IAM COMPACT

Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

D4.7 – Sectoral and cross-sectoral analysis

WP4 – Modelling – Quantitative evidence in support of post-2030 Paris- compliant climate action

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA. It should be noted that not all topics indicatively mentioned in the description of Task 4.4 in the DoA are addressed in this Deliverable D4.7 as the consortium addressed issues that were highlighted as relevant research topics in the co-creation process of the first policy response mechanism cycle (PRM-1). The deliverable was submitted in time, in December 2023; however, it was updated in February 2024 to reflect minor updates to the modelling exercise and document more detailed discussion of results.

2. Dissemination and uptake

The results of the work documented in this Deliverable D4.7 will be presented to stakeholders of the core working groups (CWGs) of Themes "European Industry", "Electrification", and "Behavioural Change" in the second iteration of CWG meetings of PRM-1. Depending on upcoming discussions with stakeholders regarding topics for PRM-2, selected parts of the work covered in this deliverable may be further elaborated or used otherwise in PRM-2.

Parts or all of the content of D4.7 will be disseminated to the scientific community via research articles and/or scientific conferences.

3. Short summary of results (<250 words)

Four in-depth analyses of sectoral and cross-sectoral issues, conducted as part of the first Policy Response Mechanism cycle (PRM-1) of the IAM COMPACT project, are presented in this deliverable:
(1) a study focussing on potential relocation of the EU steel industry to other world regions because of high energy and CO_2 prices in the EU; the associated impacts on costs, CO_2 emissions, energy demand, and employment are assessed for three scenarios, and five different models including three integrated assessment models (IAMs), one sectoral bottom-up model, and one Input – Output (I/O) model have been (soft-) linked
(2) a study analysing the impacts of implementing an increasing amount of wind and solar power technologies in terms of raw material demand; the analysis covers four global regions, including the EU, while results from one IAM regarding renewables upscaling have been processed with another model to derive raw material demands
(3) a study analysing the capacity and flexibility requirements of future electricity systems to meet carbon neutrality for the case of Greece, which soft-links a cost-optimising energy system model with a short-term power system model and analyses two scenarios for a carbon-neutral Greek electricity system up to 2050
(4) a study addressing the uptake of small-scale PV by the residential sector in Greece, using an agent-based model to analyse how consumers' investing behaviour affects the adoption of small-scale PV systems by 2030 by comparing the effects of different policies; uncertainty about the effects of policies that emerges from agents' adoption behaviour is quantified and presented.

4. Evidence of accomplishment

This report.

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Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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E3M – E3-Modelling AE	EL	E3Modelling Energy Economy Environment
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Executive Summary

This Deliverable covers four in-depth analyses of sectoral and cross-sectoral issues, which have been conducted during the first Policy Response Mechanism cycle (PRM-1) of the IAM COMPACT project, and which complement system-wide studies conducted with Integrated Assessment Models (IAMs) as part of other Studies of PRM-1. The first study reported focusses on the EU steel industry and a potential relocation thereof to other world regions because of high energy and CO_2 prices in the EU. Five different models including three IAMs (GCAM, TIAM, WILIAM), one sectoral bottom-up model (WISEE EDM-I) and one Input-Output (I/O) model (MARIO) have been (soft-) linked to assess the potential impact of different degrees of trade restrictions for steel. Three scenarios are analysed in each of which all countries implement their current climate policies and achieve the GHG emissions reduction targets aimed at in their respective NDCs and in their long-term targets but different steel-related trade constraints are assumed. The analysis showed that the EU steel industry faces tendencies for off-shoring in the time period around 2030, if no measures are taken. However, it also shows that the comparably fast decarbonisation of the EU electricity sector entails competitive advantages for steel after 2040. Low-emissions primary steel technologies will scale only after 2030, according to the models and this process will not be accelerated through keeping additional production capacity within the EU. As a consequence of increasing CO_2 prices and the transformation of the steel sector towards low-emission technologies, specific costs of steel production increase from about 500€/t in 2020 to about 700€/t in 2050, in all scenarios. If trade is restricted, EU steel related CO_2 emissions, GVA and employment are higher in line with higher production volumes in the time around 2030, while the effects on global steel related CO_2 emissions remain uncertain, based on the analysis. Parts of the analysis have been broken down to the EU member state level, by using WISEE EDM-I. This reveals that differences in renewable energy prices between member states affect locational factors, which creates a tendency for relocation of production to those member states which feature the lowest renewables costs.

The second study addresses the raw material demand for upscaling solar and wind technologies in four global regions, including the EU. The three scenarios of the steel-related study (see above) have been compared in a first step, while the extended analysis then focusses on one of them due to limited differences in results between the scenarios. Results from GCAM on renewables upscaling were used as an input to some modules of WILIAM which allowed to calculate the raw materials demands implied, which were then compared to current annual extraction and the known global reserves. Results indicate that raw material scarcity poses a serious challenge to renewables upscaling and strategies to overcome their limited availability are required.

The third study analyses the capacity and flexibility requirements of future electricity systems to meet carbon neutrality for the case of Greece. For achieving this, it soft-links a cost-optimising energy system model (OSeMOSYS-GR) with a short-term power system model (FlexTool). Two scenarios for a carbon-neutral Greek electricity system have been modelled with OSeMOSYS-GR up to 2050, one focussing entirely on variable renewable energy (VRE) and one including Carbon Capture and Storage (CCS) for natural gas and biomass power plants, in addition to VRE. FlexTool provides a more detailed picture of curtailments and required net imports, compared to OSeMOSYS-GR and it is concluded that the exploration of long-term decarbonisation pathways should combine long-term capacity planning with short-term operational assessment to provide more accurate representations of the future power system behaviour.

The fourth study addresses the uptake of small-scale PV by the residential sector in Greece. It uses an agent-based model (ATOM) to analyse how consumers' investing behaviour affects the adoption of small-scale PV systems by 2030 by comparing the effects of different policies, namely: a feed-in-tariff (FiT), net metering, and net metering in combination with a subsidy for battery energy storage systems. Uncertainty about the effects of policies that emerges from agents' adoption behaviour is quantified and presented for all cases. While the FiT achieves the highest impact, results indicate that neither of the policies is able to achieve the capacity additions required to meet the target of the Greek National Energy and Climate Plan. Simulation results suggest that one of the main drivers motivating consumers to embrace small-scale solar PV systems is profitability and that policymakers should hence advocate more robust financial incentives.

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1 Introduction

This Deliverable has been developed under Task 4.4 "A deep dive into sectoral dynamics and specific cross-sectoral aspects" of the IAM COMPACT project and covers work conducted during the first Policy Response Mechanism cycle (PRM-1) of the project (see Deliverables 2.1 "Stakeholder Engagement Plan" and D4.5 "National, regional, global mitigation pathways"). The different sections of this report present different model-based in-depth analyses of sectoral aspects, which complement system-wide studies conducted with Integrated Assessment Models (IAMs), as reported in D4.5 as well as in a series of other Studies again identified and conducted in the context of PRM-1. The analyses presented in this Deliverable have been derived under the themes of "European Industry", "Electrification", and "Behavioural Change" of PRM-1 (see Deliverable 2.2 "Scoping Relevant Research Questions").

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2 European Steel Industry

2.1 Introduction

Currently dominant primary steel production technologies such as the blast-furnace route use coke and coal for reducing iron ore to iron and for providing the heat required for this process. Consequently, steel production is responsible for 7% of global CO_2 emissions, according to the IPCC (2022). Less CO_2-intensive steel production technologies exist or are on the verge of market introduction. These include (increasing shares of) secondary steel production in electric arc furnaces, reduction of iron ore in shaft furnaces through using natural gas or hydrogen, iron reduction through electrolysis and carbon capture and storage (CCS) (see Agora Energiewende and Wuppertal Institute 2023 for an overview of CO_2 reduction technologies for steel). From a technical point of view, it thus seems possible to strongly reduce steel-related CO_2 emissions in the coming decades.

With the rising price of CO_2 certificates in the EU and the end of free allocation of CO_2 certificates to the steel industry the economic incentives for investments in low-CO_2 steel production in the EU increase (Eurofer 2021). However, the risk of carbon leakage – i.e. carbon-intensive steel production moving to regions of the world with lower CO_2 prices and less strict environmental regulations and steel being imported into the EU instead of being produced domestically – is increasing as well (Yu et al. 2021).

Furthermore, low-CO_2 steel production technologies make use of other energy carriers than conventional primary steel production in the EU – in particular electricity, hydrogen, and natural gas instead of coke and coal. This leads to a change of locational factors and may affect future investment decisions of steel companies. The availability of low-cost electricity and hydrogen may become an important factor and consequently future investments may be made in world regions which are rich in renewable energy. The effect that industrial production may be relocated to world regions where low-cost renewable energy is available in large amounts has been called the renewables pull effect (Samadi et al. 2023).

Both, carbon leakage and the renewables pull effect may lead to relocation of industrial production from the EU to other world regions, also known as "off-shoring". Carbon leakage is counterproductive from a climate change mitigation perspective and from a domestic economic perspective (Böhringer et al. 2017) while the renewables pull effect may be seen critical from the perspective of resilient value chains, national/European security, and self-sufficiency with regards to critical materials. A question for policy makers thus is whether carbon leakage and renewables pull should be countered by industrial, trade, and climate policies.

Against this background, the work described in this section has been conducted as part of PRM-1 of the IAM COMPACT project under the theme "European Industry" (see Deliverable 2.2 "Scoping Relevant Research Questions"). In a first step, topics including a potential relocation of industries because of high energy prices and climate ambitions as well as impacts of the EU Industry decarbonisation on the economy and labour were identified as a matter of high concern for high-level policy makers from national governments and the European Commission. The topic of the study was then narrowed down and refined based on discussions with the Core Working Group of policy makers, academia, industry, and NGOs gathered for this study. As a result of this co-creation process with stakeholders, the following overarching research question was selected:

What are the impacts of different degrees of trade restrictions for steel on the EU steel decarbonisation pathway and associated costs, CO_2 emissions, energy demand, environmental effects and labour in the context of a pathway to a carbon-neutral EU?

A methodological approach involving five models of the consortium (see below) has been developed in order to answer this research question comprehensively. This Deliverable presents the methodological

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approach and the results. An assessment of the results is made and an outlook on possible future research is provided.

2.2 Methodological approach

The main approach for answering the research questions is conducting a multi-model scenario study that reflects various degrees of steel trade restrictions between the EU and the rest of the world and analyses the impacts of these restrictions on steel transformation pathways in the EU with associated final energy demand, CO_2 emissions and cost figures of the steel sector, as well as systemic effects on the economy and labour. For this purpose, three scenarios are defined that all build on the same overarching global scenario but put different limits to steel-related carbon leakage and to the renewables pull effect.

The models used and the scenario definitions are outlined in the subsections below before the steps of the analysis and the data flow between models are described.

2.2.1 Models used

The models used in this study are briefly outlined in the following and documented on the I²AM Paris Platform.[1]

GCAM

GCAM is a global, partial equilibrium IAM that represents human-Earth dynamics by exploring the behaviour and interactions between the energy system, agriculture and land use, the economy and climate to model GHG emissions, energy use, energy prices, and trade patterns (Calvin 2019). It operates by looking for cost-efficient energy system solutions in a specific period and then moves on to the next time period to repeat the optimisation exercise. In this study we use GCAM version 7.0, which includes global iron and steel trade, with modifications to socioeconomic pathways and iron and steel production technologies to harmonise with the other models used in this study.

GCAM represents supply and demand for one "iron and steel" commodity in each of its 32 regions. In the version used in this study, we include 20 technology options for the production of iron and steel in each region, whose input coefficients, costs, and technology readiness are broadly consistent with the harmonisation data included in the Annex. Technology choice in each year is modelled with a logit function based on price and historically calibrated technology preferences. This logit competition allows all available technologies to take some share of the market, preventing winner-take-all behaviour. Demand for iron and steel can be met through a combination of domestic production and imports from a global trade pool.

TIAM

TIAM (Times Integrated Assessment Model) is a partial equilibrium, technology-rich IAM which covers the full energy chain from extraction of energy resources through conversion technologies, to the provision of energy service demands to end-users. It achieves equilibrium between energy supply and demand in each sector, based on a least cost-optimisation approach that takes into account all the consequences of technology deployments, fuel extraction, and energy price changes over the entire time horizon while minimising the cost of the energy system to provide energy-service demands within specified emissions constraints. Exogenous inputs of GDP, population, household size and sectoral shares of the economy are the main drivers to project future energy service demands across all sectors

[1] https://www.i2am-paris.eu/

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in each region. In this study the steel sector production demand is taken from GCAM across all scenarios.

MARIO

MARIO is a versatile modelling framework for easy input-output analyses and models handling. It is programmed in Python and comes with a set of useful features which are of paramount relevance to perform scenario and economic-environmental impact assessment and footprint analyses adopting input-output tables. In this study, MARIO was adopted to enrich the raw version of the Exiobase dataset, to account for novel steel production processes and for the complete supply chain of PV panels and wind turbines manufacturing for the case of the EU.

Three steel production processes were considered: the Blast Furnace-Basic Oxygen Furnace route (BF-BOF), already present in the database, the Direct Reduction with Natural Gas route (NG DR-EAF) and the Direct Reduction with 100% electrolytic Hydrogen route (100% H2 DR-EAF). The last two processes were modelled using as reference the inputs to the Shaft Furnace and to the Electric Arc Furnace indicated, respectively, in Suer et al. (2022) and Hay et al. (2021). In order to underline the presence of hydrogen in both processes, the inputs to the Shaft Furnace were slightly modified as follows:

- for the NG DR-EAF case, the input of natural gas was substituted by steam reforming hydrogen, produced by the "Hydrogen production with steam reforming" activity previously introduced in Exiobase
- for the 100% H2 DR-EAF case, the electricity input required for hydrogen production was substituted by electrolysis hydrogen, produced by the "Hydrogen production with electrolysis" activity previously introduced in Exiobase.

