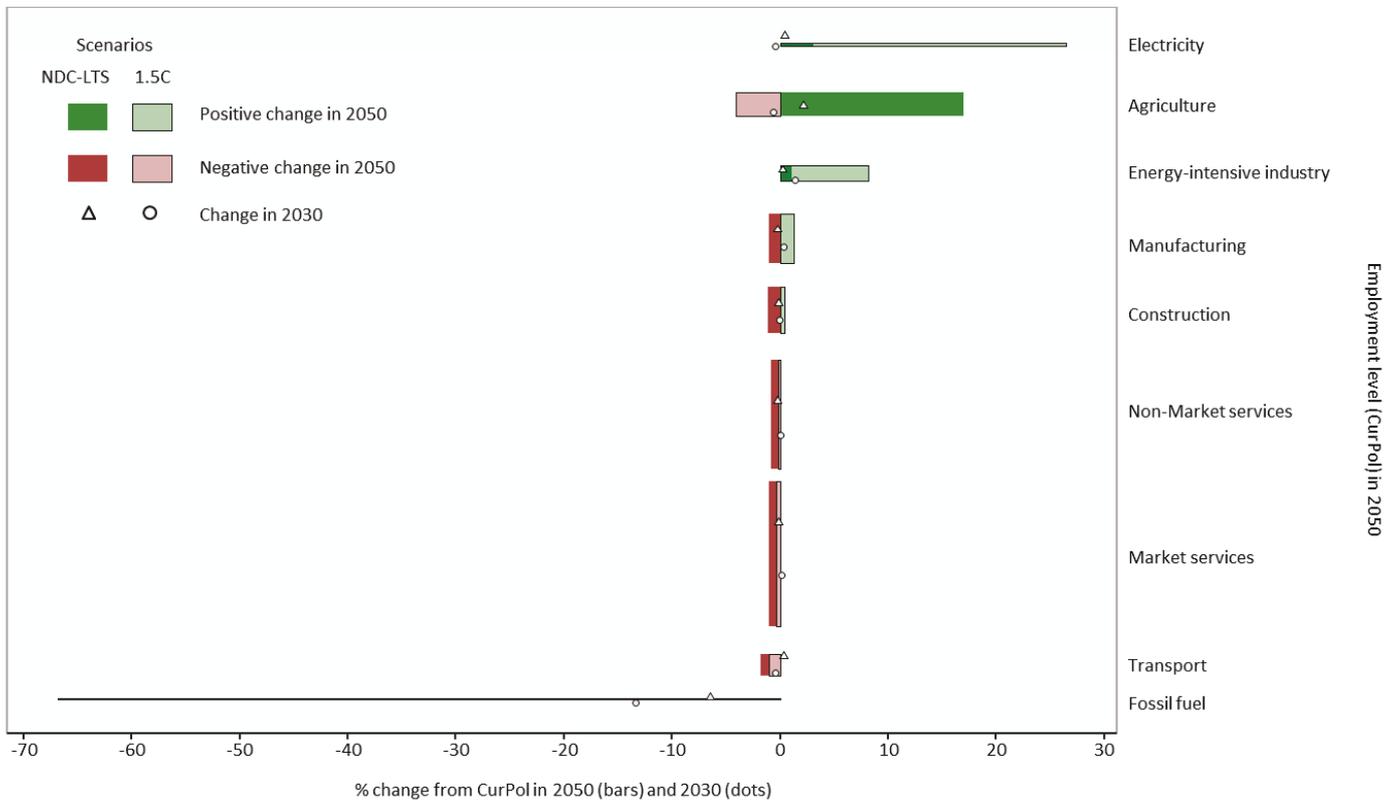
**Figure S6.** Asia – transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenario. Change in sectoral employment relative to the CurPol scenario (x-axis) and level of employment under the CurPol scenario in year 2050 (y-axis). The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.



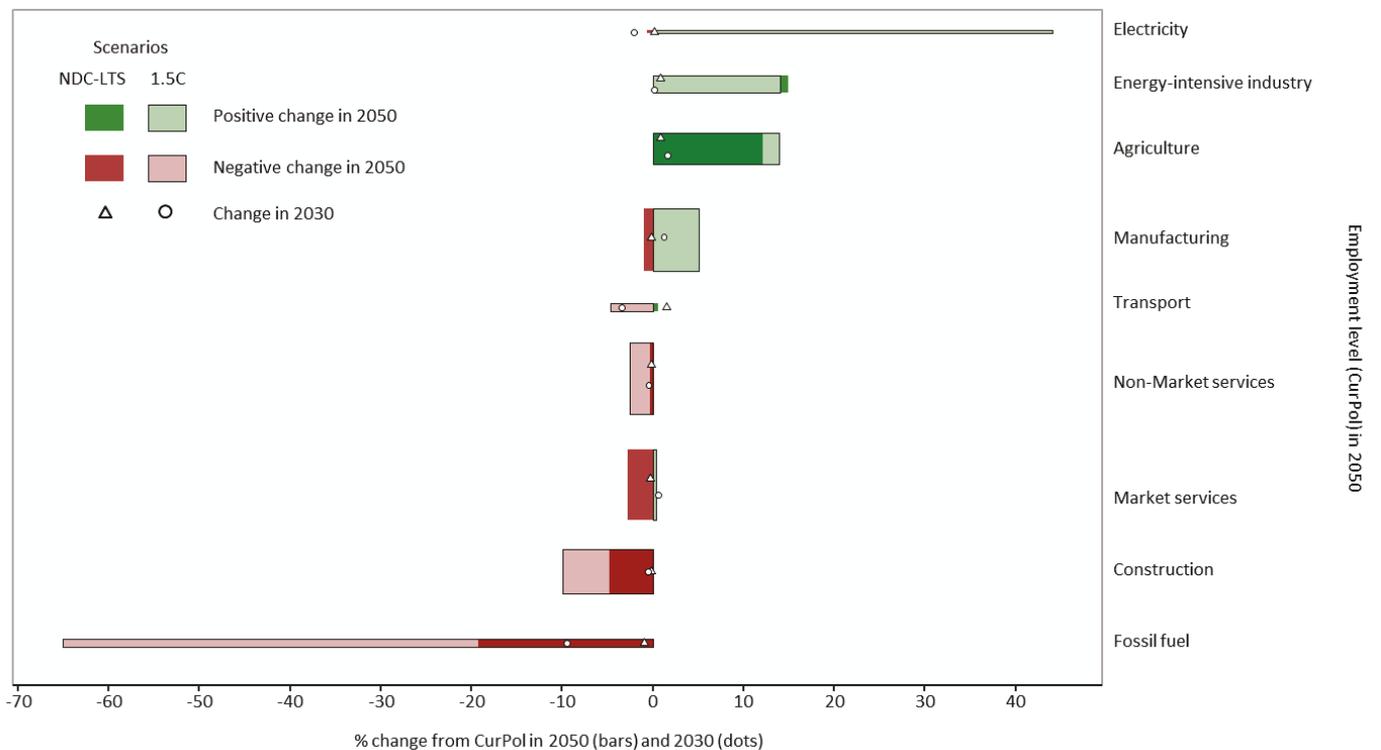
**Figure S7.** Eurasia – transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenario. Change in sectoral employment relative to the CurPol scenario (x-axis) and level of employment under the CurPol scenario in year 2050 (y-axis). The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.



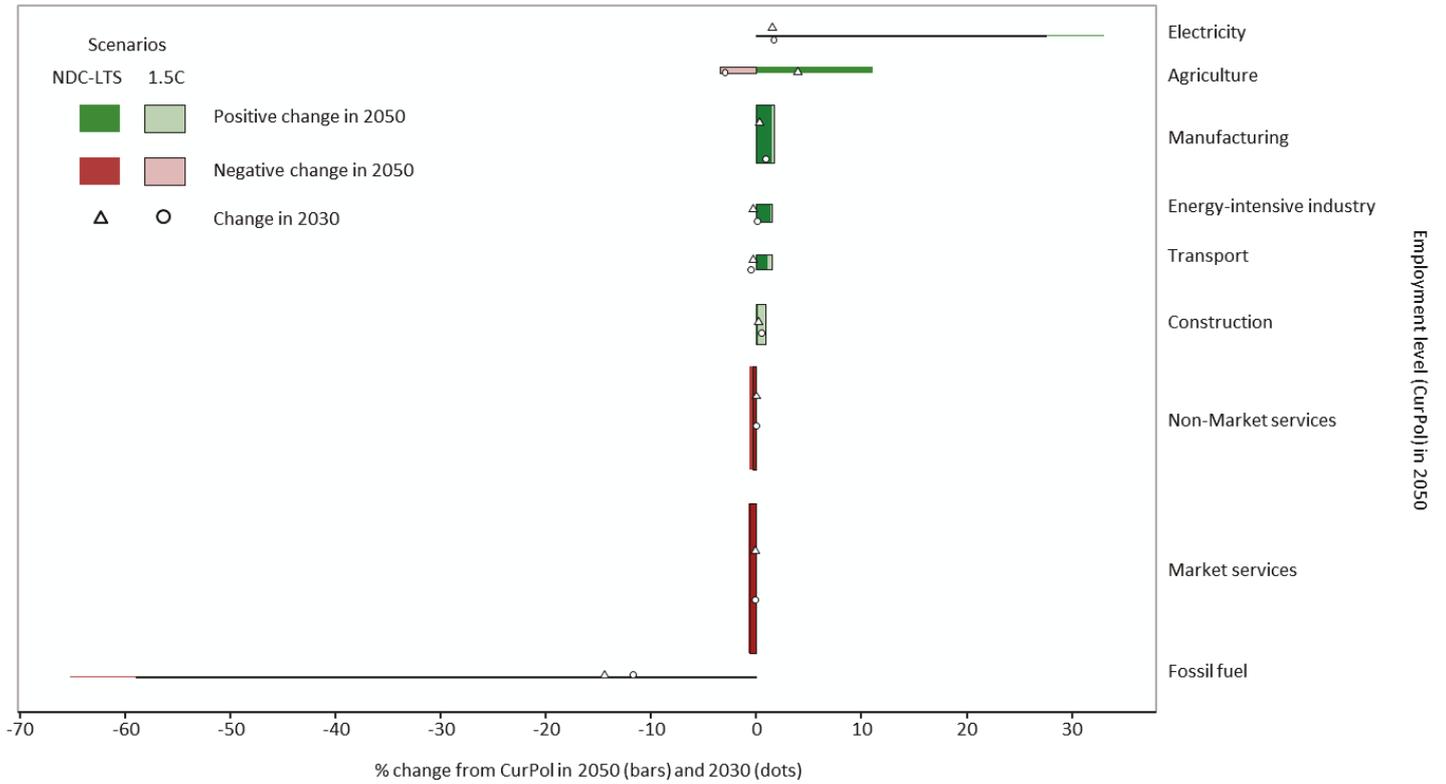
**Figure S8.** Europe (EU28 and EFTA countries) – transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenario. Change in sectoral employment relative to the CurPol scenario (x-axis) and level of employment under the CurPol scenario in year 2050 (y-axis). The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.