Due to these modifications, the impact of carbon monoxide as reducing agent in the NG-DR route was disregarded. Moreover, in both cases the input of scrap into the Electric Arc Furnace was assumed to be zero (100% input of Direct Reduced Iron) and the output of slag was neglected. The obtained extended table was then perturbated in order to perform "what-if" analyses (or "shocks"), derived from the results of other IAMs (e.g. GCAM). Each shocked table is then provided to WILIAM, to complete the macroeconomic and environmental impact assessment analysis.

WILIAM

The WILIAM model (Within Limits Integrated Assessment Model) is a new IAM based on system dynamics that has been designed by building on MEDEAS models to address limitations in the field of IAMs. System dynamics allows to capture complex feedback loops and non-linear relationships between social, economic and environmental variables. WILIAM is made up of 8 modules: (1) demographics, (2) society, (3) economics, (4) finance, (5) energy, (6) materials, (7) land and water, and (8) climate. WILIAM takes into consideration 9 regions and 35 countries, including the EU27. The model is granular, meaning that it is disaggregated in 62 different sectors. The sectoral breakdown and, in general, the production sub-module are based on Input-Output Analysis. Among the sectors included in WILIAM, we can find 9 mining & manufacturing of minerals sectors, including iron. In turn, steel is accounted for in the Manufacture of metal products sector.

WISEE EDM-I

The WISEE EDM-I is a framework for technology-rich investment modelling focussing on specific industry sectors, which is programmed in Python. It builds on site-specific information of production processes (e.g. capacity and age of assets) and cost-optimises production networks over several steps of a value chain (e.g., from iron reduction to steel making and steel finishing), considering the spatial layout of the production network and various transport options for intermediary products. A new implementation of the EDM-I for the EU steel sectors is used in this study. Investments are made to

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meet externally given production levels (differentiated for 20 types of finished steel) while considering energy and CO_2 prices as well as a range of constraints (e.g. on scrap availability). The EDM-I is designed to analyse questions related to relocation of industrial production capacity in Europe.

The model version used for this exercise differentiates five technologies for iron reduction (BF, BF_CCS, DRI with/without reformer, electrolysis[2]), three technologies for steelmaking (BOF, EAF, SAF_BOF) and 12 technologies for steel finishing. The technologies can be combined to different steel making routes across the production steps. Scrap qualities and steel qualities that result from using scrap of different quality are differentiated in five different categories that are linked to finished steel demand types (i.e. some types of demand require a minimum level of steel quality).

2.2.2 Scenarios

NDC_LTT

The NDC_LTT scenario follows the same scenario protocol as the NDC_LTT scenario developed in Study 1 of the PRM-1 (see Deliverable D4.5 "National, regional, global mitigation pathways"). It describes a world in which all countries implement all the current climate policies and achieve the GHG emissions reduction targets aimed at in their respective NDCs up to 2030. After 2030 the long-term targets (LTT) of countries, including net-zero strategies of major economies are included as a linear pathway from the 2030 NDC target. The scenario leads to a temperature increase of 1.7-1.8 °C above pre-industrial levels in 2100, as assessed in van de Ven et al. (2023).
With regards to steel trade, the scenario does not put any constraints on EU steel trade. Both carbon leakage as well as the renewables pull effects may lead to off-shoring of steel production to other world regions.

CBAM

The CBAM scenario is identical to the NDC_LTT scenario except that it adds some core features of the carbon border adjustment mechanism (CBAM) that is currently introduced by the EU (European Union 2023). In this scenario, steel imports to the EU are penalised based on their CO_2 footprint starting in 2025. This allows the EU to apply the ETS price to carbon emissions from steel imports and signal a preference for low-carbon steel imports. The scenario therefore limits carbon leakage related to steel imports but does not put constraints on the renewables pull effect.

Strategic independence

Similar to the other two scenarios, the Strategic independence scenario also builds on the NDC_LTT scenario developed in Study 1. It reflects a world in which considerations of resilience and national security are high on the agenda of the EU. This is reflected by the assumption that the steel production levels of the EU may not fall below its 2019 levels. There are no limits to imports or exports, but whereas total domestic production declines in the NDC_LTT scenario as a response to ETS pricing, in this scenario it remains constant. The scenario therefore puts limits to both carbon leakage and the renewables pull effect.

2.2.3 Steps of the analysis and data flows

In order to structure the scenario analysis, the overarching research question highlighted in the introduction to this section has been broken down into the following sub-questions:

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[2] One of the electrolysis technologies included – the MOE (see appendix) – integrates iron reduction and steel-making into one single step.

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- *To which extent will steel production be relocated from the EU to other world regions across the different scenarios?*
- *By which technology mix will steel be produced in the EU?*
- *How do system wide CO_2-emissions, costs and energy demand differ between the scenarios?*
- *What are the economic and labour effects of each scenario?*
- *How will the steel transformation unfold within the EU, on the national level?*

The analysis of the scenarios covers three steps as shown in Figure 2-1. The first and second step address the first and second sub-question, while in the third step different sub-questions are addressed in parallel by different models. In each step, all three scenarios are modelled by all of the models involved in the respective step. The data flows between models associated with this analytical structure are depicted in Figure 2-2.

Before starting model-based scenario analysis, technology data including steel production technologies considered, their energy demand, material uses, cost and CO_2 emissions have been harmonised between GCAM, TIAM and WISEE EDM-I to the largest extent possible. The data has been shared as Excel table among the partners and is provided in the Appendix.

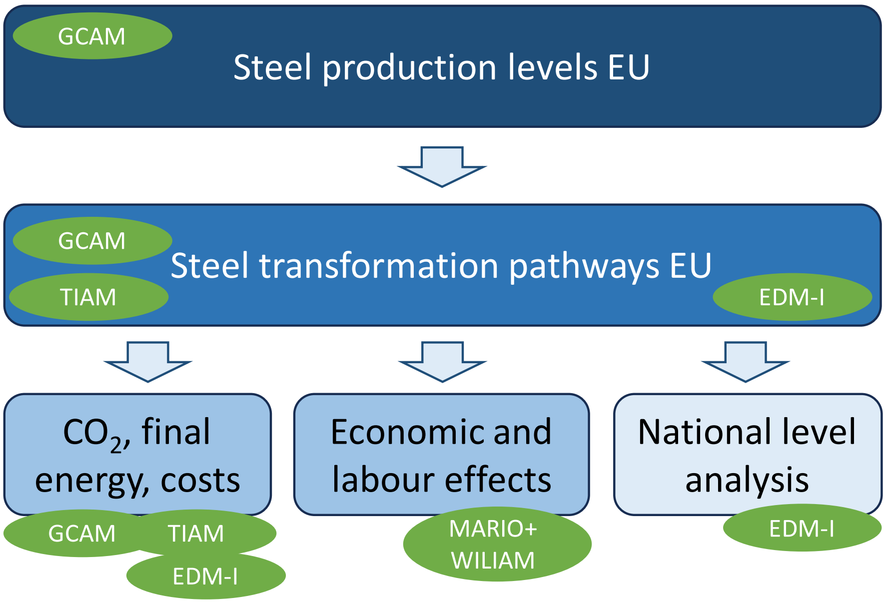

Figure 2-1: Steps of the analysis and models used in each step

Modelling steel production levels of the EU

In a first step, steel production levels in the EU are calculated by GCAM for each scenario. Steel demand per world region emerges from a non-linear model of steel consumption per capita and GDP per capita, where steel consumption per capita reaches a saturation level at higher income levels (Speizer 2023). Steel trade between world regions is represented as Armington-style trade, with a global trade market and regions choosing between domestically-produced steel and imported steel (Zhao 2022). Coefficients of the trade function have been calibrated using historical consumption of domestic and imported steel to account for regional preferences and trade barriers.

Whereas normally in GCAM all steel exports go to a single global trade pool, in this study there are three global trade pools for three steel categories: low-carbon, medium-carbon, or high-carbon production. These are determined by the CO_2 emissions provided in the harmonisation data in the Annex: technologies with emissions greater than 1.37 tCO_2/t steel are classified as high-carbon, those with emissions between 0.59 and 0.79 tCO_2/t steel are classified as medium-carbon, and all other technologies (between –0.87 and 0.37 tCO_2/t steel) are low-carbon. In the CBAM scenario, the EU can then choose to import from any of the three global trade pools with the average direct CO_2 emissions from high- and medium- carbon import categories included in the emissions cap indicated by the EU's Emissions Trading System (ETS). Low carbon imports do not receive any CBAM pricing.

In order to achieve a minimum level of domestic steel production in the EU in the *Strategic Independence* scenario, GCAM uses a subsidy to incentivise EU production. The minimum production quantity, equal to 2019 domestic steel production, is provided to GCAM and the model then determines the necessary subsidy to stimulate this level of production. The value of the subsidy required is primarily driven by the price differential between domestically produced steel and the global export market.

The GCAM model results have been provided as Excel tables in IPCC scenario format for the subsequent steps of the analysis.

Steel transformation pathways EU

The steel production levels calculated by GCAM are then used in a second step as drivers for modelling steel transformation pathways in the EU. This is done by GCAM (implicit in modelling of previous step), TIAM and WISEE EDM-I. The integrated assessment model TIAM includes the steel production levels per world region into its own global modelling for each scenario as it doesn't allow inter regional steel trade in the model. Energy prices are endogenously calculated in TIAM.

The sectoral WISEE EDM-I model adopts the EU steel production levels from GCAM as exogenous driver and in addition uses electricity, hydrogen, natural gas, coal and CO_2 costs resulting from GCAM to set the respective model parameters. Steel demand scenarios resulting from GCAM are translated into steel demands per type of finished steel using Eurofer data (Eurofer 2022) and a material flow scenario for EU steel demand, production and recycling (unpublished).

Impacts of the steel transformation

In the third step, the impacts of the steel transformation pathways are analysed with regards to CO_2 emissions, costs and final energy demand (implicitly calculated in previous step) as well as systemic effects on the economy and labour, the latter being achieved through Input-Output (I/O) analysis with MARIO and WILIAM. Adopting MARIO, an I/O table – namely, the hybrid-units table of the Exiobase database (Merciai and Schmidt 2017) – has been enriched by explicitly modelling the new prospective technologies for steel production described in Section 2.2.1, as well as PV and wind (both on- and off-shore) power plants' supply chains. The obtained table represents the baseline, which is then shocked according to the results coming from GCAM scenarios. In particular, the data exchanged between GCAM and MARIO (as shown in Figure 2-2) concerning electricity and steel supply mixes as well as PV and wind capacity additions across each modelled region and scenario.

Once the new Input-Output Tables are obtained, their results are used as inputs in WILIAM. The new sectoral interlinkages produce direct and indirect spill-over effects across the economy. Consequently, this IAM can assess the socioeconomic impacts of the defined scenarios. Structural hypothesis of WILIAM thereby are:

- Absence of technological disaggregation for mining of iron ore and steel production.
- Presence of input-output tables (assumed from MARIO), so secondary effects given the intermediate trade of products that indirectly assume steel consumption, e.g., from manufacturing vehicles or the real state.
- Presence of an oil feedback between the biophysical and economic modules. Facing a reduction in the demand of oil in some sectors, the reduction of its price generates rebound effects in the economic module. In the following way: + carbon tax --> + oil price --> - oil consumption

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--> (delay) --> + oil availability --> - oil price --> + oil consumption.

- Final demand functions in the economy module assume substitution of commodities to satisfy the money households spend in a year. The reduction of sectors highly affecting the steel demand is partially fulfilled by other – less intensive in steel but consuming something – sectors (secondary effect).

National level analysis

Furthermore, the developments of the EU steel sector are broken down to country level using the WISEE EDM-I. In the EDM-I, steel demand is defined on the EU level and therefore can directly be used from the EU level results of GCAM. Natural gas and coal[3] costs are assumed to be identical for all EU countries and also taken from GCAM. Also, average EU electricity prices are taken from GCAM but varied per country based on a pattern of differences between marginal electricity costs of EU countries. The latter was derived from data from ACER (2020) for 2019 in combination with analyses conducted with the EXPANSE model for three scenarios on the energy crisis conducted in IAM COMPACT, each run by three IAMs (D4.5 "National, regional, global mitigation pathways"; Sasse & Trutnevyte 2023). The results of the EXPANSE model were used for 2035 onwards while 2025 and 2030 have been interpolated. Hydrogen prices for the EDM-I are derived based on average hydrogen prices of the EU as calculated by GCAM and varied between countries according to the same pattern as electricity prices. However, deviations from the EU average hydrogen price are capped by a maximum deviation of 10%, assuming that possibilities for hydrogen imports and exports will lead to a smaller bandwidth of prices.

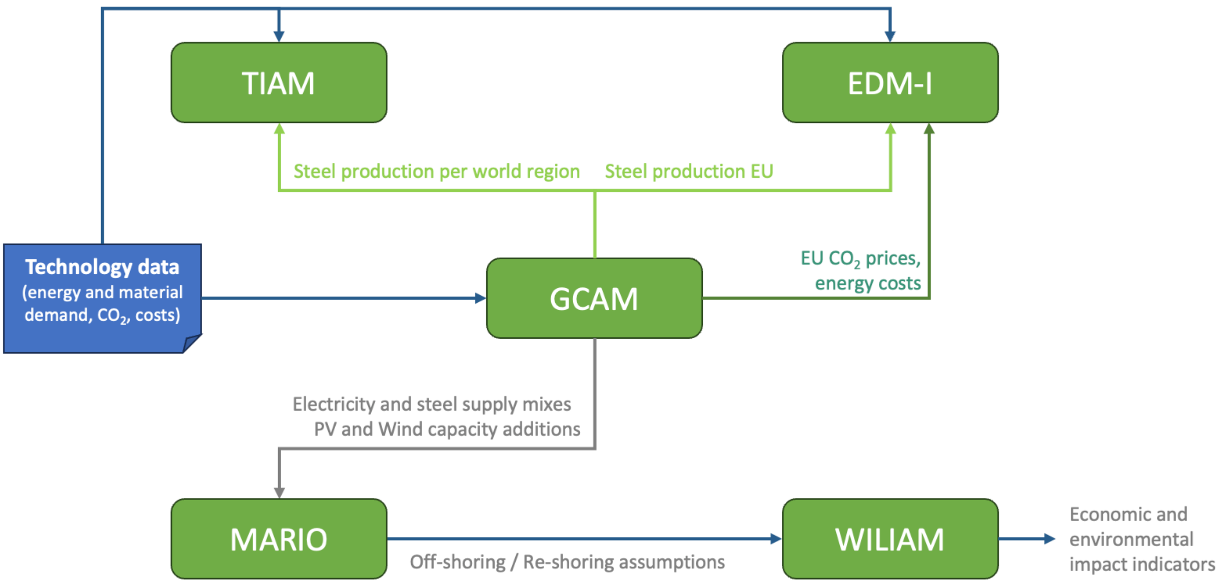

Figure 2-2: Data flows between models

[3] Coal costs calculated by GCAM are used for PCI coal costs while the costs for metallurgical coal are taken from the IEA WEO.