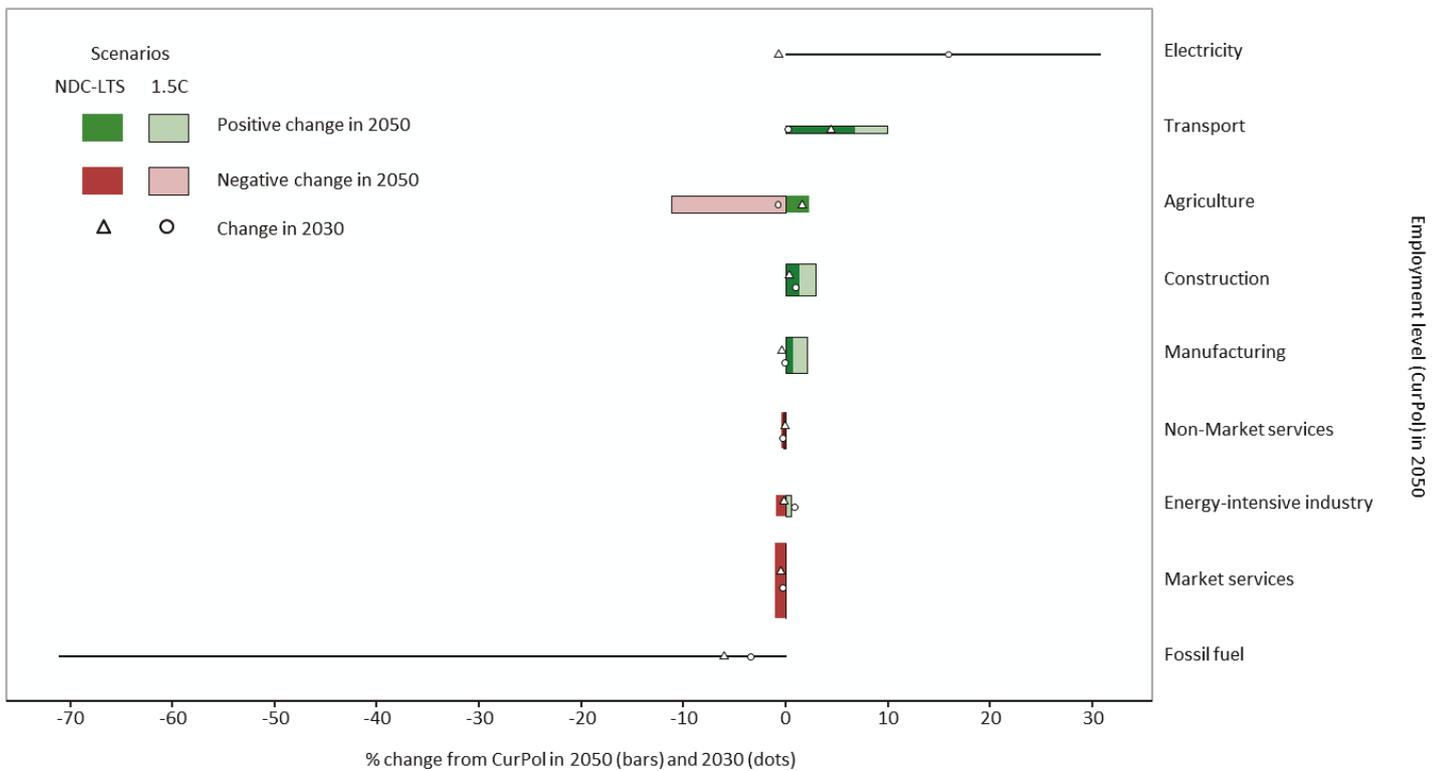
**Figure S9.** Latin America – transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenario. Change in sectoral employment relative to the CurPol scenario (x-axis) and level of employment under the CurPol scenario in year 2050 (y-axis). The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.



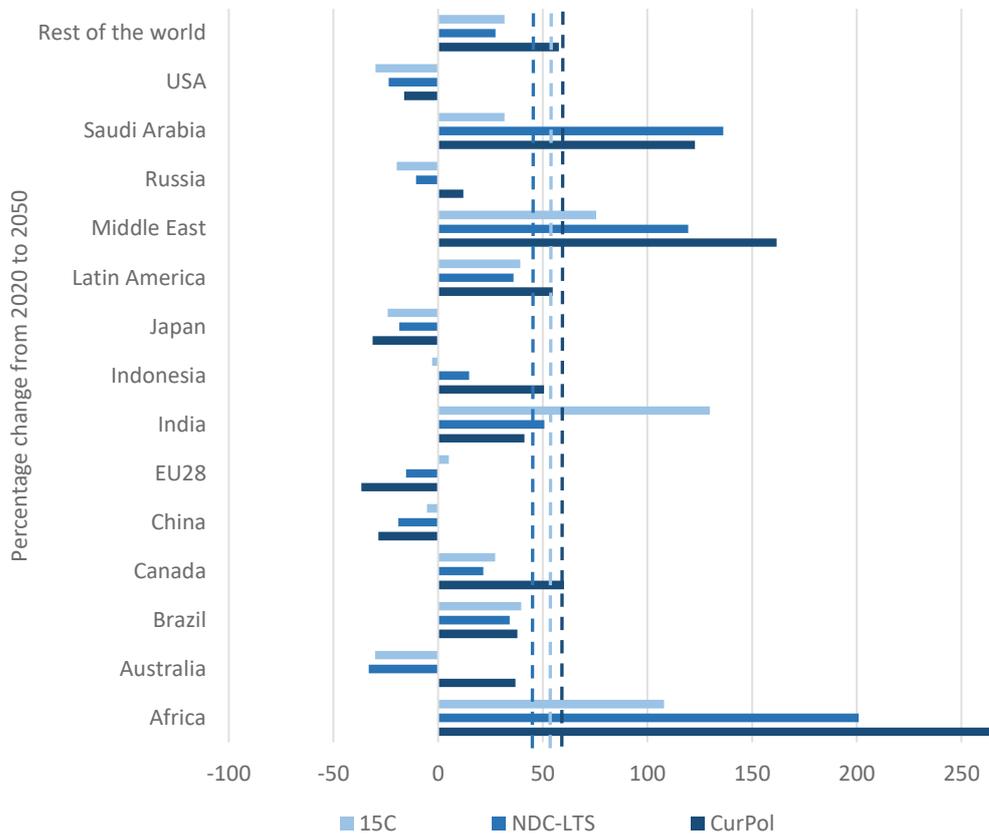
**Figure S10.** Middle East – transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenario. Change in sectoral employment relative to the CurPol scenario (x-axis) and level of employment under the CurPol scenario in year 2050 (y-axis). The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.



**Figure S11.** North America – transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenario. Change in sectoral employment relative to the CurPol scenario (x-axis) and level of employment under the CurPol scenario in year 2050 (y-axis). The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.



**Figure S12.** Oceania – transition of jobs by sector in 2030 and 2050 under the NDC-LTS and 1.5C scenario. Change in sectoral employment relative to the CurPol scenario (x-axis) and level of employment under the CurPol scenario in year 2050 (y-axis). The dots (triangle/circle) show the change in the NDC-LTS and 1.5C scenarios in 2030. The area of a bar corresponds to the volume of jobs subject to transition to/from a sector in 2050.



**Figure S13.** Regional and global changes in energy jobs from 2020 to 2050 under the CurPol, NDC-LTS and 1.5C scenarios. Dashed lines express the global change in each scenario. With the exception of 'Rest of the World', the regions are sorted alphabetically.

## Supplemental Tables

**Table S1.** Main data sources used in the simulations of the POLES-JRC model.

Series	Parameter	Historical data <sup>a</sup>
Other activity drivers	Value added	World Bank <sup>1</sup>
	Mobility, vehicles, households, tons of steel	Sectoral databases via Enerdata <sup>2</sup>
Energy resources	Oil, gas, coal	BGR <sup>3</sup> , USGS <sup>4</sup> , WEC <sup>5</sup> , Rystad <sup>6</sup> , sectoral information
	Uranium	IAEA <sup>7</sup>
	Biomass	GLOBIOM-G4M model <sup>8</sup>
	Hydro	Enerdata <sup>2</sup>
	Wind, solar	NREL <sup>9</sup> , DLR <sup>10</sup>
Energy balances	Reserves, production	BP <sup>11</sup> , Enerdata <sup>2</sup>
	Demand by sector and fuel, transformation (including power), losses	Enerdata <sup>2</sup> , IEA <sup>12</sup>
	Power plants	Enerdata <sup>2</sup> , Platts <sup>13</sup>
Energy prices	International prices, prices to consumer	Enerdata <sup>2</sup> , IEA <sup>12</sup>
GHG emissions	Energy CO2	Derived from POLES-JRC energy balances
	Other GHG Annex 1	UNFCCC <sup>14</sup>
	Other GHG Non-Annex 1 (excl. LULUCF)	EDGAR <sup>15</sup>
	LULUCF Non-Annex 1	UNFCCC national inventories <sup>14</sup> , FAO <sup>16</sup>
Air pollutants emissions		GAINS model <sup>17</sup> , EDGAR <sup>15</sup> , national sources
Technology costs		POLES-JRC learning curves based on literature, including but not limited to: EC JRC <sup>18-20</sup> , WEC <sup>5</sup> , IEA <sup>12</sup> , TECHPOL database <sup>21,22</sup>

<sup>a</sup> The POLES-JRC model further projects energy balances, including energy prices and technology costs, and energy-related CO<sub>2</sub> emissions. Other GHG emissions (including LULUCF emissions) are also projected in POLES-JRC based on exogenous data from GLOBIOM-G4M model (Other GHG Annex 1/Non-Annex 1 (excl. LULUCF), LULUCF Non-Annex 1).

**Table S2**

Global transition of jobs by sector in 2015, 2030 and 2050 under the CurPol, NDC-LTS and 1.5C scenarios. Total number of thousand jobs.

Scenario / Sector	CurPol			NDC-LTS		15C	
	2015	2030	2050	2030	2050	2030	2050
Agriculture	468,448	544,767	620,866	547,413	660,204	542,823	635,395
Fossil fuels	27,320	33,359	40,252	31,715	25,520	29,229	12,422
Electricity	32,724	37,592	43,403	38,728	51,333	40,514	58,558
Energy-intensive industry	217,750	217,013	211,811	217,356	213,560	217,998	215,715
Manufacturing	524,695	608,845	706,673	608,352	701,404	609,788	715,095
Construction	326,161	379,947	408,595	380,707	408,782	383,756	415,825
Transport	154,993	192,999	246,047	193,216	245,874	192,949	244,961
Market services	927,728	1,100,708	1,309,869	1,098,681	1,289,169	1,099,396	1,300,286
Non-Market services	501,251	590,371	703,516	589,435	695,188	589,148	692,775
<b>Total</b>	<b>3,181,070</b>	<b>3,705,601</b>	<b>4,291,033</b>	<b>3,705,601</b>	<b>4,291,033</b>	<b>3,705,601</b>	<b>4,291,033</b>

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### iii. Supplementary information on hydrogen demand and production modelling

#### Enhancements in this work

The POLES hydrogen production module already had a previously existing version [47], [99]. For this work, certain changes were implemented in the modelling:

- The statistics for hydrogen production were revised to include existing production capacities related to non-energy uses of hydrogen, as these capacities could also play a role in the production of hydrogen for energy uses.
- New technologies were added: gas pyrolysis; low-temperature electrolysis with nuclear; low-temperature electrolysis with solar PV.
- The CCS options were allowed to be retrofit on existing capacities (not just for new capacities).
- The electrolysis technology using electricity from the grid was set to use electricity that would otherwise have been curtailed.
- CCS options costs were revised to include electricity consumption related to running compressors and auxiliaries, of 120 kWh/tCO<sub>2</sub> captured (from IEA [185]).
- The electrolysis technologies with wind and PV had a cost component added for a buffer storage for hydrogen, in order to make the output comparable to other hydrogen production options, of 0.29 \$/kgH<sub>2</sub> (corresponding to a storage capacity of 2 days' needs for a DR-H2 steel plant, using hydrogen tank cost data from [186]).
- The existing parameters for process efficiency and overnight investment cost were updated to more recent values [23], [185]–[188].

#### Setup of Hydrogen demand parameters

Energy models typically include hydrogen only as an energy vector. However, in order to best assess the emissions reduction potential of hydrogen production, all uses of hydrogen have to be accounted for: projections of hydrogen demand will need to include the existing non-energy uses as well as new emerging energy uses that might become important in a low-carbon world.

Energy uses are included in the POLES model (see documentation [47]). They include: fuel cells (stationary electricity storage and combined heat and power; light and heavy vehicles); combustion (mix with natural gas in pipelines, for use in buildings and industry); input to synthetic fuels production (synthetic methane and synthetic liquids produced using hydrogen and CO<sub>2</sub> as raw inputs, for use in several transport modes).

The representation of new hydrogen uses in the POLES model is a modelling improvement in this work. New non-energy uses are detailed below; additional uses in steelmaking and cement production are detailed in the articles featured in sections 6.2 and 7.2.

The historical statistics for hydrogen demand by end-use in the following sections are derived from IEA [123].

## Fertilizers

Hydrogen (H<sub>2</sub>) is produced as an intermediary product for fertilizers, for use in agriculture. It is used in the production of ammonia (NH<sub>3</sub>, gaseous form, Haber-Bosch process, equation 1) which is then turned into ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>, solid, equation 2):

- 1)  $N_2 + 3H_2 \rightarrow 2NH_3$
- 2)  $NH_3 + HNO_3 \rightarrow NH_4NO_3$

Production of hydrogen for fertilizers is thus closely correlated with production of nitrogen-based fertilizers, as can be seen in Figure 34.

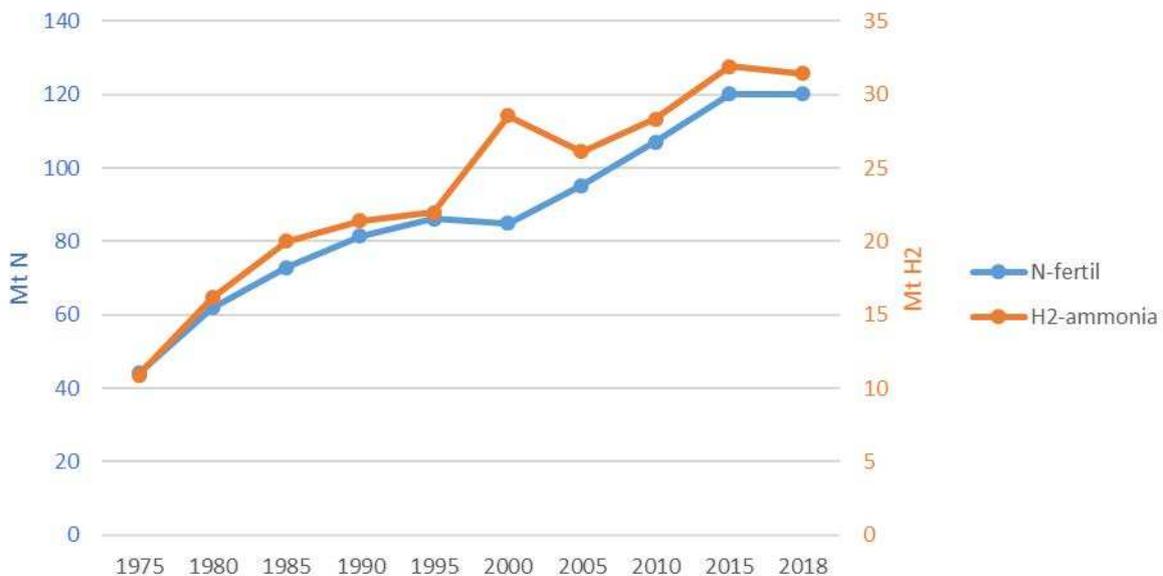


Figure 34: Production of nitrogen-based fertilizers (left axis) and production of hydrogen for ammonia (right axis)

Source: fertilizers from FAO [189], hydrogen from IEA [123].

Stoichiometrically, for each molecule of ammonium nitrate, 3/2 molecules of di-hydrogen are needed; the molecular mass of nitrogen is 14 g/mol and that of di-hydrogen is 2 g/mol. Hydrogen demand for fertilizers can be derived from N-fertilizer demand by multiplying with 3/14, in weight.

Projections of fertilizer demand are derived from a soft-coupling of the POLES model with the specialized land use model GLOBIOM-G4M, as described in [47]; the GLOBIOM-G4M data is from [125].

Fertilizer can be produced in a different country from its point of use. For simplification, fertilizer trade has not been considered in the modelling.

Ammonia has also been posited as a possible energy carrier itself, with combustion in substitution to methane gas [190]. This was not considered in the modelling.

### Oil refineries

Hydrogen is used in refineries in the conversion of crude oil into oil products that can be used by final users. In particular, hydrogen is used to lower the sulphur content of oil, in the production of diesel fuel; it is also used in the treatment of crude oil with high sulphur content, such as heavy oils [191].

Figure 35 displays the correlation between the global demand for diesel and the demand for hydrogen in refineries. A strong linear correlation can be derived ( $R^2=0.95$ ). The affine function of the correlation is used to derive hydrogen demand, using the diesel demand projections of the POLES model.

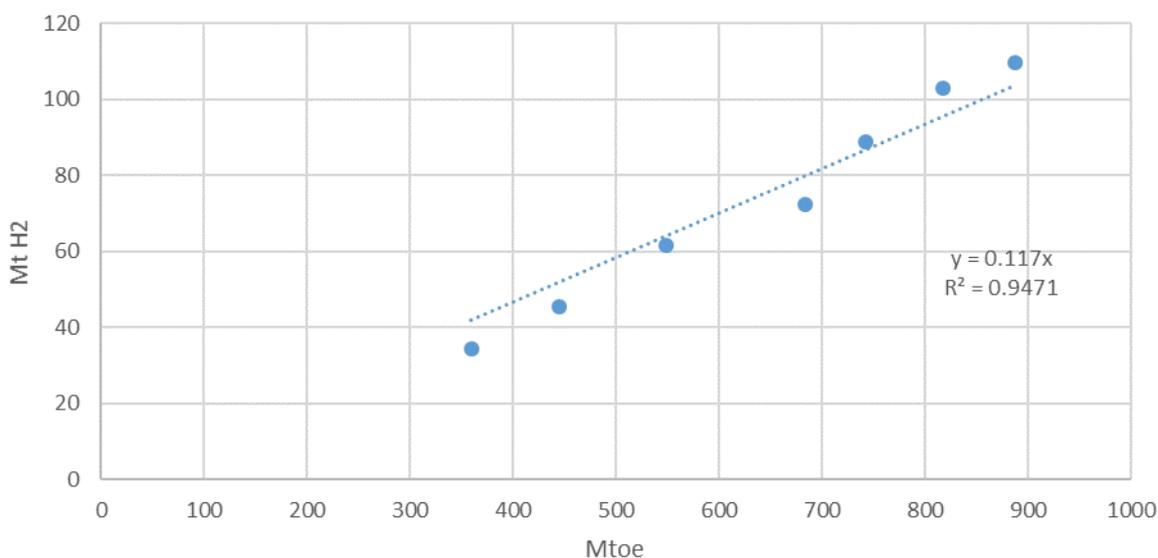


Figure 35: Correlation between hydrogen for refineries and demand for diesel, world

Sources: diesel from POLES (itself from IEA/Enerdata [192]), hydrogen from IEA [123].

Diesel can be produced in a different country from its point of use. For simplification, diesel trade has not been considered in the modelling.

### Other industries

A small share of hydrogen (5-6%) is used in other processes of the chemical industry. This hydrogen use shows a good correlation with the value added of the global chemical industry ( $R^2=0.96$ , Figure 36). This affine function is used to derive hydrogen demand, using the projections of chemical industry value added of the POLES model.

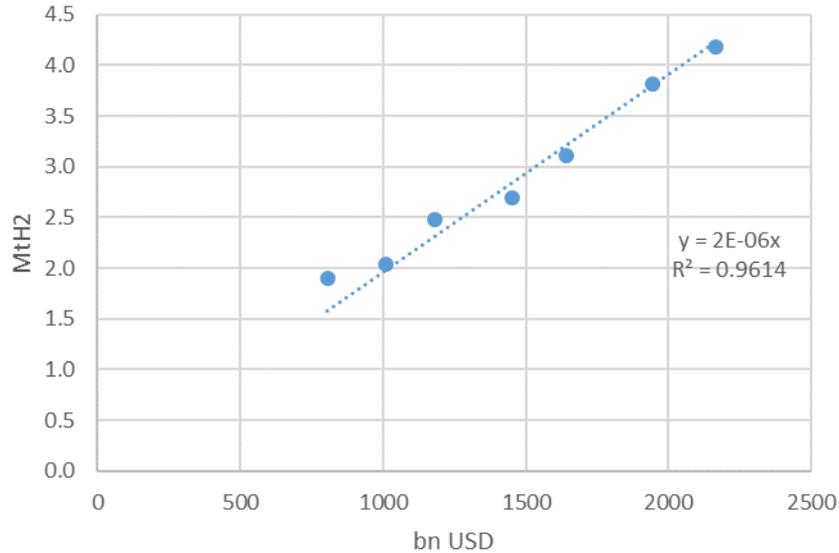


Figure 36: Correlation between hydrogen for refineries and chemical industry value added, world

Source: value added from World Bank [193], hydrogen from [123].

To this hydrogen demand is added the demand from the steel sector for the direct reduction process in the projections, as detailed in section 6.

### Setup of Hydrogen production parameters

The existing module for hydrogen production is described in the POLES documentation [47] and has been in existence since the “World Energy Technology Outlook – H2” study (2006) [99].

This work resulted in the following updates compared to the previously existing model version, in order to capture non-energy hydrogen demand sources and recent developments in hydrogen production technologies.

#### Production technologies

Several production processes, existing and emerging, are modelled, represented by their fixed investment costs, efficiency and cost of inputs. The hydrogen production technologies that were modelled were:

- steam methane reforming;
- coal and biomass gasification;
- gas and biomass pyrolysis;
- low- and high-temperature electrolysis powered by nuclear;
- low-temperature electrolysis powered by wind; by solar; and by the grid

The reforming and gasification technologies also have CCS options.

The existing techno-economic parameters [47], [99] were updated to more recent values [23], [185]–[188].

*Table 2: Hydrogen production processes efficiency (hydrogen output/energy inputs)*

	2015	2030	2050
Steam Methane Reforming	76%	76%	76%
Steam Methane Reforming +CCS	69%	69%	69%
Coal gasification	63%	63%	67%
Coal gasification +CCS	57%	57%	61%
Biomass gasification	50%	50%	53%
CCS premium	45%	45%	48%
Gas pyrolysis	39%	44%	46%
Biomass pyrolysis	39%	44%	46%
Electrolyser (low-temperature)	62%	67%	73%
Electrolyser (high-temperature)	78%	81%	84%

*Table 3: Overnight investment costs for hydrogen production processes (USD/kW)*

	2015	2030	2050
Steam Methane Reforming	880	880	880
Coal gasification	1280	1130	1070
Biomass gasification	1550	1320	1250
CCS premium	880	440	360
Gas pyrolysis	880	710	670
Biomass pyrolysis	880	710	670
Electrolyser (low-temperature), pessimistic	1290	820	480
Electrolyser (low-temperature), optimistic	1290	135	98
Electrolyser (high-temperature)	4340	1740	730

An example of results in the projections is provided in Figure 22 in section 5.2.2 on hydrogen production.

#### *Initialization with historical statistics*

Currently, the production of hydrogen is dominated by steam methane reforming (SMR) and, in some markets (especially China), coal gasification [194]. Existing hydrogen production capacities are mostly integrated with the associated processes the hydrogen is used for, with little hydrogen being actually marketed and transported across sites [191]. No dataset on detailed processes mix per country for hydrogen production was found; the analysis was mainly based on the global numbers from IEA [194].

In energy balances such as those of the IEA, the energy inputs hydrogen production typically appear in the non-energy uses of energy fuels. They are classified together with the inputs in plastics and rubber production, which typically use oil and gas. Additionally, in emissions balances such as those of UNFCCC, CO<sub>2</sub> emissions from hydrogen production are included in the non-energy combustion emissions of industrial processes.

Starting from the energy statistics of POLES (itself from IEA/Enerdata) for non-energy uses and the hydrogen demand (from the above section 0), a database for energy inputs to hydrogen production by country/region was set up. Non-energy coal use was considered to be coming from coal gasification in hydrogen production<sup>28</sup>; the rest of hydrogen production is considered to make use of natural gas steam reforming.

The existing hydrogen module of POLES was initialized with this dataset, singling out energy statistics (and associated emissions) for hydrogen production from other non-energy uses and process emissions. A comparison between IEA [194] and the enhanced POLES model is provided in Table 4.

*Table 4: Key figures on hydrogen production*

2018	H <sub>2</sub> production	Gas	Coal	Emissions
<b>IEA</b>	70 Mt	205 bcm, 76%	107 Mt, 23%	830 MtCO <sub>2</sub>
<b>POLES</b>	72 Mt	230 bcm, 83%	67 Mt, 17%	734 MtCO <sub>2</sub>

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<sup>28</sup> Non-energy use of coal in China amounted to 96% of world non-energy coal use in 2015, and China is where the essential part of coal gasification for hydrogen is situated.

iv. Supplementary information to article 2: Opportunities and roadblocks in the decarbonisation of the global steel sector: a demand and production modelling approach

# Opportunities and roadblocks in the decarbonisation of the global steel sector: a demand and production modelling approach

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## Supplementary Information

### Contents

1. Scenario assumptions .....	176
2. Specific material consumption assumptions.....	177
<b>2.1. Buildings</b> .....	177
<b>2.2. Road transport</b> .....	178
<b>2.3. Power sector</b> .....	178
3. Parameters for sectoral material demand drivers .....	179
3.1. Buildings .....	179
3.2. Road transport.....	180
3.3. Power sector .....	180
3.4. Steel scrap availability for recycling .....	180
4. Steel production processes.....	181
4.1. Sector perimeter and processes.....	181
4.2. Techno-economic parameters.....	182
4.3. Energy and emissions balances.....	185
5. Sensitivity analyses .....	185
6. Comparison with previous POLES modelling .....	188
Supplementary References.....	191

# 1. SCENARIO ASSUMPTIONS

The main data sources used by POLES are summarized in Table S1.