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2.3 Results

2.3.1 Steel production levels in the EU

The development of global steel demand as calculated by GCAM is (almost) identical for all scenarios analysed in this study and increases from 1.8 Gt in 2020 to 2.1 Gt in 2030 and 2.4 Gt in 2050. This growth predominantly comes from low- and medium-income regions where steel demands are expected to increase with rising income. India, the Middle East, and Southeast Asia in particular become major consumers of steel by 2050. Similarly, steel consumption of the EU evolves (almost) identically for all three scenarios, dropping from 166 Mt in 2020 to around 150 Mt in 2030 and to 125 Mt in 2050. GCAM assumes that demand for steel is fairly price inelastic, leading to similar consumption pathways despite differences in steel prices in the EU in these scenarios. But steel imports and exports and EU steel production levels differ significantly between the scenarios due to the divergent assumptions on trade restrictions. In the *NDC_LTT* scenario, off-shoring of EU steel production is seen in 2030 due to the higher production costs arising from ETS pricing of steel production emissions, with production falling 36% from 2020 and net imports reaching 51 Mt. This off-shoring is moderated in the *CBAM* scenario, as higher prices of imported steel limit the decrease in domestic steel production to 27% and net imports in 2030 reach 35 Mt. In contrast, in the *Strategic independence* scenario the EU production remains constant, and the EU becomes a net exporter, with net exports of 5 Mt of steel in 2030. These differences between scenarios largely disappear by 2050 as emissions limits/pricing around the globe reduce or even invert the price differences between EU-produced steel and imported steel.

NDC_LTT scenario

Figure 2-3 shows the EU steel production, consumption, imports, and exports in the *NDC_LTT* scenario as calculated by GCAM. While EU steel production and consumption start from similar levels in 2020, the domestic demand is not entirely covered by domestic production. Instead, parts of the production are dedicated to exports while parts of the consumption draw on imports. In the time period from 2020 to 2030, the EU steel production drops significantly from 156 Mt to 100 Mt. About 33 Mt of the reduction is related to production for domestic consumption and about 23 Mt to production for exports. Imports increase and fill the gap between consumption and EU production for domestic consumption.

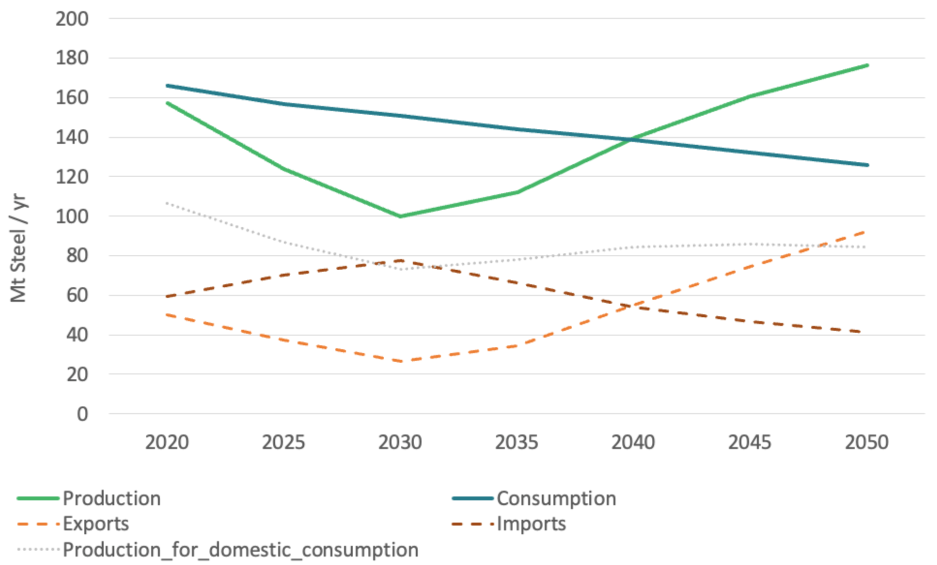

Figure 2-3: EU steel production, consumption, imports and exports in the NDC_LTT scenario as calculated by GCAM. Production for domestic consumption is shown in addition and has been calculated as production minus exports.

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After 2030, production increases significantly until 2050, reaching 177 Mt in 2050. The increase is mainly driven by increases in exports (66 Mt), while production for domestic consumption recovers to some extent as well (11 Mt). As displayed in Figure 2-6 in section 2.3.2 and Figure 2-4 (left) below, the increase of steel production levels goes hand in hand with a strong change in the production structure towards higher levels of secondary steel in combination with EU electricity prices becoming very competitive, compared to other global regions. Figure 2-4 (right) shows, that future low electricity prices in the EU are facilitated by very low – negative[4] – CO_2 prices for electricity production. The comparatively early decarbonisation of the EU electricity sector hence leads to comparatively high prices in 2030 but facilitates the provision of electricity to very competitive prices from 2040 onwards.

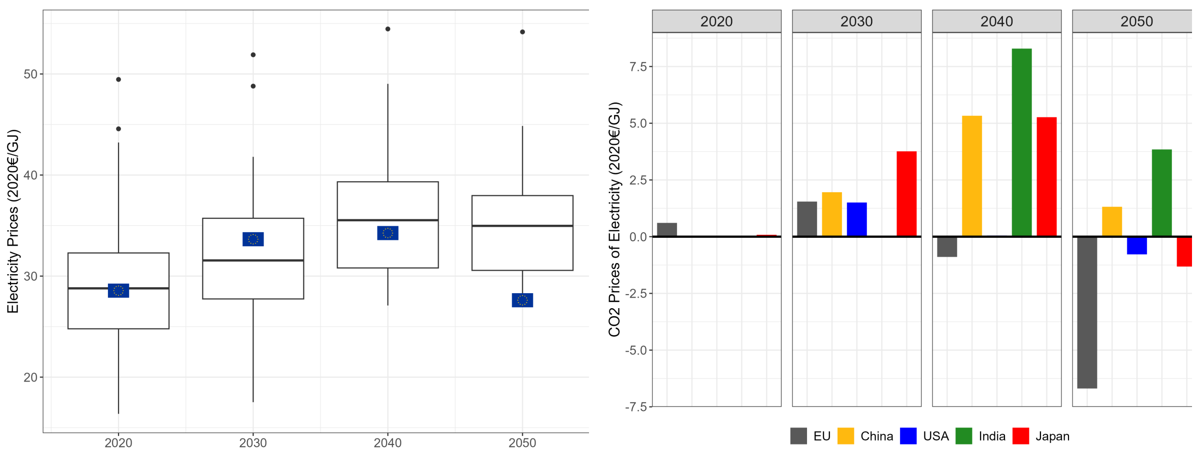

Figure 2-4: Comparison of electricity prices in the EU, compared to other global regions, as projected by GCAM (left). Comparison of CO_2 prices to electricity production in global key steel producing regions, as projected by GCAM (right).

CBAM scenario

In the CBAM scenario, production for domestic consumption drops by about 21 Mt from 2020 to 2030, i.e. less compared to the *NDC_LTT* scenario (Figure 2-5). The reduction in the production for exports is 21 Mt, similar to the *NDC_LTT* scenario. After 2035, production for domestic consumption remains mostly stable and exports increase strongly, to the same extent as in the *NDC_LTT* scenario (66 Mt). Overall, 182 Mt of steel are produced in 2050 in the *CBAM* scenario, which is slightly higher than in the *NDC_LTT* scenario due to higher production for domestic consumption. The effects of the CBAM are relatively insignificant by 2050 because pricing on emissions makes low-carbon steel more price-competitive with steel produced by high emitting technologies. For EU imports, emissions pricing in the EU allows low-carbon steel imports to compete with higher emitting domestic steel technologies. For EU exports, emissions pricing in other global regions leads global production to move towards more expensive low-carbon technologies, making EU steel production more cost competitive with exports from other regions.

According to the scenario results, CBAM is effective for protecting production for domestic consumption being replaced by (additional) imports to some extent. It does not, however, protect the export business of the EU steel industry from the effects their higher production costs have in the competition on the

[4] Resulting from biomass use in combination with CCS.

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global market. The design of the CBAM, which addresses only steel entering the EU, does not allow for the latter – an issue that has prompted energy-intensive EU industries subject to CBAM to demand tangible export solutions in addition to the current import-oriented regulations.[5] CBAM is thus effective in reducing relocation of the EU steel industry to some extent, but not fully.

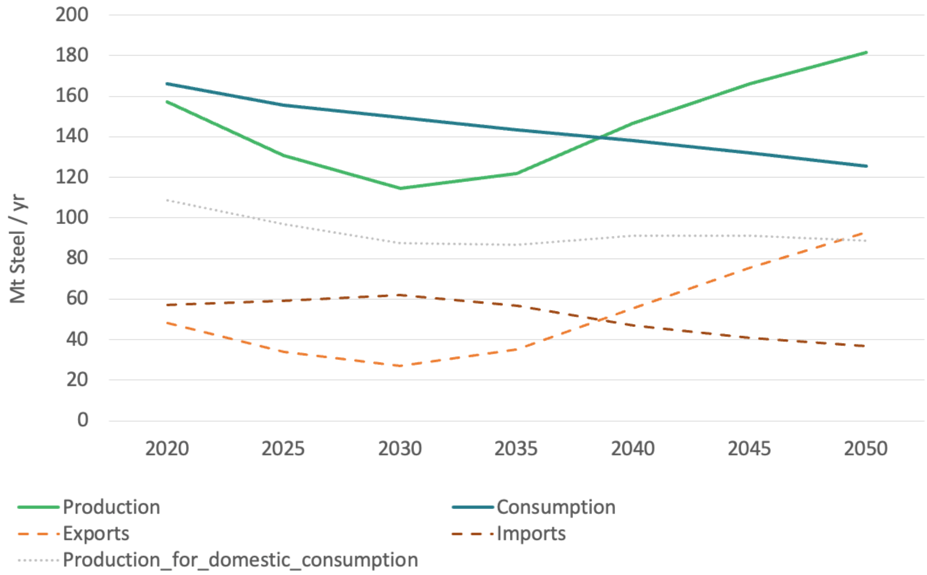

Figure 2-5: EU steel production, consumption, imports and exports in the *CBAM* scenario as calculated by GCAM. Production for domestic consumption is shown in addition and has been calculated as production minus exports.

Strategic independence scenario

In the strategic independence scenario, production must remain at least at 2019 levels, by scenario design. The production for domestic consumption drops by 14 Mt between 2020 and 2030, while in contrast to the other two scenarios, exports increase in the time period from 2020 to 2030 already, by 14 Mt. In sum, production stays constant until 2040 and then increases, reaching levels similar to the other two scenarios. The developments are depicted in Figure 2-6.

5 https://www.eurofer.eu/publications/position-papers/cbam-sectors-statement-on-ets-and-cbam-trilogues

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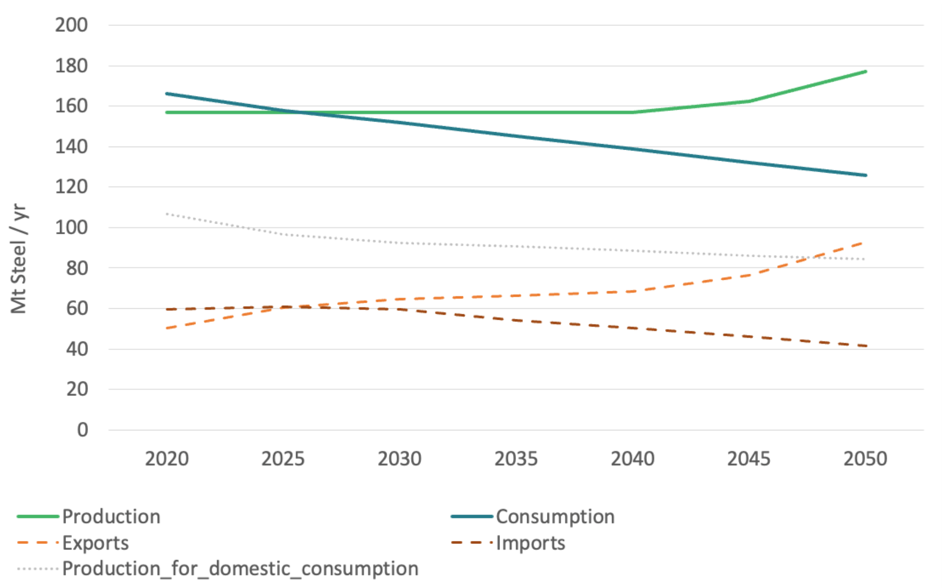

Figure 2-6: EU steel production, consumption, imports and exports in the *Strategic independence* scenario as calculated by GCAM. Production for domestic consumption is shown in addition and has been calculated as production minus exports.