Table S1: POLES-JRC model historical data and projections

Series		Historical data	Projections
<b>Population</b>		Joint Research Centre[1], Eurostat[2]	
<b>GDP, growth</b>		World Bank[3], IMF[4]	European Commission[5], OECD[6],[7]
<b>Other activity drivers</b>	Value added	World Bank[8]	POLES model
	Mobility, vehicles, households, tons of steel, ...	Sectoral databases via Enerdata[9]	
<b>Energy resources</b>	Oil, gas, coal	BGR[10], USGS[11], WEC[12], Rystad[13], sectoral information	
	Uranium	IAEA[14]	
	Biomass	GLOBIOM-G4M model[15]	
	Hydro	Sectoral databases via Enerdata[9]	
	Wind, solar	NREL[16] and DLR[17]	
<b>Energy balances</b>	Reserves, production	BP[18], Enerdata[9]	
	Demand by sector and fuel, transformation (including. power), losses	Enerdata[9], IEA[19]	
	Power plants	Enerdata[9], Platts[20]	
<b>Energy prices</b>	International prices, prices to consumer	Enerdata[9], IEA[19]	POLES model
<b>GHG emissions</b>	Energy CO <sub>2</sub>	Derived from POLES energy balances	POLES model
	Other GHG Annex 1	UNFCCC[21]	POLES model, GLOBIOM-G4M model
	Other GHG Non-Annex 1 (excl. LULUCF)	EDGAR [22]	POLES model, GLOBIOM-G4M model
	LULUCF Non-Annex 1	UNFCCC national inventories[21], FAO[23]	POLES model, GLOBIOM-G4M model
<b>Air pollutants emissions</b>		GAINS model[24], EDGAR[22], national sources	GAINS model, national sources
<b>Technology costs</b>		Learning curves based on literature, including but not limited to: JRC, WEC, IEA, TECHPOL database	

Monetary values provided as results are in constant United States dollars of 2015.

## 2. SPECIFIC MATERIAL CONSUMPTION ASSUMPTIONS

### 2.1. Buildings

Specific material consumption assumptions for buildings were adapted from [25] for residential buildings and [26] for commercial buildings. Values are kept constant in the projections.

*Table S2: Specific steel use coefficients for buildings by region*

Type	Region	kg/m <sup>2</sup>
<b>Residential</b>	Canada	48
	USA	24
	Mexico	66
	Rest of Central America	66
	Brazil	62
	Argentina, Chile, Rest of South America	59
	Egypt, Morocco & Tunisia, Algeria & Libya	66
	South Africa	68
	Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom	72
	Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia, Rest of Western Balkans	70
	Turkey	43
	Ukraine	66
	Rest of Commonwealth of Independent States	66
	Russia	66
	Iran, Saudi Arabia, Rest of Persian Gulf, Mediterranean Middle East	130
	India	53
	South Korea	52
	China	141
	Malaysia, Thailand, Vietnam, Rest of South East Asia	55
	Indonesia	64
	Japan	119
	Australia, New Zealand, Rest of Pacific	51
	Rest of South Asia	70
Rest of Sub-Saharan Africa	67	
<b>Commercial</b>	World	95

The above applies to new floor surfaces. We include a specific steel demand per floor area of renovated surface, defined as 20% of the specific steel demand for the region's new buildings (own assumption).

## 2.2. Road transport

Specific steel demand per vehicle was defined it as 900 kg for private cars, 1800 kg for vans and 9000 kg for heavy duty vehicles (trucks and busses) per vehicle from [27], [28], kept constant.

## 2.3. Power sector

Specific material consumption assumptions for the power sector are presented in Table S3. The sources used were: [29], [30], [31], [32].

*Table S3: Specific steel use coefficients by power production technology*

Power technology	Kg steel/kW
Coal - lignite	376
Coal - conventional	376
Coal - advanced	376
Coal - advanced + CCS	391
Coal - gasification	376
Coal - gasification + CCS	391
Oil - conventional	376
Oil - gas turbine	376
Gas - conventional	113
Gas - gas turbine	113
Gas - combined cycle	113
Gas - combined cycle + CCS	123
Biomass - conventional	98
Biomass - gasification	98
Biomass - gasification + CCS	102
Hydro - run-of-river	175
Hydro - dam	175
Hydro - small	175
Nuclear - Gen III	39
Nuclear - Gen IV	39
Wind - onshore	123
Wind - offshore	499
Solar - CSP	556
Solar - PV plant	68
Solar - PV small	68
Geothermal	592

<b>Ocean</b>	465
<b>Small CHP</b>	376
<b>Fuel cell - gas</b>	70
<b>Fuel cell - hydrogen</b>	70
<b>Hydro - pumped storage</b>	175

These values were applied to all world regions and were kept constant.

For power transport and distribution grid, specific steel consumption was derived indirectly, using the estimated steel in the existing grid of the UK [33] and divided by the total amount of electricity transiting through that grid in a year, resulting in 1018 kg/GWh. This is applied to all regions and kept constant.

### **3. PARAMETERS FOR SECTORAL MATERIAL DEMAND DRIVERS**

A number of equations calculate the energy services and energy-consuming equipment that are used as a basis for materials demand.

#### **3.1. Buildings**

##### **Surface of residential**

Historical residential floor surfaces were adapted from [26], [34]; historical commercial floor surfaces were collected from the literature [35]–[37].

Residential floor surfaces are calculated with occupancy size (capita per household) and surface size (surface per household) and renewal rate.

##### **Surface per household**

Using regression analysis on historical data, the surface per household is projected with a correlation with per capita income; it is also indexed to the region's population density and the share of the population living in urban areas.

##### **Size of household**

Using regression analysis on historical data, the number of capita per household is projected with a correlation to per capita income.

##### **Buildings: informal and formal housing**

A large part of households in poor areas of the world are constituted of informal housing (“slums”) which disappear with economic development and growing living standards. Informal housing tends to use various materials, usually natural materials and re-used materials, such as mud, straw, wood, plastic or corrugated metals (tin, aluminium, steel). Formal housing will use modern industrial materials such as steel, cement and glass. In order to better estimate the demand for steel and cement, the share of informal/formal housing was estimated.

Data India (housing census distribution by material of wall[38]) and Russia (EBRD report[39]) was used. A 100% formal construction was assumed for a per capita income of 15,000 USD. The resulting polynomial correlation of share of informal housing with per capita income was used in the projections.

**Surfaces in services:** Commercial floor surfaces are calculated with the number of employees in services (active population and share of commercial value added in GDP) and a per employee surface level (correlated with average income). A literature search for total surfaces of services together with the macroeconomic indicators from World Bank[8] yielded an estimation for the surface per employee.

Data for India[40], China[41] and USA[42] was used to establish a polynomial correlation between the surface per employee and income per capita.

Although future automation might change the number of employees needed to be active, the surfaces themselves would still be needed to a great extent (e.g. warehouses, workshops, retail, hotels, restaurants).

### **Buildings: scrapping and renovation rates**

Buildings' scrapping rate is determined by their lifetime. All buildings are considered to have a 70 years lifetime, taking a global average from[26], [43].

Buildings' renovation rate (reflecting efforts to increase building shell insulation and reduce energy consumption for space heating and cooling) is set at 1-2.5%/year, depending on the region's per capita income, with richer regions having lower rates. The renovation rate is accelerated by the implementation of climate policy, up to a maximum of 3%/year for a duration of 5 years if the carbon price exceeds 150 \$/tCO<sub>2</sub>; after which, the renovation rate decreases progressively to its default value.

## **3.2. Road transport**

Vehicle needs for passenger and goods are calculated on the basis of utilization (distance travelled, depending on energy prices and income), ownership ratios (depending on income) and equipment lifetime.

Historical fleet and usage data was provided by[9]. All vehicles are considered to have the average lifetime of the USA fleet, 12 and 15 years for light and heavy duty, respectively[44].

## **3.3. Power sector**

POLES includes 35 technologies for power production and electricity storage. See POLES description above and in [45], [46].

## **3.4. Steel scrap availability for recycling**

The modelling distinguishes new scrap and old scrap.

New scrap is generated as residues from steel production itself. It is considered that each year, new scrap amounting to 10% of steel production is generated. It is available as input to new production the next year.

Old scrap is generated from retired equipment. At the end of its lifetime, the retired equipment releases steel scrap. 10% is considered to be technically unrecoverable. Out of the remaining recoverable scrap, it is considered that 90% is recovered for recycling, as the steel scrap recycling industry is already very developed[47].

A lifetime of equipment is associated to each of the end-uses, as per Table S4, also mentioned above.

*Table S4: Assumptions on lifetimes of equipment using steel*

End-use	Equipment	Lifetime (years)
Buildings	New buildings (renovation does not change the building's age)	70
Road transport	Light duty vehicles (passenger cars, vans)	12
Road transport	Heavy duty vehicles (busses, trucks)	15
Power sector	Power generation technologies	25-70 (depending on the technology)
Infrastructure and other	Machinery	15
Infrastructure and other	Other	70

Furthermore, the “Infrastructure and other” category is a diverse category, encompassing equipment that might have longer lifetimes (public works, roads, rail network, oil and gas and mining extractive industries, maritime vessels) and other equipment with comparatively shorter lifetimes (machinery parts, other transport vehicles, containers, packaging, domestic appliances, other uses). Given the importance of this category in overall steel demand (52% in 2015), an attempt was made to distribute it across two sub-types with different lifetimes: a “machinery” part that has the same lifetime as heavy-duty vehicles and an “other” part that has the same lifetime as buildings. The distribution was made such as to recreate the total steel scrap available for recycling over 2000-2021[47]: this resulted in two thirds of the category classified as “machinery” and one third as “other”.

## 4. STEEL PRODUCTION PROCESSES

### 4.1. Sector perimeter and processes

The iron and steel sector as modelled covers the process steps of sintering, pelletizing, iron reduction, steelmaking and steel finishing (casting, rolling).

Iron ore mining and the transformation of energy fuels and other materials into the feedstock used by the processes are not included in the iron and steel sector: electricity production, coke ovens, hydrogen production, iron electrolysis consumables (e.g., sodium hydroxide solution), carbon capture consumables (e.g., amine solvent, membranes).

The transformation of finished steel products into parts used in finished products (e.g., machinery, automotive parts, rods for reinforced concrete) is not included in the iron and steel sector.

Trade of finished steel products and recuperated scrap is allowed; however, there is no trade of intermediate products (briquettes).

The following processes were modelled (with ULCOS project equivalents[48], where applicable):

- BF-BOF: blast furnace and basic oxygen furnace combination;
- Smelt: refers to the direct smelting process with a reduction reactor and a basic oxygen furnace (HIsarna)
- DRI: direct reduction furnace and electric arc furnace combination (using as input natural gas, NG, or hydrogen, H<sub>2</sub>) (ULCORED)
- EAF: electric arc furnace
- E-winn: low-temperature electrolysis (ULCOWIN, SIDERWIN[49])
- BF-BOF, Smelt and DRI-NG processes with carbon capture (CCS)

#### 4.2. Techno-economic parameters

The assumptions for specific energy consumption and overnight investment costs by steel production process are presented in Table S5 and Table S6. The sources used were [50]–[59].

Energy demand is split into non-electric fuels and electricity, across all stages of the steel production process (sintering, pelletizing, iron reduction, steelmaking, steel finishing). In the case of EAF and E-winn, a certain amount of non-electric fuels is required for the steps before and after the furnace; the electrification potential of these steps was not assessed.

Table S5: Specific energy consumption (GJ/t steel), by steel production process

	Non-electric fuels (GJ/t steel)			Electricity (GJ/t steel)		
	2015	2030	2050	2015	2030	2050
<b>BF-BOF</b>	16.68	15.57	15.00	1.37	1.37	0.80
<b>BF-BOF+CCS</b>	16.68	15.57	15.00	4.11	4.11	3.54
<b>Smelt</b>	13.19	13.19	13.19	1.52	1.52	1.52
<b>Smelt+CCS</b>	13.19	13.19	13.19	4.71	4.13	4.13
<b>DRI-NG</b>	12.81	12.81	12.81	3.33	3.32	3.32
<b>DRI-H<sub>2</sub></b>	11.04	11.04	11.04	3.08	3.07	3.07
<b>DRI+CCS</b>	12.81	12.81	12.81	3.74	3.73	3.73
<b>EAF</b>	2.43	2.32	2.32	3.11	2.49	2.49
<b>E-winn</b>	1.61	1.61	1.61	11.87	11.87	11.87

CCS technologies consist in capturing emissions from the reactor. As modelled, CCS technologies include a fixed CO<sub>2</sub> capture rate that is applied to emissions from the entire process, from[57], [60], [61]:

- BF-BOF: 65% (sorption enhanced water gas shift (SEWGS) and compression); corresponds to post-combustion capture from multiple flue gas sources, as described in the ULCOS BF-BOF with CCS process
- DRI: 55% (vacuum pressure swing absorption (VPSA) and compression); corresponds to 93% capture rate at the reactor, as described in the ULCOS ULCORED process

- Smelt: 80% (cryogenic distillation and compression); corresponds to 100% capture rate at the reactor, as described in the ULCOS HIsarna with CCS process

In the projections, costs decrease with an elasticity to cumulated installed capacity (elasticity of -0.05) to reflect a learning-by-doing effect. The 2050 values presented in Table S6 represent the lower-end floor values reached with the maximum learning; actual scenario values differ, depending on their respective deployment realized.

*Table S6: Overnight investment costs for steelmaking processes (USD/t steel)*

Process	2015	2050
<b>BF-BOF</b>	1180	1000
<b>BF-BOF+CCS</b>	1380	1170
<b>Smelt</b>	1160	980
<b>Smelt+CCS</b>	1360	1150
<b>DRI-NG</b>	920	770
<b>DRI-H2</b>	1200	1010
<b>DRI+CCS</b>	1080	910
<b>EAF</b>	370	320
<b>E-winn, pessimistic</b>	1090	920
<b>E-winn, optimistic</b>	730	620

The CCS premium of 17% on top of the equivalent technology without CCS from [50] is probably a conservative estimate. While [53] assumed a 1%-9% premium, more recent studies for CCS applied to power production technologies point to significantly higher numbers: 75% for sub-critical coal post-combustion; 37% for pre-combustion in integrated coal gasification; 91% for oxy-combustion [62].

Retrofitting is set to cost a percentage of the overnight investment cost of the destination technology. The relative costs of the allowed retrofitting options, taken from [63], are presented in Table S7.

Table S7: Retrofitting costs as a share of overnight investment costs

Process from i to j	Cost share of j
<b>BF-BOF to BF-BOF+CCS</b>	0.40
<b>Smelt to Smelt+CCS</b>	0.40
<b>DR-NG to DR-NG+CCS</b>	0.40

Overnight investments were annualized using an 8% discount rate and a 35 years equipment lifetime (own assumptions). In the 1.5°C scenarios, the lifetime was gradually reduced to 23 years by 2030 and onwards to reflect increased pressure to renew the stock towards more low-carbon processes. The steel sector presents the possibility to replace part of the equipment when relining furnaces, which is typically done every 20-25 years instead of more in-depth overhauls every 35-40 years. This scheduling aligns well with the assumption to shorten the lifetime in the 1.5°C scenarios.

A fixed operation and maintenance cost is added to the investment cost (annualized), amounting to 5% of the overnight investment cost (own assumption).

Each process consumes a fixed amount of iron ore and steel scrap[50], [53], [63], as shown in Table S8.

Table S8: Iron ore and steel scrap inputs in steelmaking processes (t/t steel)

Process	Iron ore	Steel scrap
<b>BF-BOF</b>	1.41	0.14
<b>BF-BOF+CCS</b>	1.44	0.14
<b>Smelt</b>	1.33	0.18
<b>Smelt+CCS</b>	1.33	0.18
<b>DRI-NG &amp; DRI-H2</b>	1.36	0.18
<b>DRI+CCS</b>	1.36	0.18
<b>EAF</b>	0	1.12
<b>E-winn</b>	1.17	0.26

The fixed costs are combined with operational costs to obtain total production costs per ton of steel produced. Operational costs are endogenously produced in the model and are dependent on the scenario, region and year. They are determined by the functioning of the energy markets and energy transformation sectors of the rest of the model, as well as international transport costs (see model description above). An example of total production costs breakdown is provided in Table S9.

Table S9: Example of steel production cost breakdown for USA, BF-BOF, 15C\_CCS scenario

\$/t steel	2020	2030
<b>Fixed costs</b>	166	162
<b>Iron ore</b>	339	315
<b>Scrap</b>	27	52
<b>Energy inputs: electricity</b>	24	68
<b>Energy inputs: coal &amp; coke</b>	60	28
<b>CO2 price on coal &amp; coke</b>	0	216
<b>Slag sales (revenue)</b>	-1	-1
<b>Total</b>	614	839

### 4.3. Energy and emissions balances

The iron and steel sector includes the energy needed to transform iron ore into intermediate steel products (e.g. hot-rolled steel). It does not include energy used in the iron ore mining, nor the energy used in the conversion of intermediate products into final products (e.g. vehicle parts). Coke ovens energy demand was not accounted in the iron and steel sector but in the energy transformation sector, as per IEA energy balances.

Emissions for iron and steel, separated into energy combustion and processes, were collected from the UNFCCC national inventories[21], where available. This was compared to the energy balances for the iron and steel sector from Enerdata/IEA[9] in order to estimate the distribution of carbon across emissions from energy combustion, emissions from process and absorptions in the blast furnace process.

A share of carbon from coal and coking coal was considered to be absorbed in the steel product, amounting to 1% of steel by weight (average value from ASTM International standards[64]).

A steam coal and coking coal emissions index was created with the above data, distributing the carbon across energy and process emissions. If no inventory data was available, the index was set as 30% assigned to energy emissions (based on average value of countries with inventory data), with the rest assigned to process emissions. If inventory data was in conflict with energy data (i.e., if total inventory emissions exceeded the estimation of available carbon from the energy statistics), process emissions were capped to the level of available carbon. This index was kept constant in projections.

## 5. SENSITIVITY ANALYSES

A sensitivity analysis was conducted on certain select parameters in order to assess the robustness and pertinence of the results.

The findings are presented in Figure S1. The default case was the 15C\_CCS scenario. The analysis was done by changing the parameters +/-25%: carbon price (S-shaped curve, see section 5); the overnight investment cost of the three DRI technologies (see SI section 6.2);

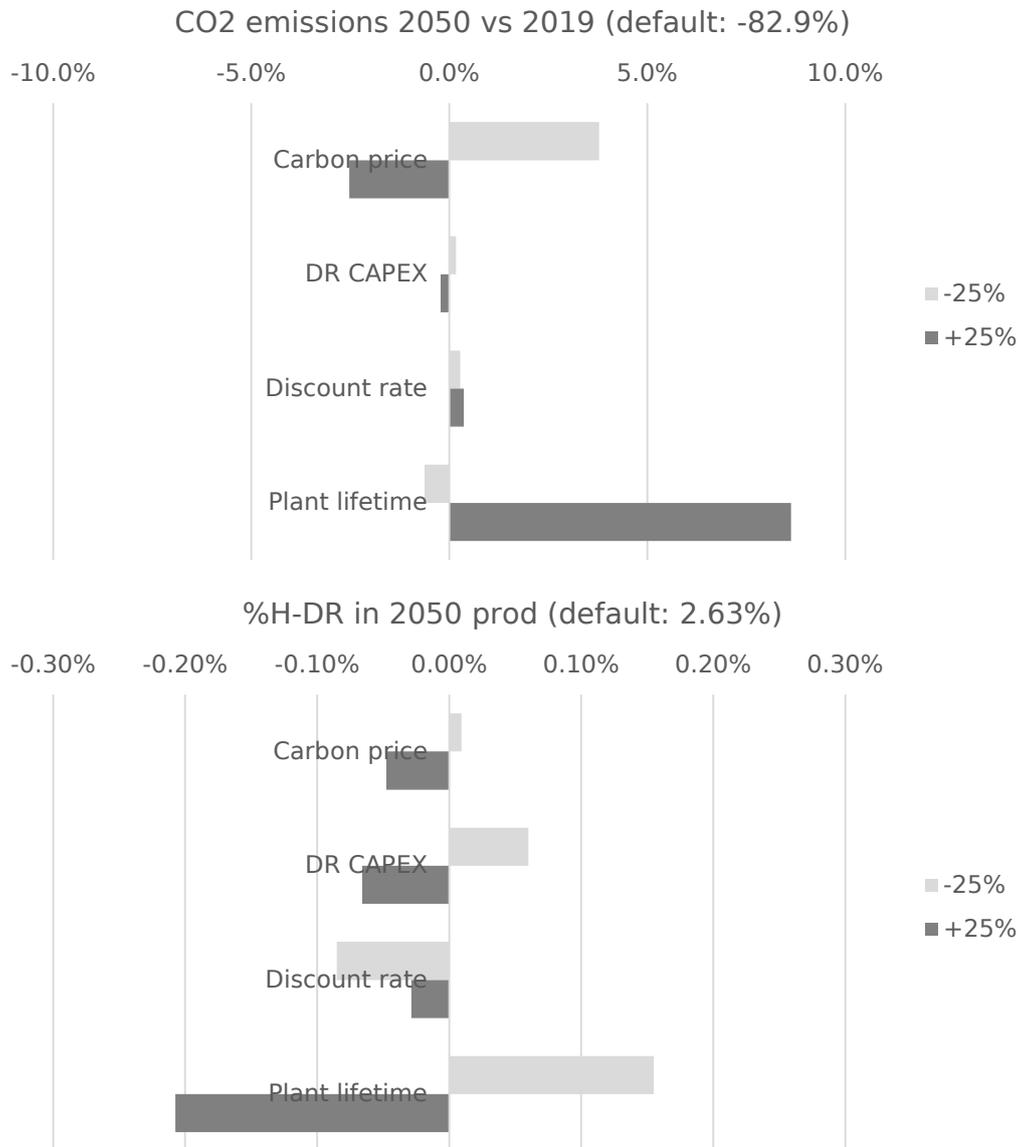
the discount rate used to amortize fixed costs (8% default value); and the steel plant lifetime (23 years from 2030 default value, see SI section 6.2). The values displayed represent deviations from the default value of the 15C\_CCS in 2050.

We find a strong dependence of CO<sub>2</sub> emissions on the carbon price and plant lifetime. CO<sub>2</sub> emissions are largely driven by how the carbon price changes the competitiveness of low-carbon technologies. A longer lifetime would render the renewal of the plants stock slower, resulting in more plants with unabated emissions being operational for a longer period of time.

The share of steel production with hydrogen direct reduction is found to be dependent on all four factors. Costlier CAPEX and longer plant lifetimes would reduce the amount of DRI-H<sub>2</sub> capacities installed. The carbon price impacts DRI-H<sub>2</sub> competitiveness in several ways, either in the total cost comparison with other steelmaking processes or via the technology choices in the production of hydrogen and electricity. However, the changes in the resulting share are relatively minor in this sensitivity analysis; differences are larger between the 15C\_CCS and 15C\_Elec scenarios (electrolyser cost, delay in CCS availability).

In addition, the comparison between 15C\_CCS and 15C\_Elec provides a sense of the importance of CCS availability for emissions mitigation. In 2050, 15C\_Elec emissions are 9% higher than 15C\_CCS emissions. Although they differ on more than just the timing of CCS availability (no CCS in 15C\_Elec until 2050; see main text Table 1), the differences in emissions in 2050 are to a large extent due to that single factor.

Figure S1: Sensitivity analysis from the 15C\_CCS default on four parameters testing global steel sector emissions (top) and the share of DRI-H2 in global steel production (bottom)



Furthermore, an additional important factor in inter-process competition is the CCS technologies capture rate. CCS can be applied to the reactor for the direct reduction and smelting reduction processes, where most emissions come from, achieving high capture rates. For the BF-BOF process, flue gases emerge from multiple sources. Various methods have been proposed to implement carbon capture; estimates for capture rates (considering not just at the furnace but for the entire process) range from 47% to 65% [57], [60], [65]. Differences arise from the perimeter of application (which process steps are considered for flue gases treatment for capture) and from the depth of equipment changes needed (top-gas recycling, oxygen-blown blast furnace). Correspondingly, the complexity and cost to implement these solutions on existing or new plants will be different.

For this work, the higher rate of 65% was chosen, so as to achieve the highest mitigation possible. Even so, the resulting emissions per tonne of steel produced (using coal and coke) are still the highest among steel processes with CCS, which would act as a driver to pursue

processes with higher mitigation rates [66]. CCS solutions with BF-BOF might attract fewer investments and thus lower capture rates might be achieved.