2.3.2 Steel transformation pathways in the EU

The three scenarios have been modelled with GCAM, TIAM and WISEE EDM-I, using the steel production volumes for the EU as calculated by GCAM as input. Figure 2-7, Figure 2-8 and Figure 2-9 show the steel production by technology for the time period 2020 to 2050 for the three scenarios for each model. It can be noted that the technology mix is similar in 2050 between scenarios, according to each of the models. The difference in production volume in the years around 2030 is "filled up" with production from technologies that have been available before 2030, while the diffusions of low-emission primary steel production in absolute capacity appears to be very similar between the scenarios, for each model.[6]

The pathways differ, however, significantly between the models. GCAM – based on its Logit-approach – leads to results with a broad portfolio of technologies being actively used for production, also in the long-term. Secondary steel, however, stands out to play the dominant role in GCAM results after 2035, reaching about 76% of the production in 2050. According to TIAM, the BF/BOF with and without CCS remains the dominant production technology for primary steel, also in the long-term.[7] In the results of WISEE EDM-I, hydrogen-based DRI in combination with either EAF or BOF become the main primary steel production routes in the long-term, with natural gas-based DRI building a "bridge" towards this. The use of secondary steel is limited in the EDM-I depending on scrap contamination with copper and covers approximately half of the production in the long-term. In 2030, however, the available high-quality scrap (without contamination) is sufficient to satisfy most of the demand for high-quality steel

[6] The exception being 2035 in the WISEE EDM-I. In this case the *Strategic Independence* scenario shows significantly higher production technology for low-emissions primary steel, compared to *NDC_LTT* and *CBAM*. This difference is, however, almost leveled-out by 2040.

[7] It should be noted that TIAM calculates own energy and CO_2 costs, while the results of GCAM and WISEE EDM-I are based on the (almost) same set of cost values.

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in the NDC_LTT and CBAM scenarios, (according to the model).

Figure 2-7: Steel production by technology in the ***NDC_LTT, CBAM and Strategic Independence (from top to bottom)*** **scenarios resulting from GCAM.**

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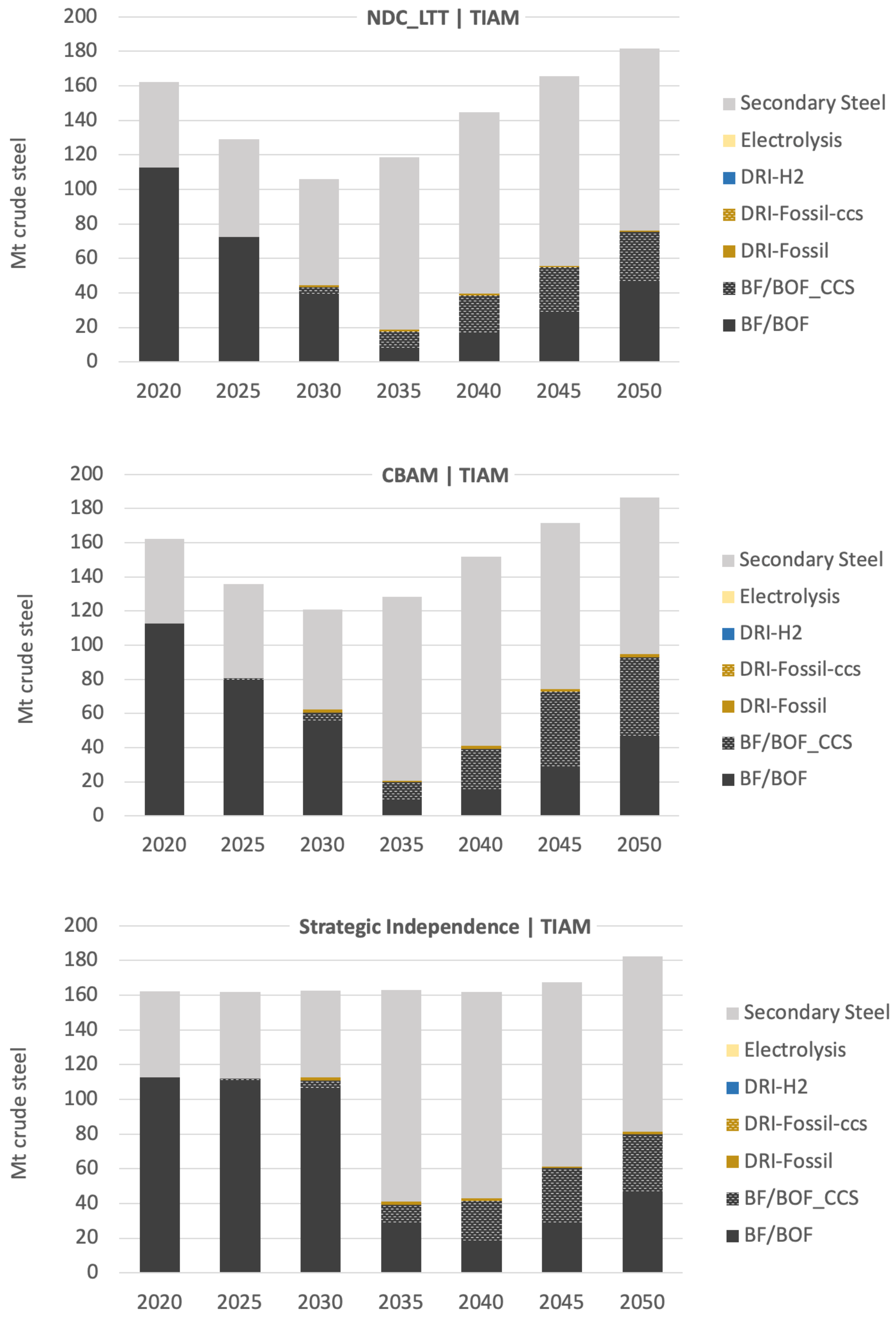

Figure 2-8: Steel production by technology in the ***NDC_LTT, CBAM and Strategic Independence (from top to bottom)*** **scenarios resulting from TIAM.**

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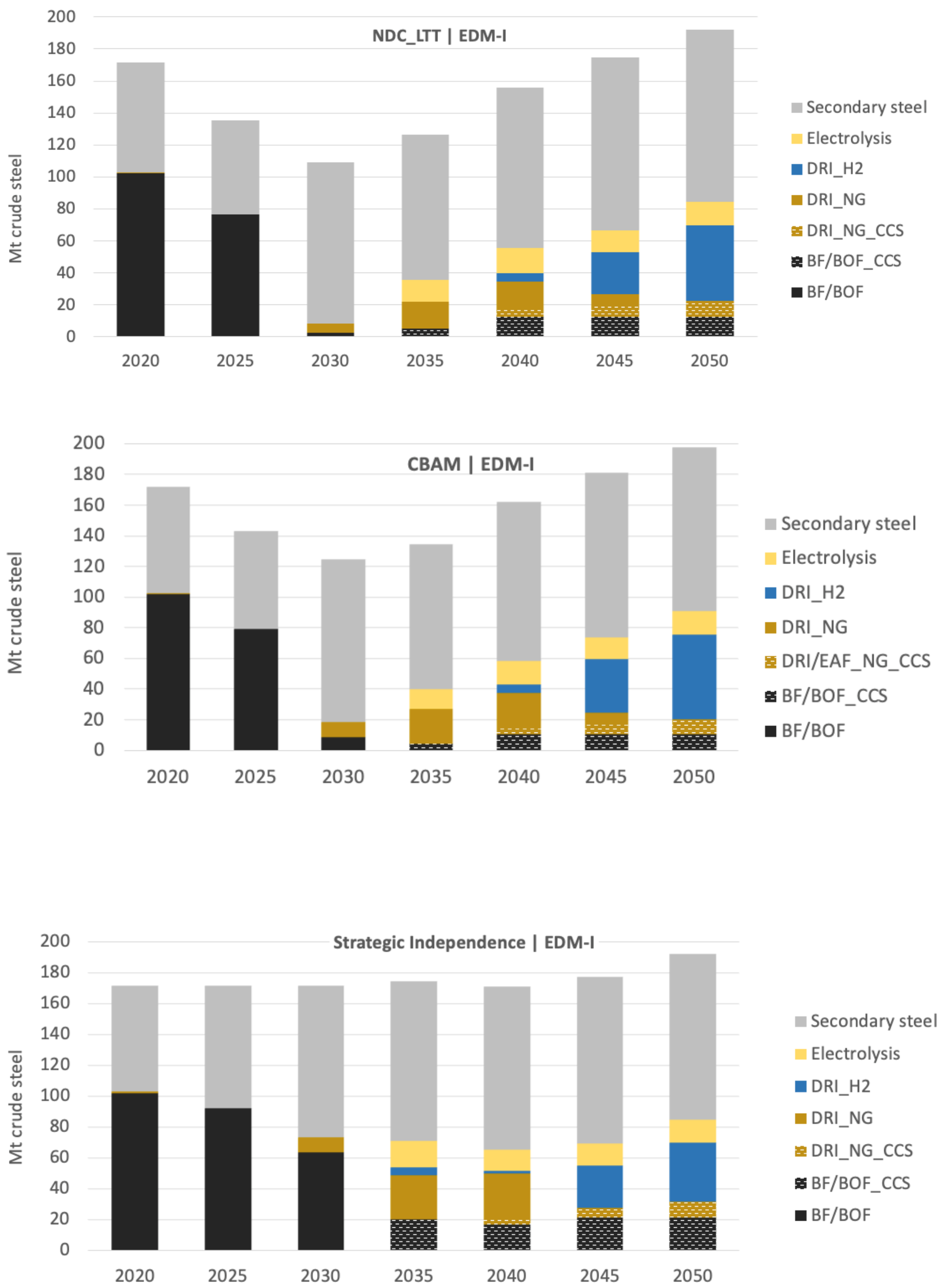

Figure 2-9: Steel production by technology in the *NDC_LTT, CBAM and Strategic Independence (from top to bottom)* scenarios resulting from WISEE EDM-I.

2.3.3 CO_2 emissions, costs and final energy demand

CO_2 emissions

Figure 2-10 shows the CO_2 emissions of the EU steel industry that result from the production volumes and technology pathways outlined above. It can be observed that CO_2 emissions of the *Strategic Independence* scenario are significantly higher until 2035 than in the other scenarios, in line with the higher production volume. Besides that, there are no strong differences between the scenarios, reflecting the similarity of technology pathways. While CO_2 emissions decrease over time according to GCAM and WISEE EDM-I, TIAM shows a different pattern in which CO_2 emissions start to increase again after 2035, in line with the revival of (unabated) BF/BOF.

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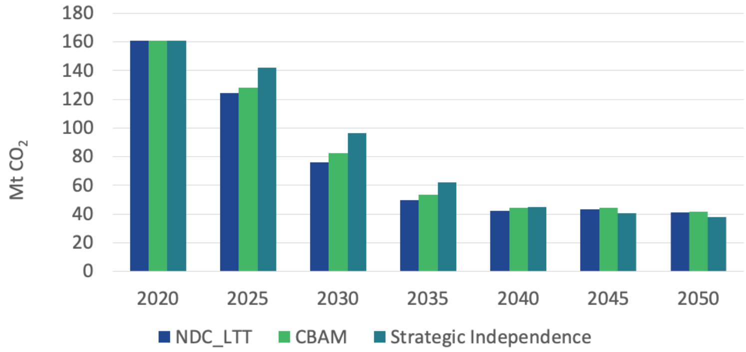
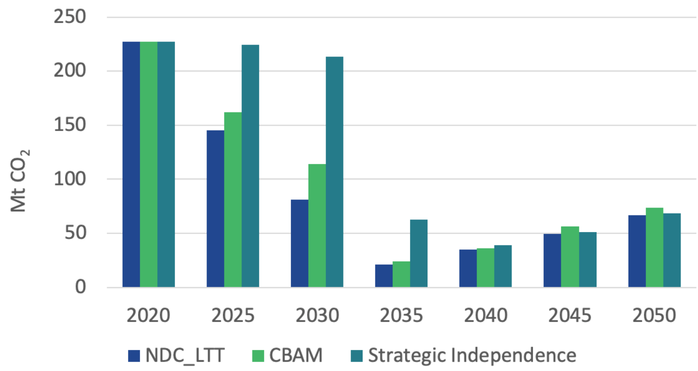
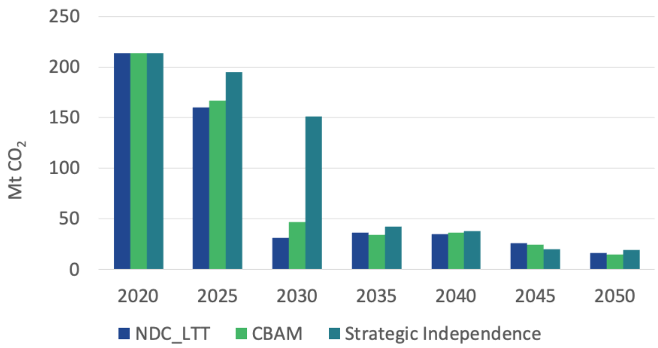
CO_2 emissions of the EU steel industry reported for the (modelled) base year 2020 differ to some extent between the models, what indicates potential for further harmonisation. The following factors explaining this could be identified: a) slightly different production volumes of primary steel due to differences in shares of secondary steel; b) consideration of different coal types.



(a) GCAM



(b) TIAM



(c) WISEE EDM-I

Figure 2-10: Development of CO_2 emissions of EU steel industry resulting from (a) GCAM, (b) TIAM, and (c) WISEE EDM-I.