In order to assess the effect of different assumptions on BF-BOF CCS capture rates, we created a variant scenario of the 15C\_CCS scenario (capture rate: 65%) with a different capture rate for BF-BOF+CCS (15C\_CCS\_v2; capture rate: 50%, as per Case 2A in [65]). Key results are presented in Table S10.

*Table S10: Process market share and total steel sector emissions from a sensitivity analysis on BF-BOF+CCS capture rate*

	15C_CCS	15C_CCS_v2	difference
<b>BF/BOF</b>	1.5%	1.7%	0.3%
<b>BF/BOF+CCS</b>	13.4%	10.4%	-3.0%
<b>Smelt</b>	4.9%	5.1%	0.2%
<b>Smelt+CCS</b>	10.1%	10.7%	0.7%
<b>DR-NG</b>	4.6%	4.7%	0.1%
<b>DR-NG+CCS</b>	8.8%	9.1%	0.3%
<b>DR-H2</b>	2.0%	2.0%	0.1%
<b>EAF</b>	49.8%	50.8%	1.0%
<b>E-winn</b>	5.0%	5.4%	0.3%
<b>Emissions (MtCO<sub>2</sub>)</b>	395	408	3.4%

The slight decrease in adoption of BF-BOF+CCS is counter-balanced by a slight increase in EAF and the other two CCS technologies, Smelt+CCS and DR-NG+CCS. Under the same climate policy configuration, it also results in higher emissions. While this is informative for prioritizing which processes to invest in, it does not change the overall picture of mitigation options.

## 6. COMPARISON WITH PREVIOUS POLES MODELLING

This study presents the modifications done on the POLES model pertaining to steel demand and production.

The previously existing steel module in POLES consisted in a single steel demand function (intensity of use curve correlating annual demand per unit of GDP with GDP per capita) and two production functions (electricity; other), with price-dependent energy efficiencies; no explicit production pathways or processes were modelled.

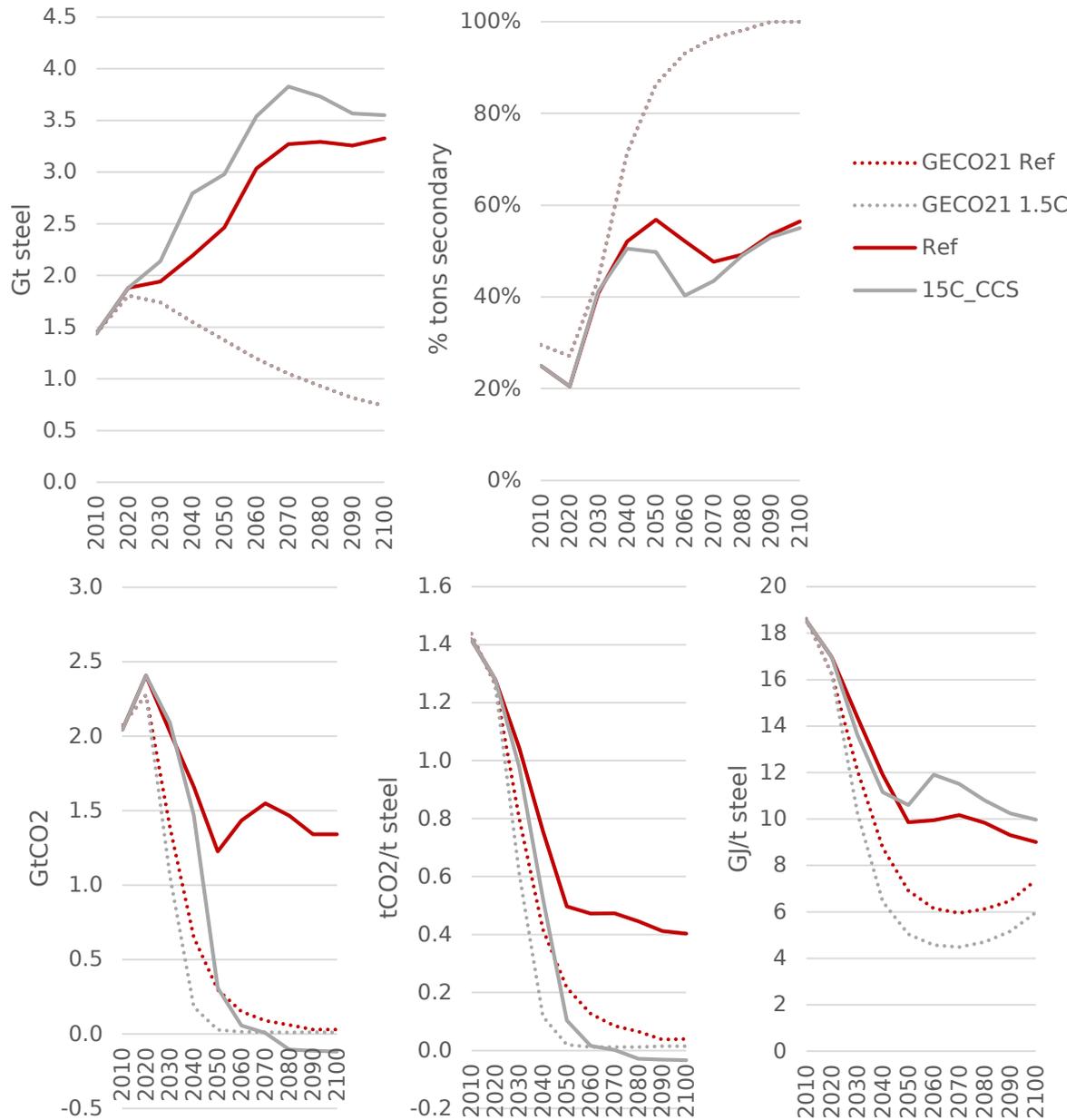
Due to the extended development time of the steel module presented in this paper, an exact before/after comparison is not possible, as other model developments occurred in parallel. For the purposes of this comparison, two scenarios in this study (Ref and 15C\_CCS) have been compared with two scenarios from the Global Energy and Climate Outlook 2021[67].

Scenarios differ in a number of issues (this study's has more recent macroeconomic and energy statistics, more recent modelling in aspects other than iron and steel). However, the two sets of scenarios are similar in design (current policies and global carbon price to reach a 1.5°C goal, respectively).

As can be seen in Figure S2, the changes are significant. Demand for steel is projected to be higher and includes a climate policy feedback effect. Secondary steel is dependent on EAF's relative competitiveness and cannot cover the entirety of production. Emissions and energy demand are significantly different. The essential part of the mitigation in the older modelling came from demand reduction and autonomous (i.e., not dependent on climate policies) electrification.

The new modelling can be considered a significant improvement in capturing steel sector demand, production and mitigation dynamics.

Figure S2: Global steel production (top left), share of production that is secondary steel (top right), iron and steel sector emissions (bottom left), steel emissions intensity (bottom middle) and steel energy intensity (bottom right) for select scenarios



Source: POLES model, GECO 2021 and this study.

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- v. Supplementary information to article 3: Opportunities and roadblocks in the decarbonisation of the global cement sector: a demand and production modelling approach

# Opportunities and roadblocks in the decarbonisation of the global cement sector: a demand and production modelling approach

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## Supplementary Information

### Contents

1. Specific material consumption assumptions .....	198
1.1. Buildings .....	198
1.2. Road transport infrastructure .....	199
1.3. Power sector .....	199
2. Parameters for sectoral material demand drivers .....	200
2.1. Buildings .....	200
2.2. Road transport infrastructure .....	200
2.3. Power sector .....	201
3. Cement production processes .....	201
3.1. Sector perimeter and processes .....	201
3.2. Techno-economic parameters .....	202
3.3. Energy and emissions balances .....	205
4. Calculation of the carbonation sink .....	205
Supplementary References .....	207

# 1. SPECIFIC MATERIAL CONSUMPTION ASSUMPTIONS

## 1.1. Buildings

Specific material consumption assumptions for buildings were adapted from [1] for residential buildings and [2] for commercial buildings. Values are kept constant in the projections.

Table S1: Specific cement use coefficients for buildings by region

Type	Region	kg/m <sup>2</sup>
<b>Residential</b>	Canada	148
	USA	164
	Mexico	160
	Rest of Central America	159
	Brazil	205
	Argentina, Chile, Rest of South America	200
	Egypt, Morocco & Tunisia, Algeria & Libya	159
	South Africa	185
	Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom	202
	Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia, Rest of Western Balkans	160
	Turkey	214
	Ukraine	159
	Rest of Commonwealth of Independent States	131
	Russia	133
	Iran, Saudi Arabia, Rest of Persian Gulf, Mediterranean Middle East	157
	India	162
	South Korea	160
	China	161
	Malaysia, Thailand, Vietnam, Rest of South East Asia	238
	Indonesia	173
Japan	160	
Australia, New Zealand, Rest of Pacific	92	
Rest of South Asia	157	
Rest of Sub-Saharan Africa	160	
<b>Commercial</b>	World	134

The above applies to new floor surfaces. We include a specific cement demand per floor area of renovated surface, defined as 10% of the specific cement demand for the region's new buildings (own assumption).

### 1.2. Road transport infrastructure

The size of paved road infrastructure is multiplied by an average cement consumption per length of road (tons/km), which was applied to all regions and held constant. This coefficient was obtained using depth, width, length and details on the size and relative importance of highways and non-highway roads derived from [3]–[6], as per Table S2. A cement content of concrete of 12.5% [3] and a cement density of 1440 kg/m<sup>3</sup> were used.

Table S2: Cement use coefficients for road infrastructure

	Highway	Non-highway	Average used
<b>Lanes</b>	5	2	
<b>Width (m)</b>	4	3	
<b>Depth (cm)</b>	26	15	
<b>Volume (m<sup>3</sup>/km)</b>	5200	900	
<b>Composition</b>	20%	80%	
<b>Cement content</b>	12.5%		
<b>Cement (t/km)</b>	936	162	317

### 1.3. Power sector

Specific material consumption assumptions for the power sector are presented in Table S3. The values were taken from [7], with an own assumption of 20% cement content in concrete.

Table S3: Specific cement use coefficients by power production technology

Power technology	t/MW
Coal - lignite	102
Coal - conventional	50.4
Coal - advanced	50.4
Coal - advanced + CCS	50.4
Coal - gasification	102
Coal - gasification + CCS	102
Oil - conventional	48.8
Oil - gas turbine	48.8
Gas - conventional	0.8
Gas - gas turbine	0.8
Gas - combined cycle	7.2
Gas - combined cycle + CCS	7.2
Biomass - conventional	102
Biomass - gasification	102
Biomass - gasification + CCS	102
Hydro - run-of-river	600

Hydro - dam	600
Hydro - pumped storage	600
Hydro - small	200
Nuclear - Gen III	104.6
Nuclear - Gen IV	104.6
Wind - onshore	84.2
Wind - offshore	130
Solar - CSP	2
Solar - PV plant	2
Solar - PV small	0
Geothermal	20
Ocean	0

These values were applied to all world regions and were kept constant.

For power transport and distribution grid, specific cement consumption was derived indirectly, using the estimated cement in the existing grid of the UK [8] and divided by the total amount of electricity transiting through that grid in a year, resulting in 349 kg/GWh. This is applied to all regions and kept constant.

## 2. PARAMETERS FOR SECTORAL MATERIAL DEMAND DRIVERS

A number of equations calculate the energy services and energy-consuming equipment that are used as a basis for materials demand.

### 2.1. Buildings

For sources and calculations of surfaces of residential and services, see supplementary information of the article on steel (annex iv).

### 2.2. Road transport infrastructure

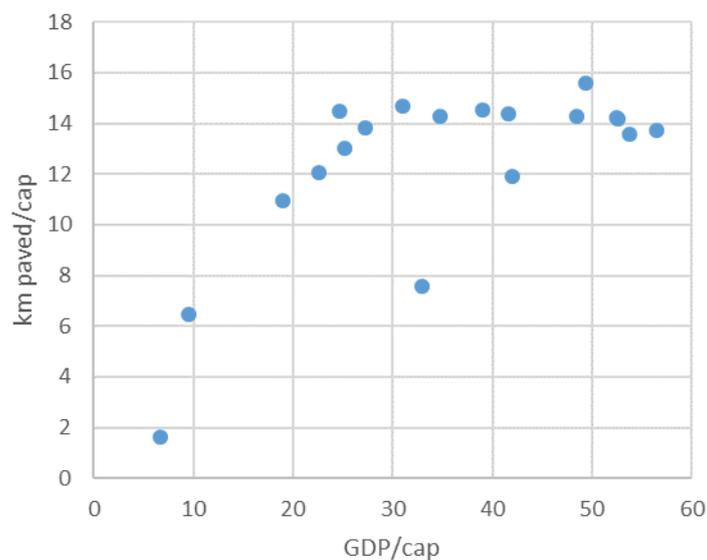
For each region, the length of paved road network is based on a correlation between length per capita and per capita income.

The historical lengths of paved road network were collected for the USA[9], European countries[10] and China[11], and were complemented by [12] for large countries[13]. A distinction must be made between total road network and paved network, as the former does not require materials such as cement.

A polynomial law was derived from the data using length of the network per capita versus GDP per capita. The length of the network per capita versus GDP per capita showed a good correlation, better than versus land surface or population density.

Apart from economic development itself, differences across countries could be explained by different forms of spatial planning (urban/suburban/rural, zoning).

Figure S1: Paved road network per capita vs GDP per capita



Note: the law is considered valid up to values of GDP/cap of 45 k\$/cap.

As a saturation could be observed at high income values, this law was used with GDP/cap capped at 45 k\$/cap. In the projections, countries start from their last historical point; a catch-up to the law over 30 years is incoded in the projections.

A lifetime of 70 years is applied to derive annual newly built length of road each year.

### 2.3. Power sector

POLES includes 35 technologies for power production and electricity storage. See POLES description above and in [14], [15].

## 3. CEMENT PRODUCTION PROCESSES

### 3.1. Sector perimeter and processes

The cement sector as modelled covers the process steps of:

1. grinding of raw material (calcareous material);
2. heating (dehydration, calcination, clinkering, cooling), the product of which is clinker;
3. grinding and mixing (with inert products like gypsum), the product of which is cement.

Raw material mining (calcareous material, gypsum) and the transformation of energy fuels and other materials into the feedstock used by the processes are not included in the cement sector: electricity production, bioenergy production, carbon capture consumables (e.g., amine solvent, membranes).

The transformation of cement into concrete (mixing of cement with water, gravel and other inert materials) is not included in the cement sector.

Trade of cement is modelled; however, there is no trade of intermediate products (clinker).

The following processes were modelled:

- *Shaft*: vertical shaft kiln (residual technology, <1% globally in 2020, no new construction is allowed)
- *Mixed*: short rotary kiln with semi-dry and semi-wet mixtures
- *Dry+pre-h*: long dry rotary kiln with pre-heater as an energy efficiency measure
- *Dry+pre-c*: long dry rotary kiln with pre-heater and pre-calciner as energy efficiency measures (also known as new suspension with preheater kiln, NSP)
- *Elec-k*: long dry rotary kiln with indirect electric heating (new technology, available starting from 2030)

All processes can have carbon capture and storage (CCS) retrofit on them.

### 3.2. Techno-economic parameters

The assumptions for specific energy consumption and overnight investment costs by cement production process are presented in Table S4 and Table S5. The existing technologies are mature in terms of costs and efficiencies, with little evolution expected to occur. The electric kiln technology is still new and there are no estimates of its costs.

Energy demand is split into upstream preparation and downstream mixing (the steps 1 and 3 in the list above; consists exclusively in electricity) and heating (step 2; consists in combustion fuels, can be electricity as part of the pre-calciner in the Dry+pre-c process, or for the electric kiln in the Elec-k process). The sources used were [16]–[18]. For the electric kiln, the same values as the Dry+pre-c process were used.

Table S4: Specific energy consumption for new capacities (GJ/t cement), by cement production process

	Heating (GJ/t cement)		Upstream and downstream (GJ/t cement)	
	2020	2030	2020	2030
<b>Shaft</b>	4.46	4.32	0.49	0.47
<b>Mixed</b>	4.30	4.17	0.42	0.41
<b>Dry+pre-h</b>	3.54	3.43	0.41	0.40
<b>Dry+pre-c</b>	3.32	3.22	0.31	0.30
<b>Elec-k</b>	3.32	3.22	0.31	0.30

Investment costs were taken from [19]. For the electric kiln, given the lack of data, the default case was set as twice the unit cost of Dry+pre-c and the optimistic case as 1.33 times the unit cost of Dry+pre-c (own assumptions). In the projections, costs decrease with an elasticity to cumulated installed capacity (elasticity of -0.05) to reflect a learning-by-doing effect. Actual scenario values differ, depending on the respective deployment realized.

Table S5: Overnight investment costs for cement processes (USD/t cement)

Process	2020	2050	2100
Shaft	260	260	260
Mixed	324	316	306
Dry+pre-h	324	311	295
Dry+pre-c	355	347	336
Elec-k, default	716	716	653
Elec-k, optimistic	477	477	428

Note: 2020 values are common to all scenarios. Projected values are dependent on process deployment. The values here are from the 15C\_CCS scenario, except Elec-k, optimistic, from the 15C\_Elec scenario.

Once installed, capacities are allowed to be retrofitted from one process to the other. A certain amount of existing capacities is subject to be retrofit each year (5% of existing capacities). Retrofitting is set to cost a percentage of the overnight investment cost of the destination technology; the decision to retrofit is made by comparing the post-retrofit costs (extra investment cost and operating costs) with pre-retrofit costs (operating costs). The relative costs of the allowed retrofitting options, taken from [19] (and own assumptions for the electric kiln), are presented in Table S6.

Table S6: Retrofitting costs as a share of overnight investment costs

Process from i to j	Cost share of j
Mixed to Dry+pre-h	0.37
Mixed to Dry+pre-c	0.55
Dry+pre-h to Dry+pre-c	0.14
Dry+pre-h to Elec-k	2.00
Dry+pre-c to Elec-k	2.00

Overnight investments were annualized using an 8% discount rate and a 35 years equipment lifetime (own assumptions). In the 2°C and 1.5°C scenarios, the lifetime was gradually reduced to 23 years (by 2040 in the 2°C scenario, by 2030 in the 1.5°C scenarios) and onwards to reflect increased pressure to renew the stock towards more low-carbon processes.

CCS technologies include a fixed CO<sub>2</sub> capture rate of 90%, typical of post-combustion capture processes[20]. An extra investment cost for CCS retrofit was derived from post-combustion coal power plants[21], considering the capacity in terms of captured CO<sub>2</sub> throughput in the conversion from power capacity (\$/kW) to cement production (\$/t cement), as per Table S7.

Table S7: Extra overnight investment cost for implementation of CCS (USD/t cement)

	2020	2050
<b>Mixed, Dry+pre-h, Dry+pre-c</b>	137	117
<b>Elec-k</b>	92	78

An efficiency loss was added to production capacities with CCS, consisting in an additional electricity need of 0.77 GJ/tCO<sub>2</sub> captured, derived from [22] (sorption-enhanced water-gas shift, SEWGS); it was considered that additional steam demand to drive the capture process would come from waste heat recuperation.

As the electric kiln process results in a flue gas stream that is purer in CO<sub>2</sub>, the capture process is easier: we considered a 33% discount in cost and electricity penalty for the Elec-k process (consistent with the difference between pre- and post-combustion capture in coal power plants[21]).

In addition, a fixed CO<sub>2</sub> transport cost away from the cement plant of 5 \$/tCO<sub>2</sub> was used[23].

A fixed operation and maintenance cost is added to the investment cost (annualized), amounting to 5% of the overnight investment cost (own assumption).

The fixed costs are combined with operational costs to obtain total production costs per ton of cement produced. Operational costs are endogenously produced in the model and are dependent on the scenario, region and year. They are determined by the functioning of the energy markets and energy transformation sectors of the rest of the model, as well as international transport costs (see model description above). An example of total production costs breakdown is provided in Table S8, assuming a process consuming only coal and electricity and which is progressively retrofit with CCS.

Table S8: Example of cement production cost breakdown for USA, Dry+pre-c, 15C\_CCS scenario

\$/t cement	2020	2030	2040
<b>Fixed costs</b>	48	48	51
<b>Raw materials</b>	5	5	5
<b>O&amp;M costs</b>	5	5	5
<b>Energy inputs: electricity</b>	5	14	16
<b>Energy inputs: coal</b>	7	9	9
<b>CO2 price on coal</b>	0	30	120
<b>CO2 price on process emissions</b>	0	49	163
<b>CCS credit</b>	0	0	-55
<b>CO2 transport cost</b>	0	0	1
<b>Total</b>	70	160	310

Source: POLES model.

### 3.3. Energy and emissions balances

The cement sector includes the energy needed to transform calcareous material into cement. It represents most of the energy consumption of the non-metallic minerals (NMM) industry sub-sector. Other NMM sub-sectors are lime, ceramics and glass. NMM energy consumption is provided by Enerdata/IEA energy balances[24].

The energy and emissions balances of the cement sub-sector were subtracted from the NMM sub-sector; the model then calculates energy and emissions of an “other NMM” sub-sector.

In order to initialize the energy consumption of the existing stock, the specific energy consumption levels by process for new installations (Table S4) were adapted to reflect a stock that is on average less efficient than new installations. Regions were grouped in five classes on the basis of the historical energy efficiency of their non-metallic minerals sector (total sector energy consumption over sector value added). Depending on their efficiency level, they were assigned specific energy consumption values that ranged between 100% and 112% the values for new capacities (with 12% being twice the distance of best available technology to existing capacities in Europe[18], own assumption).

CO<sub>2</sub> emissions for cement are calculated with a carbon content per fuel for energy combustion emissions and a country-dependent clinker-to-cement ratio for process emissions.

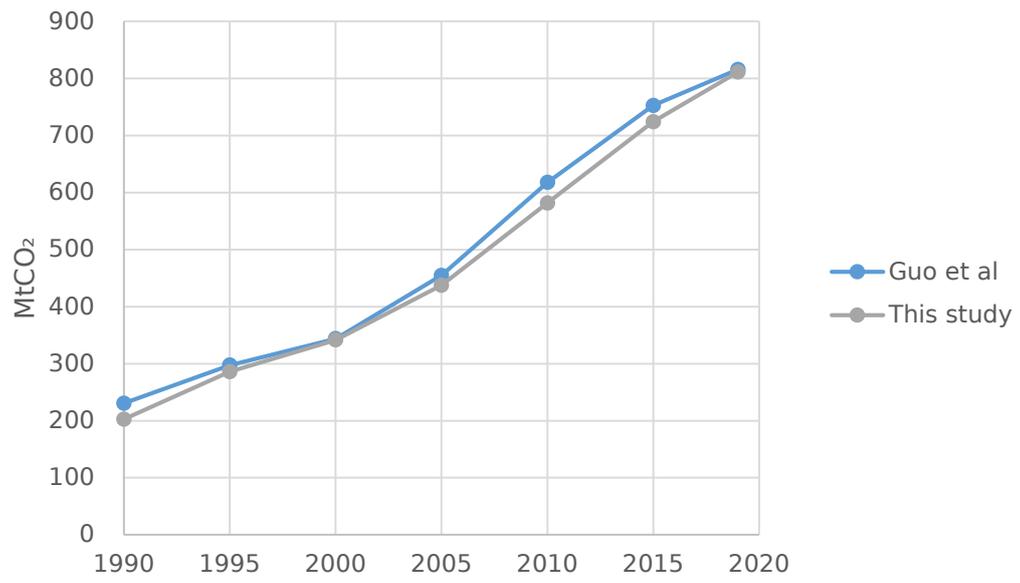
## 4. CALCULATION OF THE CARBONATION SINK

The carbonation sink depends on a large number of parameters: type of material (concrete, mortar), clinker content, compressive conditions, surface exposed to the air, atmospheric conditions and CO<sub>2</sub> content of the air, what happens to the material after its use (e.g., if it is ground into finer elements, and if yes how fine).

Given the granularity of representation of the cement use in our energy system model approach, we calculated the carbonation sink using simple parameters. For cement produced each year in each region, the additional carbonation sink is calculated using the clinker/cement ratio, a diffusion speed, and maximum absorption. The clinker ratio determines the presence of material subject to carbonation. The diffusion speed represents Fick’s law of diffusion of CO<sub>2</sub> within the material, following a power law (0.25) over time. The theoretical maximum corresponds to the entirety of the emissions released during calcination (i.e., 570 kgCO<sub>2</sub>/t clinker). The maximum absorption was set at 75% of the theoretical maximum over a period of 100 years, as per [25] and the European standard EN 16757 on the sustainability of construction works.