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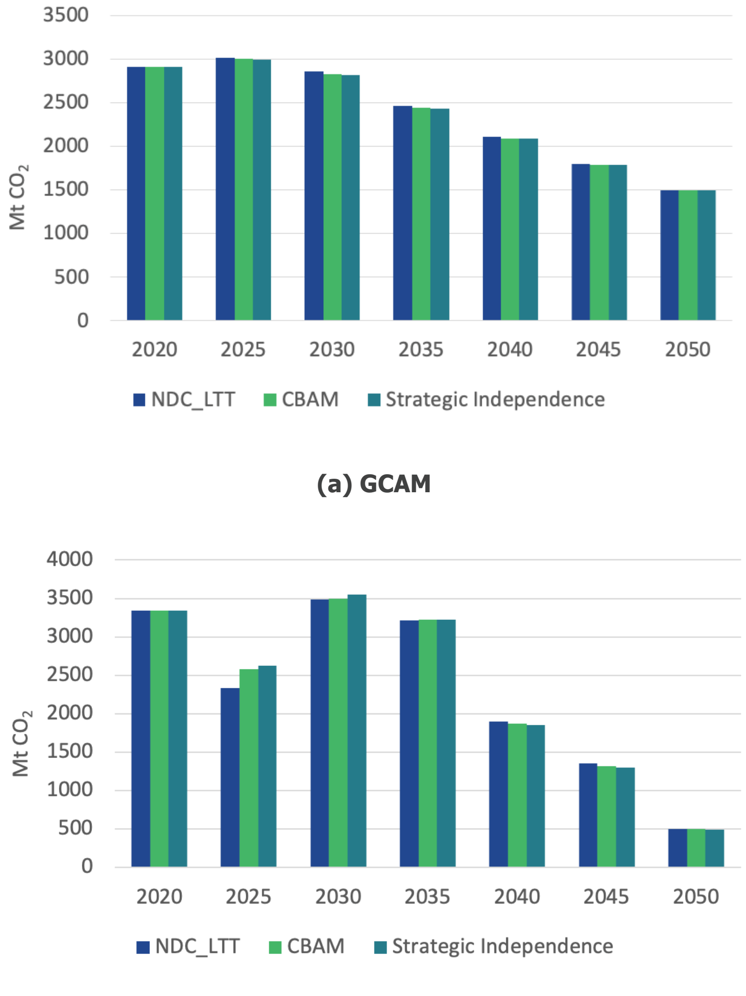
Figure 2-11 displays the CO_2 emissions of the global steel industry, as resulting from the two global models GCAM and TIAM. It can be observed that the emissions start to drop after 2030 / 2035 in both models and across all scenarios, despite a further increase of global steel production volume. I.e. the pattern of rising CO_2 emissions after 2035 generated by TIAM for the EU is not reflected on the global level. The difference of CO_2 emissions of the global steel industry is small between scenarios in both models. Increased amounts of production in the EU (*CBAM*, *Strategic Independence*) in the years around 2030 slightly reduces global steel related CO_2 emissions according to GCAM, but slightly increases them according to TIAM. These results deserve closer scrutinization in future work but the small differences between scenarios indicate that trade restrictions of the EU overall have a limited effect on global steel-related emissions.



(b) TIAM

Figure 2-11: Development of CO_2 emissions of the global steel industry resulting from (a) GCAM and (b) TIAM.

Electricity and hydrogen demand

Several of the low-emissions steel production technologies such as hydrogen-based DRI and electrolysis make use of large amounts of (renewables based) electricity and hydrogen. Due to the steel sector's

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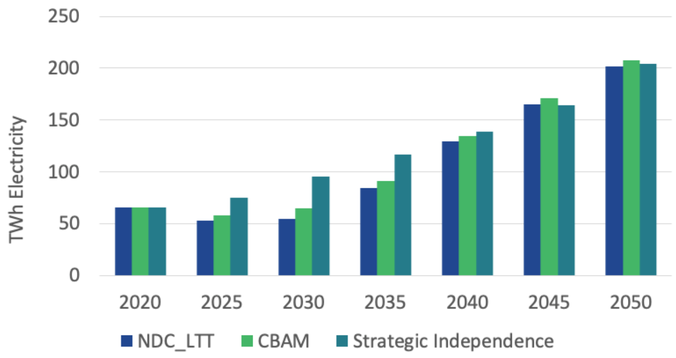
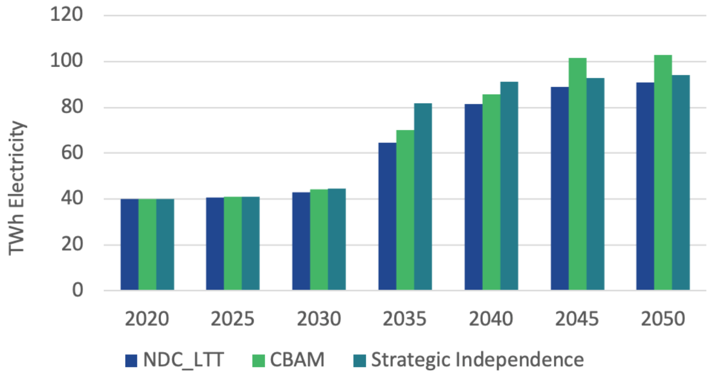
(potential) large consumption of renewables, the development of the sector's energy demand is of importance for the planning of renewables upscaling and associated infrastructure development. For example, steel is a potential key user of hydrogen and plays a prominent role in roadmaps and strategies for hydrogen upscaling such as the EU hydrogen strategy (European Commission 2020).

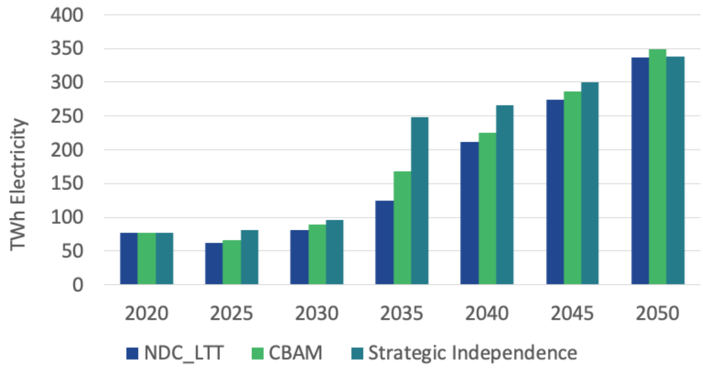
The direct electricity demand of the steel sector resulting from the scenarios at least doubles, according to the models (see Figure 2-12). Although the models project different technology pathways, each of them requires significant amounts of electricity – be it for electric arc furnaces, electrolysis or CCS. The direct electricity demand differs only to some extent among scenarios, mostly in line with production volumes.



(a) **GCAM**



(b) TIAM



(c) WISEE EDM-I

Figure 2-12: Development of direct electricity demand of the EU steel industry resulting from (a) GCAM, (b) TIAM, and (c) WISEE EDM-I.

The difference of direct electricity demand in the base year between models indicates potential for further harmonisation. The main reasons presumably are different production volumes and different

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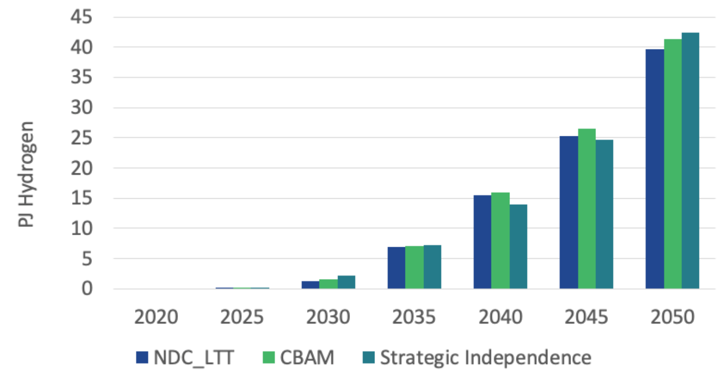
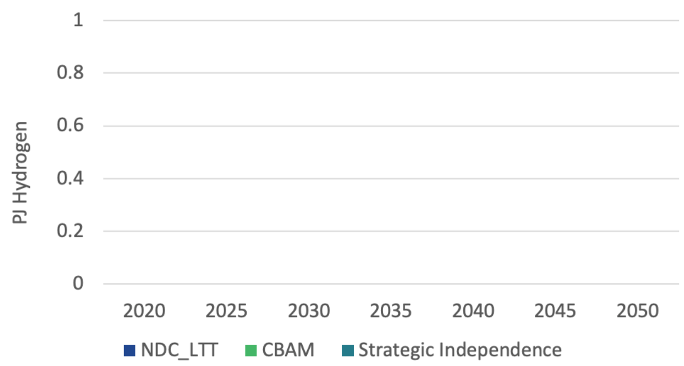
amounts of secondary steel production.

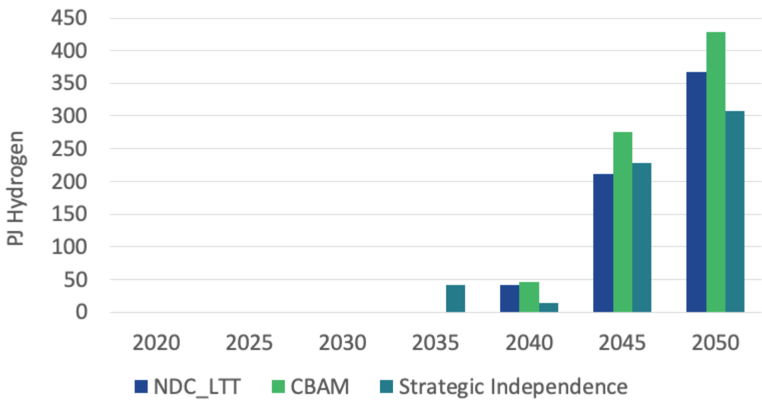
Figure 2-13 shows the hydrogen demand of the EU steel industry that results from the scenarios. Similar to the direct electricity demand, the differences are much more significant between models than between scenarios, due to the very different technology pathways resulting from the different models. While WISEE EDM-I projects high hydrogen demands of about 300-450 PJ, the projected demand is much lower in GCAM (less than 45 PJ) and zero according to TIAM.



(a) GCAM



(b) TIAM



(c) WISEE EDM-I

Figure 2-13: Development of hydrogen demand of the EU steel industry resulting from (a) GCAM, (b) TIAM, and (c) WISEE EDM-I.

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Costs

Results for costs have been derived from GCAM and WISEE EDM-I (**Figure 2-14**). According to GCAM, specific production costs develop similarly across all scenarios: they increase from around 505€/t to around 710€/t in 2035 and then slightly drop to around 680 €/t by 2050. Considering the large share of secondary steel in GCAM's results, the main reason for the cost decrease after 2035 (presumably) is a drop in electricity costs in the EU by 20% in the period 2035 to 2050. According to EDM-I, specific costs of steel increase more slowly in the *NDC_LTT* and *CBAM* scenarios and reach a cost level of about 720€/t by 2050 in all scenarios, which is slightly higher as projected by GCAM.[8] For the *Strategic Independence* scenario the EDM-I projects significantly increased costs of steel production for 2030. As the use of secondary steel is limited in the EDM-I and low-emission technologies become available at scale only after 2030[9], the model is forced into the production of BF/BOF steel, whose significant CO_2 emissions are penalized with 195€/t CO_2. This is the case to a much lower extent in the *NDC_LTT* and *CBAM* scenarios.

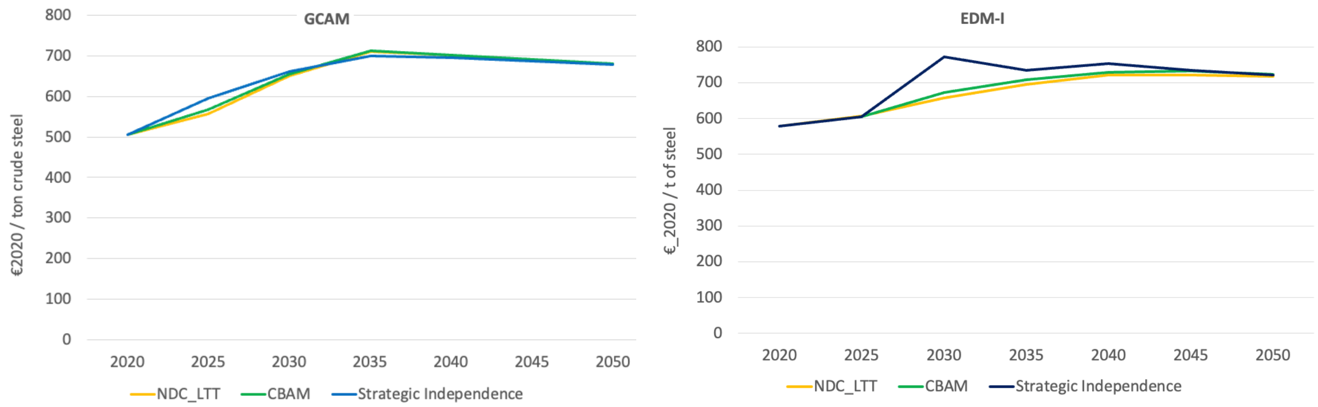

Figure 2-14: Steel production costs in the EU in all three scenarios, according to GCAM (left) and EDM-I (right)

GCAM in addition allows to calculate steel consumption costs (Figure 2-15). These follow a pathway that is similar to domestic steel production costs but are slightly lower due to imports being cheaper than domestic production. In the NDC_LTT scenario, the dampening effect of cheap imports on consumption costs is strongest. It should be noted that the constantly high level of domestic production in the *Strategic Independence* scenario is achieved through subsidies to domestic steel production. If – taking a societal perspective rather than a customer perspective – these subsidies are added to steel consumption costs, the resulting costs of steel consumption are higher in this scenario than in the other two scenarios most of the time (dashed line in Figure 2-14).

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[8] Specific costs differ between GCAM and WISEE EDM-I due to a) higher shares of secondary steel in GCAM results, compared to EDM-I; b) EDM-I assumes coking coal being used for steel making which has higher costs compared to the stylized (average) coal costs calculated by GCAM.

[9] DRI production is limited to 10 Mt/year in 2030 due to considerations of limited engineering capacity to build-up these plants before 2030 and CCS is not allowed before 2030, mirroring that up to date no company has announced plans to apply CCS at integrated steel plants in Europe.

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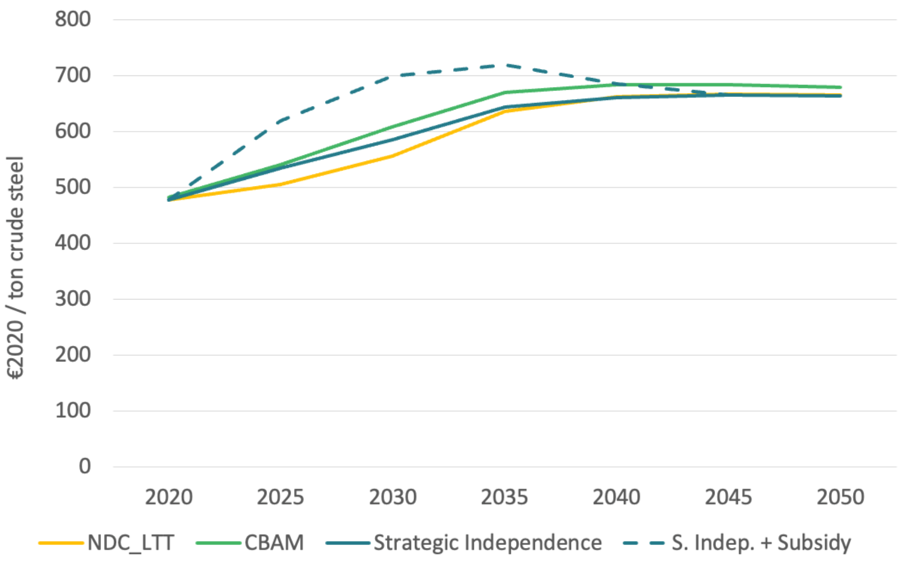

Figure 2-15: Specific consumption costs of steel in the EU in all three scenarios, according to GCAM

2.3.4 Economic and labour impacts

In this section, we show and describe the macroeconomic and employment impacts of the scenarios simulated under the MARIO-WILIAM protocol. Following this protocol, MARIO has provided the input-output tables of all the scenarios each 5 years from 2005 to 2050 as off-shoring/re-shoring assumptions to WILIAM. The structure of intermediate trade in regional economies is exogenously determined. For instance, the flow of sales from the 100%-hydrogen steelmaking industry to other sectors of the European Union is 26% higher in 2030, from the CBAM to the NDC_LTT scenario, and 8% higher in 2050. As result of the independence policy, these values are even higher, 56% in 2030 and 38% in 2050.

There were some limitations in the harmonization of the scenarios with the rest of IAMs. In order to avoid misunderstanding in results, we described how the exercise has been translated into this model in section 2.2.3 above.

Consequently, the scenario is reproduced by applying:

- A percentual reduction of steel consumption as final demand of those sectors affecting more steel, i.e., highest technical coefficients within the I/O table, and highest final consumption. Over time, 12-13% from 2015 to 2030 and 16-17% from 2030 to 2050 in the three scenarios, *NDC_LTT*, *CBAM*, and *Strategic Independence*.
- The offshoring and then onshoring effect in Europe is reproduced through the implementation of two different trends, applying to 2015-2030 and 2030-2050, in the import share of the steel sector. This means an increasing ramp of a total 88% (*NDC_LTT*), 28% (*CBAM*), and 0% (*Strategic Independence*) for the first period, and a decreasing ramp of 71%, 64%, and 47%, respectively (see Figure 2-16).

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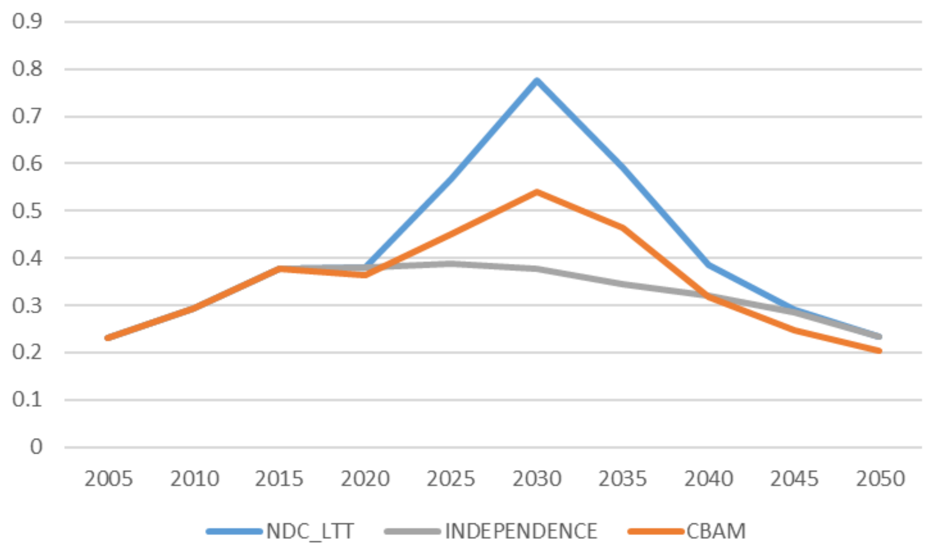

Figure 2-16. Evolution of the import share in the three scenarios. Data used as input parameter in WILIAM.

The results are shown for 2030 and 2050. In this deliverable, we focus on gross domestic product (GDP) and employment in sectors of the EU27 and China (the largest supplier of steel worldwide), providing a broad view on the topic. It should be noted that WILIAM 1.2 BETA was used for this exercise, so the results should be considered as preliminary.

Gross Value Added by the Steel industry

WILIAM could not reproduce the V-shape trend for steel production since it does not feature an explicit technological disaggregation of the steel industry but the sector is economically accounted in the model as a whole. The economic output of this sector in EU-27 would grow in the *NDC_LTT* scenario, from 20 to 25 billion $2015/year from 2015 to 2030, and up to around 43 billion $2015/year in 2050. Related to it, *CBAM* delivers 3% higher output during the offshoring period and 0% during the second period; meanwhile, *Strategic Independence* is 6% higher in 2030 and 1% lower in 2050. However, this simulation has been conducted by models without any biophysical limitation, which implies to consider the economy as an intangible system. Therefore, the economic growth may here be partially misleading because of the neglect of biophysical constraint feedbacks in WILIAM. For example, a shutdown in the extraction or international trade of iron ore could generate a bottleneck in the value chain of steel, limiting the capacity to grow.

Interesting findings are present in the regional trade (Figure 2-17). Germany, Spain, Italy and France are the main suppliers of steel in the EU. Their future production shares are assumed to be constant in the scenarios. From 2015 to 2030, results indicate a negative variation in the gross value added of the sector for Germany and Italy, while France and Spain increase (except *NDC_LTT* for Spain, whose value is -11%). So, the impact of the offshoring period does not equally benefit EU-27 countries. Due to the conditions of the international market, Germany is most affected and its gross value added falls in between 10-18%. However, France is benefited in between 9-26%. According to our data, France imported 99.8% of the final demand of steel (2015) while Germany imported 18.2%. So, an offshoring trend in France is negligible in comparison to Germany, where the import share in 2030 could reach up to 45% (*NDC_LTT* scenario).

The second period (onshoring, 2030-2050) turns the steel sector into a situation where Germany and Italy would grow in all the scenarios given the higher independency in the imports. France could take advantage of the *Strategic Independence* scenario and follow Germany with 13% growth for this period. The case of Spain is paradigmatic, a country whose steel sector would increase by 80% in the *NDC_LTT* or 57% in the *CBAM* scenario.

The input-output matrix reveals secondary effects in sectors highly influenced by the steel sector. Spain, for example, shows -0.6% (2030) and -0.5% (2050) in the gross value added of manufacture of vehicles in the *CBAM* scenario related to the *NDC_LTT*. However, the *Strategic Independence* scenario implies a small increase of 0.2% and then 0% in 2030 and 2050, respectively. In the other countries, the *Strategic Independence* scenario also shows higher values for this sector. So, the German manufacture of vehicles would be 0.07% (2030) and 0.08% (2050) higher than in *NDC_LTT*. In Italy, these values are 0.24% and 0.01%; and in France, 0.81% and 0.76%.

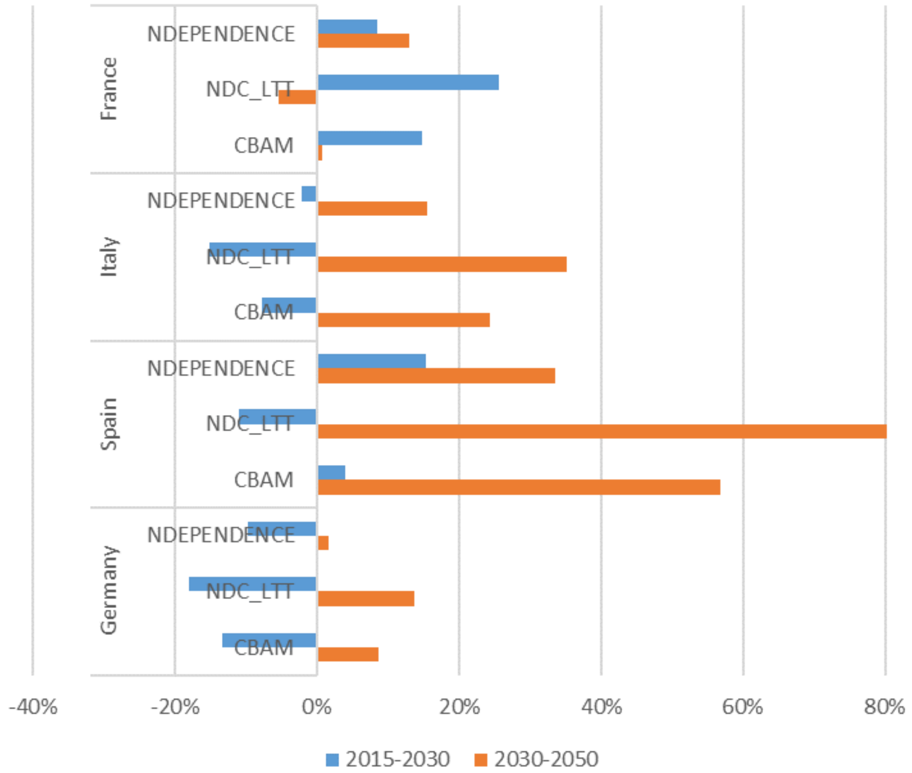

Figure 2-17. Variation in the gross value added in the steel sectors of the four main European suppliers of steel for the three scenarios (NDC_LTT, Strategic Independence and CBAM).

Employment

The effect on the employment of the steel sector is tightly connected to the evolution of production. Similarly to the previous indicator, *CBAM* presents 1.6% (3.6% in *Strategic Independence*) higher employment than *NDC_LTT* by 2030, to then decrease. At the end of the simulation, 2050, the employment of the Steel sector in *CBAM* is just -0.03% lower, while *Strategic Independence* is around 0.7% lower than the NDC_LTT scenario. The total employment in the economy is slightly affected, -0.52% (*CBAM*) and 0.36% (*Strategic Independence*) by 2030, and 0.12% and 0.15% by 2050, respectively related to *NDC_LTT*. This is explained by comparatively higher employment intensity of the sectors involved in the transition regarding steel (i.e. cement, mining, fuels extraction, electricity, as pointed out in Section 2.2.1).

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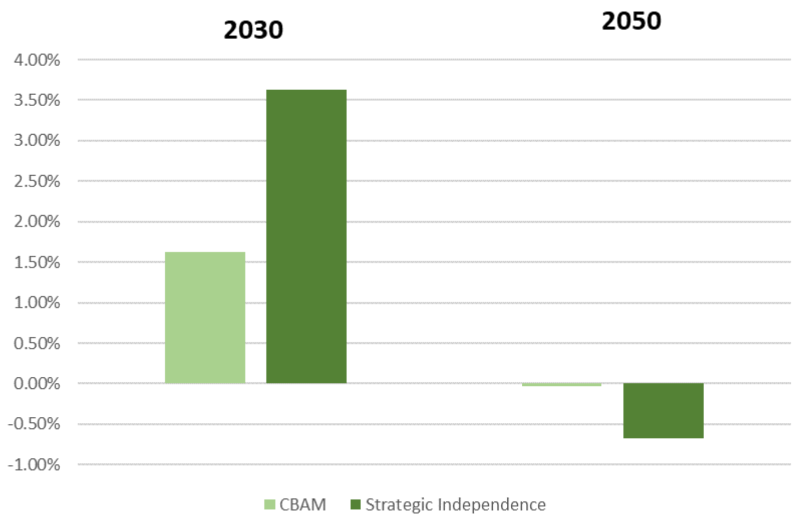

Figure 2-18: Employment in the steel sector of the *Strategic Independence* and *CBAM* scenarios, as compared to the *NDC_LTT* scenario.

Worldwide, the geological extraction of ferrous minerals (Mton/year) is more intensive in the *Strategic Independence* scenario (0%, related to *NDC_LTT*) than *CBAM* (-0.19%, related to *NDC_LTT*) by 2030, and similarly by 2050, 0.14% and 0.10% related to the *NDC_LTT* scenario.

Model enhancement options

The exercise delivers ideas to further improve WILIAM. This model would benefit from a bottom-up approach to detail the technological set for steel production. The annex of this deliverable helps in this task, which contains data of energy and emission intensities. However, material intensities are missing so far. Furthermore, the data for extraction and prices of iron ore grades can be further improved with an additional careful review of this module and the connection with the corresponding economic sector. These improvements would allow a new realm of findings related to scenarios of onshoring and offshoring, showing the effects of having the mining of iron production abroad while the steel processes at home.