This method allows to recreate the global carbonation sink of [26] quite closely, as shown in Figure 2.

Figure 2: Global carbonation sink, 1990-2019



Source: [26], own work

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## vi. Additional results on drivers, demand and stocks

The main drivers behind the calculations of energy and materials demand in the POLES scenarios in this work are presented in Figure 37. See annexes iv and v on how these are translated into annual steel and cement demand. Globally, the increase in equipment is considerable; these global totals hide regional heterogeneity, where more decorrelation to economic growth or even saturation can be observed.

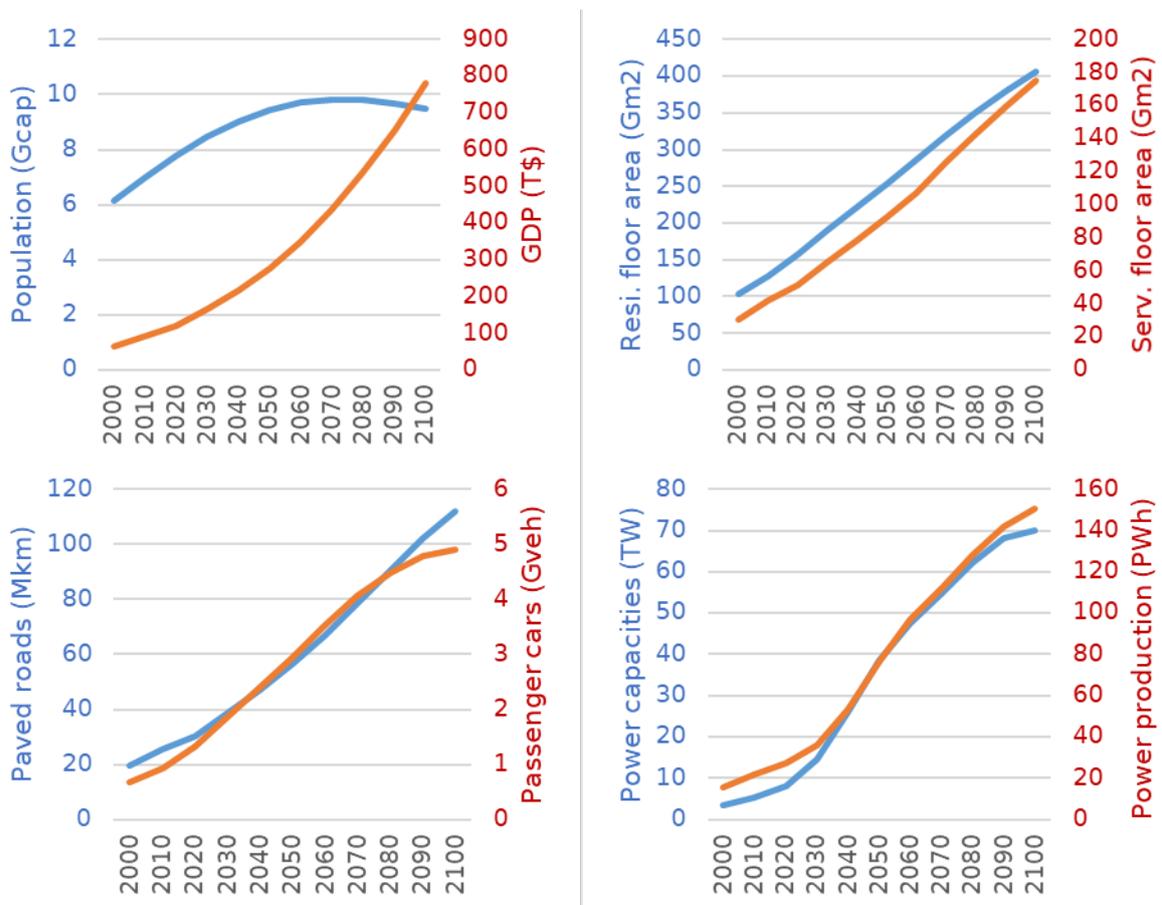


Figure 37: Main drivers for materials demand, 15C\_CCS scenario

Source: POLES model. Population and GDP are common across all scenarios in this work.

Information in how drivers translate into materials demand is provided in the relevant annexes (iv section 3 for steel, v section 2 for cement). A visual example of using macroeconomic drivers to derive buildings floor area and demand for materials in buildings for India is provided in.

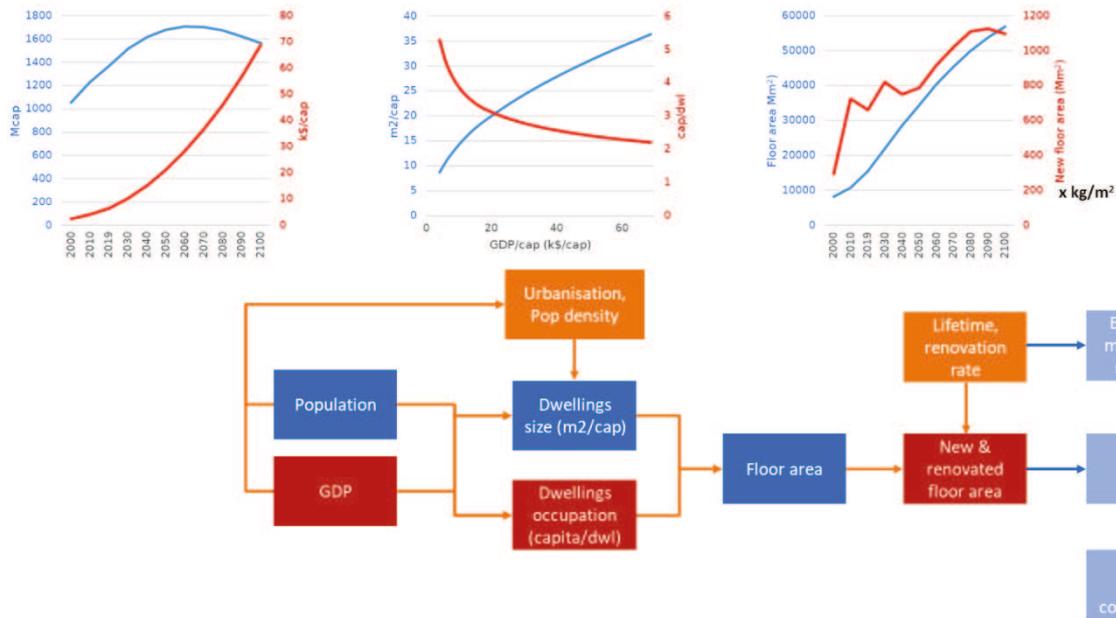


Figure 38: Schematic for the estimation of annual materials demand in POLES, India, buildings

Source: POLES, own work.

In a biophysical stock-flow approach that represents the human socio-economic system's metabolism, the materials stock is directly proportional to these drivers (or equipment), and the annual materials flow is the annual demand discussed in the articles above. One is the integral of the other, with the adjustment of retired equipment.

Using the annual demand from the past back to 1930 (Figure 27, Figure 30), the projections of annual demand per end-use and the lifetimes of the equipment per end-use presented above, we constituted material stocks in use in the economy per capita. They are presented in Figure 39 for select countries and the world average.

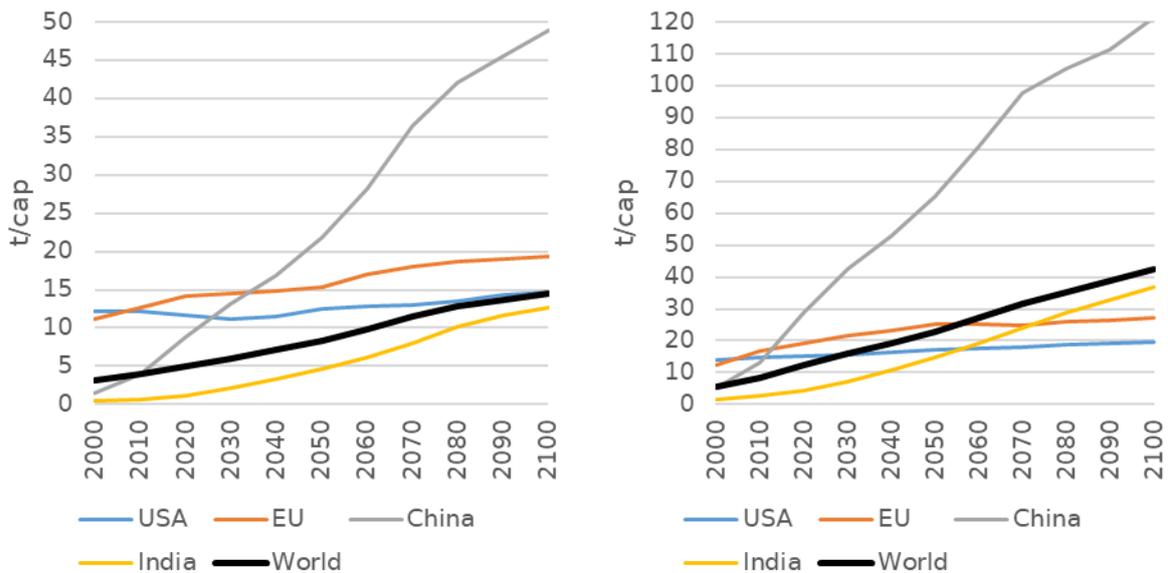


Figure 39: Stocks per capita for steel (left) and cement (right), 15C\_CCS scenario

Source: POLES, own work.

In developed economies like the USA and the EU, the stocks per capita have reached a saturation level that is continued throughout the projection period. For developing economies like India, the stocks per capita increase and follow a sigmoid curve towards saturation. The case of China appears to be an outlier.

In China, a large part of historical materials demand cannot be explained by the three end-uses identified in this work, leaving a large part for “other infrastructure”. The recent plateau and drop in annual demand for both steel and cement point towards future demand contracting, now that buildings and infrastructure have been constructed. The future demand might decrease faster than in our projections, resulting in a lower stock. The speed of annual demand increase will determine the final level at which the stock in use will stabilize. The projections of demand in the 15C\_LD scenario show such a configuration (see Figure 40). Given the high growth reached in the past decade, China’s annual steel and cement demand would have to drop very sharply if the stock in use per capita is to stabilize at a level comparable to developed economies.

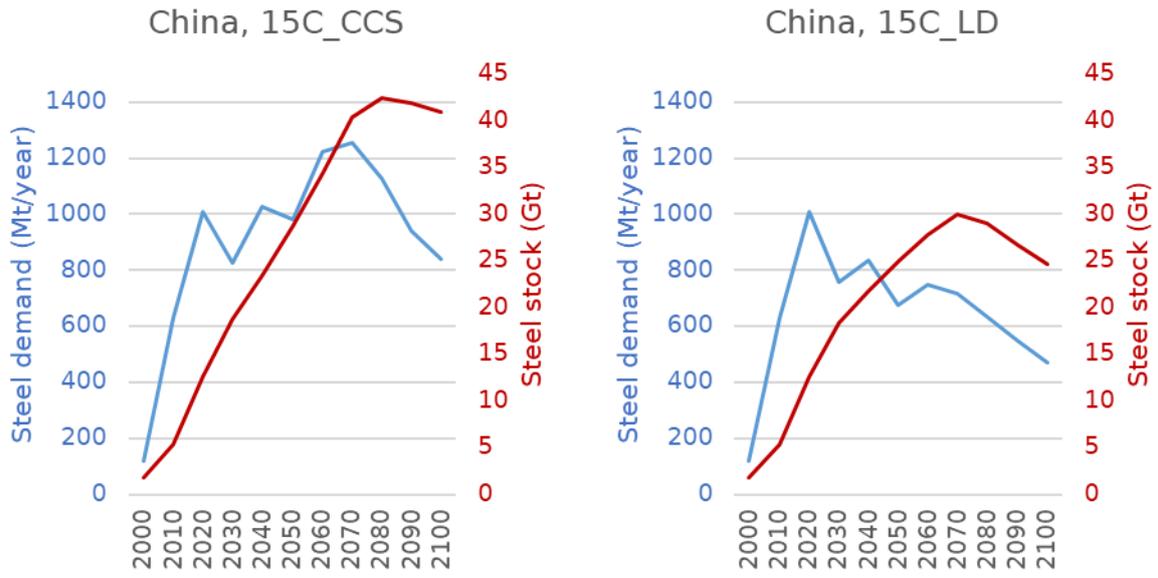


Figure 40: Annual steel demand and total steel stock in use for China

Source: POLES model.