2.3.5 National level analysis

The results of the WISEE EDM-I are further analysed on the national level of EU member states. A main input into the modelling is the pattern of electricity and hydrogen price deviation from the EU average price which has been derived from empirical data and EXPANSE results on marginal electricity costs (see section 2.2.3). This pattern, which is depicted in Figure 2-19, has been applied to the average electricity and hydrogen costs, as calculated from GCAM, for all modelled years (including the base year) to calculate the electricity and hydrogen costs per country and year.

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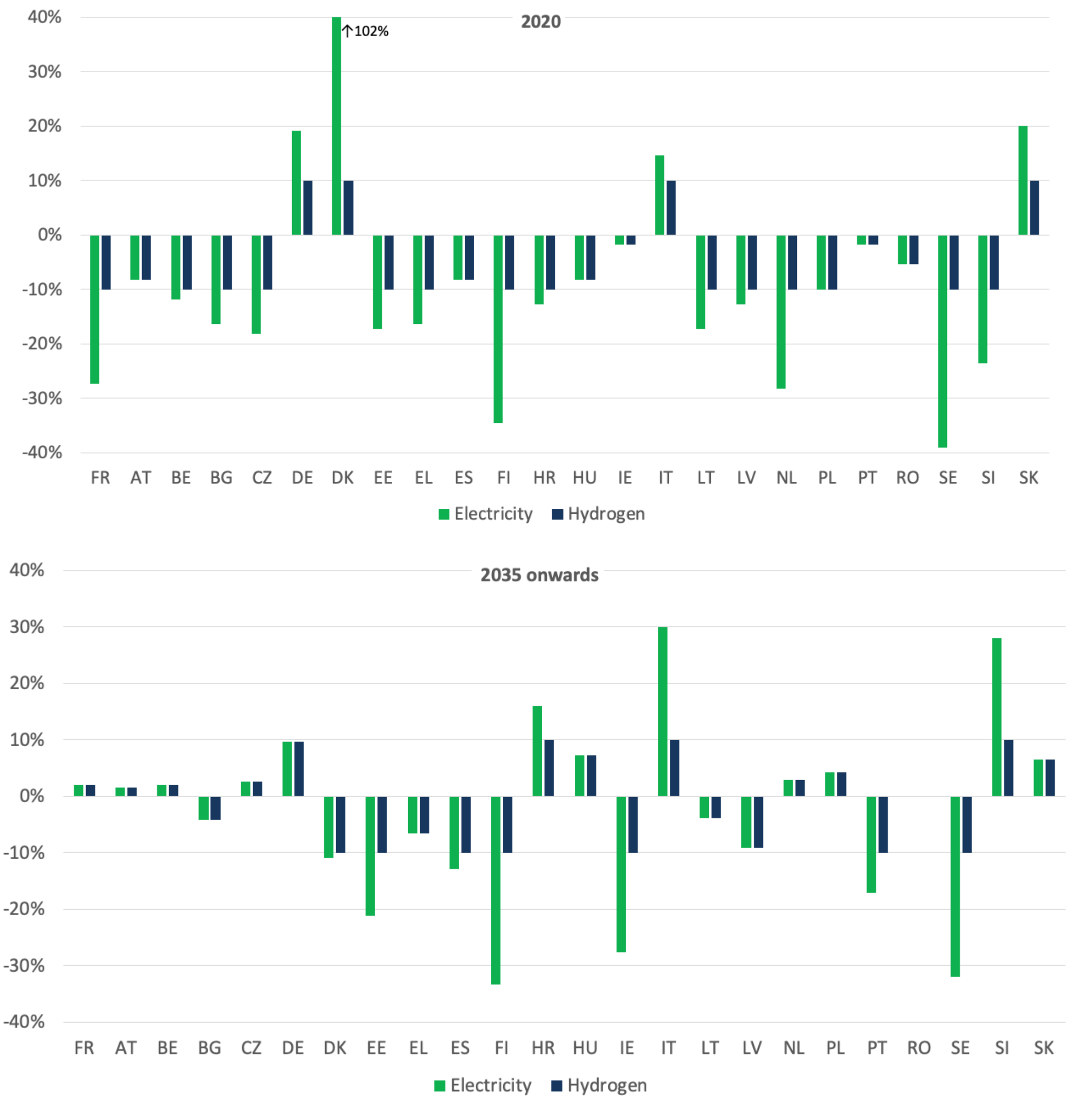

Figure 2-19: Deviation of electricity and hydrogen prices in EU member states from average price in the EU in the year 2020 (top) and 2035 onwards (below)

Figure 2-20 (top) shows that the model approximates the distribution of crude steel production in the EU in the base year well. In all scenarios, the crude steel production then becomes relocated over time to countries with low electricity and hydrogen costs, with Finland taking a very dominant role in 2050 (Figure 2-20 middle and bottom). This relocation happens on the one hand in the context of changing primary steel production routes (see Figure 2.8). Existing BF/BOF capacities reach their end-of-life in currently dominant steel producing countries (e.g. Germany) while new capacity is built up where energy costs are lowest. On the other hand, also secondary crude steel production relocates to countries with low electricity costs, while existing capacity in current secondary steel producing countries are still existing but become stranded assets. The development of capacity is exemplified for electric arc furnaces (EAF) and the *NDC_LTT* scenario in Figure 2-21.

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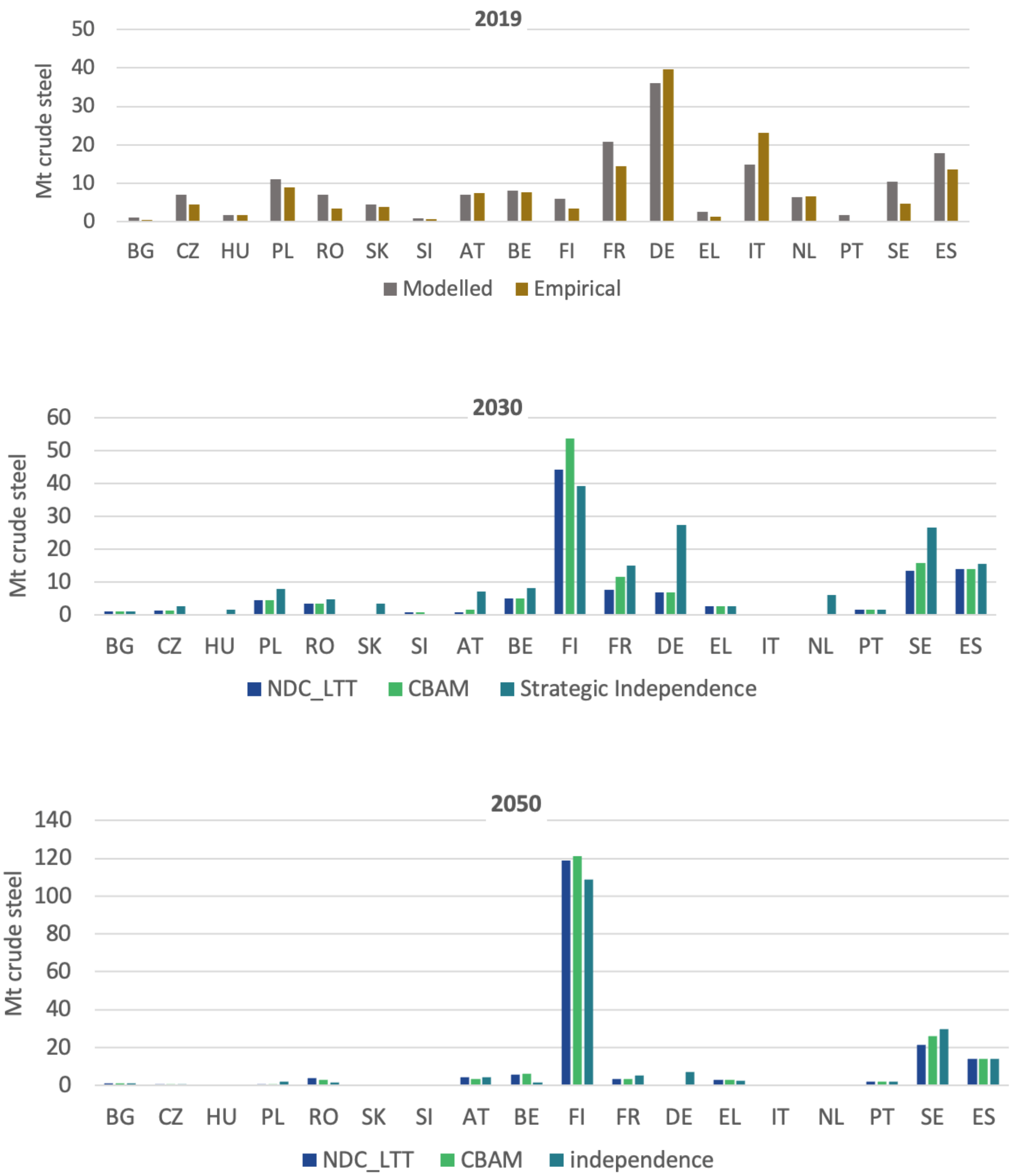

Figure 2-20: Crude steel production in EU member states in 2019 (top), 2030 (middle) and 2050 (below)

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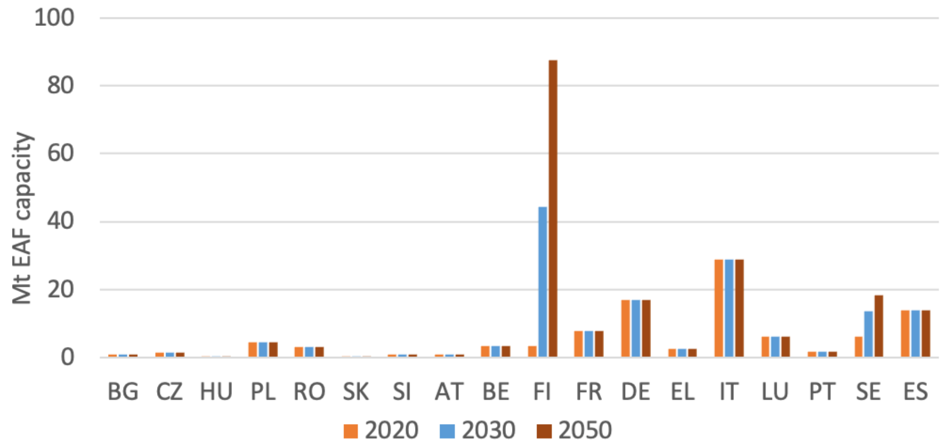

Figure 2-21: EAF capacity in EU member states over time in the NDC_LTT scenario

The relocation does not stop with crude steel production, but also affects steel finishing (Figure 2-22), according to the model. I.e., crude steel is not transported from newly built-up crude steel capacity to existing steel finishing plants. Instead, new steel finishing capacity is built-up at locations with low electricity costs, in addition to crude steel production capacity. In sum, the (assumed) energy price differences between member states have higher impacts on the steel transformation than path-dependencies due to existing production stock, leading to a complete relocation of production capacities to countries with low energy costs.

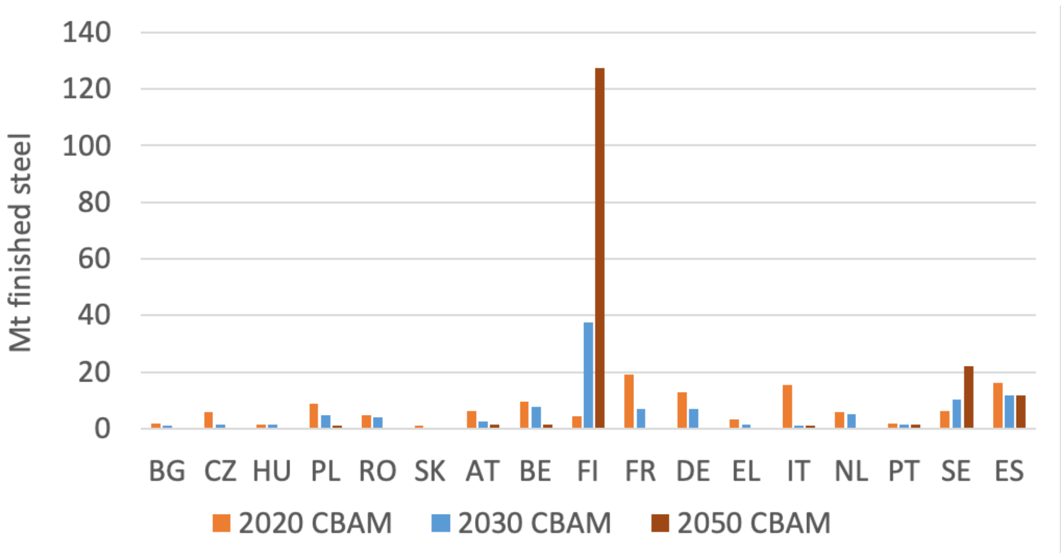

Figure 2-22: Production of finished steel in main steel producing EU member states over time in the CBAM scenario

These results demonstrate the capacity of the WISEE EDM-I to model relocation effects within the EU while differentiating different steps of the production value chain (iron reduction, crude steel production, steel finishing) as well as considering production volumes and production capacities. The

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national-level granularity of the model allows to take the role of "sweet-spots" for specific production routes into account and the effects that deviation from average energy costs may have on the transformation pathway on the EU level.

However, it should be noted that the current version of the model is not able to take into consideration several locational factors that likely influence the real-world transformation of the industry, including potential impacts of high electricity and hydrogen demands on the energy systems of member states and related energy costs, the existence or creation of production ecosystems (e.g. skilled workforce, suppliers) and advantages of spatial proximity of steel production to costumers.[10] Hence, the scenario results should only be understood as carving out some tendencies from a techno-economic perspective.

2.4 Conclusions and Outlook

The work conducted so far and presented in this Deliverable established the interconnection between all models involved in this exercise and demonstrated the analytical power of the combined models. The analysis of the steel sector as integral part of the energy system showed that the EU steel industry faces tendencies for off-shoring in the time period around 2030, if no measures are taken. However, it also shows that the comparably fast decarbonisation of the EU electricity sector entails competitive advantages for steel after 2040. Low-emissions primary steel technologies will scale only after 2030, according to the models and this process will not be accelerated through keeping additional production capacity within the EU. As a consequence of increasing CO_2 prices and the transformation of the steel sector towards low-emission technologies, specific costs of steel production increase from about 500€/t in 2020 to about 700€/t in 2050, in all scenarios. If trade is restricted, EU steel related CO_2 emissions, GVA and employment increase in line with higher production volumes, while the effects on global steel related CO_2 emissions remain uncertain, based on the analysis. Concerning the EU-member-state level, the analysis reveals that differences in renewable energy prices between member states affect locational factors, which creates a tendency for relocation of production to those member states which feature the lowest renewables costs.

The comparison and analysis of these results allowed the identification of potential for further harmonisation and enhancement of the involved models as well as for extending the analysis to the inclusion of DRI trade and to the subnational level. The work may thus be continued in the PRM-2 cycle of the IAM COMPACT project, depending on the outcomes of the co-creation process with stakeholders.

[10] An enhanced version of the EDM-I which allows to define steel demand on a sub-EU level (e.g. member state level) has been developed while this report was written. But member state level data on steel demand per steel product type still needs to be gathered. We aim to apply the improved model in PRM-2 of this project.

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3 Re-shoring critical industries to the EU

3.1 Introduction

Recent crises such as the Covid pandemic disclosed the dependence of the European economy on imports of critical technologies and materials and the vulnerability of global value chains. As a reaction to that, the EU aims to increase the shares of domestic production of critical net-zero technologies and raw materials. For achieving this, the EU Commission proposed the Net-Zero Industry Act (NZIA)[11] which sets a benchmark for the manufacturing capacity of so-called strategic net-zero technologies to meet at least 40% of the EU's annual deployment needs by 2030. According to the NZIA, strategic net-zero technologies include: solar photovoltaic and solar thermal technologies, onshore and offshore renewable technologies, battery/storage technologies, heat pumps and geothermal energy technologies, electrolysers and fuel cells, sustainable biogas/biomethane technologies, carbon capture and storage (CCS) technologies, and grid technologies. Besides the NZIA, the EU Commission made a proposal for a Critical Raw Materials Act (CRM Act)[12]. The CRM Act lists strategic raw materials such as rare earth, lithium, cobalt, nickel, silicon, and others. Those materials are most crucial for strategic technologies used for the green, digital, defence and space applications. The CRM Act then sets the benchmarks that domestic capacities should be able to cover at least 10% of the EU's annual consumption for extraction, at least 40% of the EU's annual consumption for processing and at least 15% of the EU's annual consumption for recycling by 2030. Furthermore, no more than 65% of the EU's annual consumption should come from a single third country.

Against this background, the purpose of this section is an assessment of material impacts of the renewable installations by 2050 to show future strengths and weaknesses. Specifically, solar PV technologies and wind turbines are present in both NZIA and CRM Act, highlighting their relevance for Europe in the energy transition. As it is highlighted later, results should be shown from a World perspective. The regions analysed, i.e., Europe, India, China, and USCMA (USA, Canada, and Mexico), are not alone in the decarbonization race. This takes importance since the availability of minerals in the periodic table varies from one region to the other globally, and the accumulation of a mineral by one or few countries over time may constrain the transition of the rest. For example, Figure 3-1 shows low future availability of germanium, gallium and zinc, while "plentiful" supply of silicon and sulphur, given the current rates of extraction. The threat of scarcity is related to both the extraction rate and to the availability in nature. Meanwhile oxygen and carbon are much more common than polonium and radon, none of the latter are used by humanity to large amounts, so the supply would be guaranteed, for the same level of consumption.

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[11] https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

[12] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en

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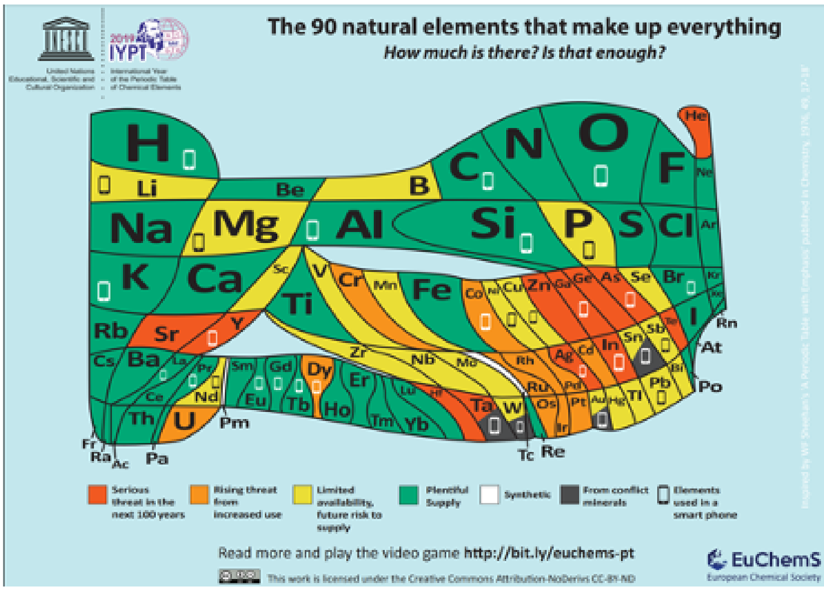

Figure 3-1: The periodic table with the 90 natural elements with areas according with their availability in the Earth. The figure also indicates how serious is the thread to supply the element. Source: European Chemical Society

The work described in this section has been conducted as part of PRM-1 of the IAM COMPACT project under the Theme "European Industry" (see Deliverable 2.2 "Scoping Relevant Research Questions"). In a first step, the topic of a potential re-shoring of critical industries to the EU due to considerations of strategic independence was identified as a matter of high concern for high-level policy makers from national governments and the European Commission. The topic of the study was then narrowed down and refined based on discussions with the Core Working Group of policy makers, academia, industry, and NGOs gathered for this study. As a result of the co-creation process with stakeholders, the following overarching research question was defined:

What are the consequences, in terms of critical raw materials, of re-shoring industries for the production of strategic net-zero technologies to the EU?

3.2 Methodological approach

To estimate mineral requirements, WILIAM has been adapted to be used as a "calculator" exogenizing the capacity expansion of the critical technologies of interest in order to compute the impacts in terms of material requirements. The exogenous capacity expansion comes from GCAM. By exogenously setting these capacity expansion levels, the functionality of WILIAM is focussed on the bottom-up computation of material requirements, primary extraction and secondary extraction as a function of the exogenously set recycling rates. Figure 3-2 summarizes the method. GCAM exports the flow of new installed capacities of solar CSP, solar-PV (we assume all is installed on ground), onshore wind and offshore wind in the three scenarios described in section 2 (*NDC_LTT*, *CBAM*, and *Strategic Independence*). The inclusion of the material requirements for electrolysers is an ongoing task which will be ready for the second cycle of modelling in the project. Then, data management rearrange the values based on the regionalization of WILIAM. Finally, WILIAM internally evaluates the requirements of 61 materials for these technologies.

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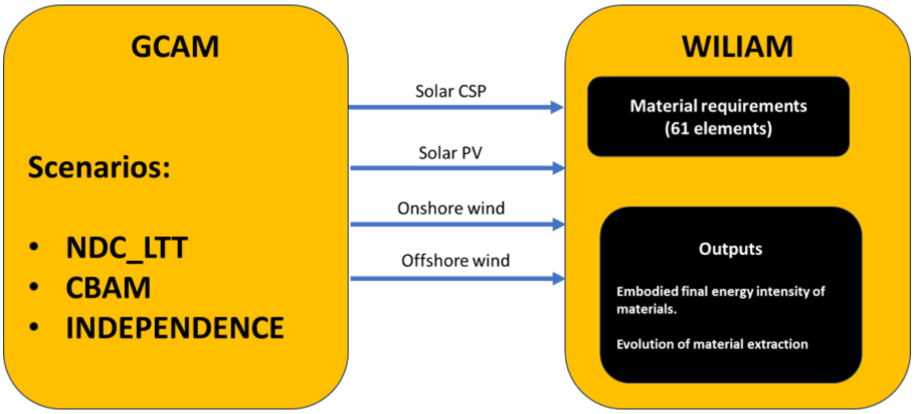

Figure 3-2: Protocol to extend the scenario assessment from GCAM to WILIAM.

The case of solar-PV is particular as GCAM does not include sub-technologies (mono-crystalline silicon, poly-crystalline silicon, cadmium telluride, copper-indium-gallium selenide) which are critical to assess further material criticalities. Given the uncertain forecasting and missing information about the influencing variables that determine the future evolution of photovoltaics market, we have assumed the relative share of sub-technologies in the last year of historical data (2020) according to Fraunhofer ISE (2023) remaining constant over the simulated time period. Figure 3-3 shows the historical evolution of solar-PV sub-technologies. The global market is dominated by Si-Mono due to its performance and affordable price, with small participations of Si-Poly and even less thin films (CIGS and CdTe). For purposes of comparison, WILIAM assumes 79% of silicon monocrystalline cells, 16% of silicon polycrystalline, 4% of cadmium telluride, and 2% of copper-indium-gallium selenide.

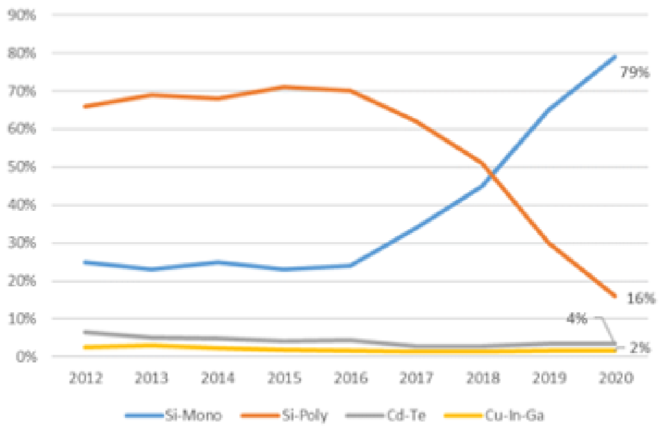

Figure 3-3: Historical shares of solar-PV sub-technologies in WILIAM. Percentages of 2020 are adopted **for the three scenarios (NDC_LTT, CBAM, Strategic Independence). Source: Fraunhofer ISE (2023).**

Regarding regionalization, India and China are explicitly represented in both models, GCAM and WILIAM. However, USCMA (USA, Mexico and Canada) and EU27 (EU-12 and EU-15) needed homogenization in WILIAM (from GCAM). These four regions are at the top of the list of renewables installing regions.

From the 61 materials represented in WILIAM, we selected 5 critical raw materials for the analysis: cadmium, copper, gallium, indium, and silver. This selection is made as these are assumed to be potential bottlenecks of the energy transition, based on the WILIAM team expertise on the state-of-the-art and the typical outputs which the model delivers. Since the CRM Act is a general benchmark ("at least 15% of the EU's annual consumption for recycling"), we decided to maintain historical recycling

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rates (cf. Table 1). On the other hand, cadmium, gallium and indium are by-products while copper and silver primary productions. For purposes of comparison, the five minerals are compared to the reference value of annual production in 2019; besides, copper and silver being compared to the world known reserves estimated in 2022.

Table 3-1: Recycling rates assumed in WILIAM and global references in 2019 / 2022. Source: U.S. Geological Survey[13]

Mineral	Recycling rate (%)	Reference value
Cadmium	15 %	0.025 Mt world refinery production (2019)
Copper	48 %	20 Mt (mine production, 2019); 890 Mt (world known reserves in 2022)
Gallium	0.5 %	320 tonnes world primary production (2019)
Indium	0.5 %	760 tonnes world refinery production (2019)
Silver	63.5 %	0.027 Mt (mine production, 2019); 0.55 Mt (world known reserves in 2022)

On the other hand, material intensities of strategic net-zero technologies are assumed from the supplementary material in de Castro & Capellán-Pérez (2020) for solar CSP and wind, and Pulido (2022) for the data about solar-PV sub-technologies. Table 2summarizes the material cost of installing a new megawatt of renewable technology. Material intensities considers all the material construction of 1 MW of installed capacity, e.g., the solar cell, structure with the panel, auxiliary devices (solar inverter, transformer), wiring from generators to the grid, operation and maintenance.

Table 3-2: Mineral intensities for new power plants. Units in kg/MW

Mineral	Solar-PV on ground				Solar CSP	Onshore wind	Offshore wind
	C-Si-mono	C-Si-poly	CIGS	CdTe			
Cadmium (Cd)	0	0	21	85	0	0	0
Copper (Cu)	2214.6	2440.6	92	42.8	3200	2700	22200
Gallium (Ga)	0	0	7.5	0	0	0	0
Indium (In)	0	0	23	15.9	0	0	0
Silver (Ag)	21	21	0	0	13	0	0
Source	Pulido (2022)			de Castro & Capellán-Pérez (2020)			

[13] https://www.usgs.gov/products/data

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3.3 Results

In the figures below, the historical data covers the years from 2015 to 2020 while after 2020 scenario results are shown. Results of WILIAM (continuous simulation) show leaps caused by the discrete data gathered from GCAM, assuming the same value for each 5-year period following a scenario year provided by GCAM.

Renewable energy sources are increasingly exploited. The expansion of capacities grows for all regions and scenarios in a similar way. Over time, the accumulation of minerals by the society is higher and higher, infrastructure embodying critical raw materials from origin to developed regions. As shown in Figure 3-4, there are few differences across scenarios in the Europe-27 region. *Strategic Independence* is slightly more intensive in mining due to the higher number of solar and wind power plants (e.g., roughly 3% by 2050, except for copper, which is below 1.5%).

The other regions show similar differences. So, the impact of mining industry is similar in the three scenarios and the rest of this section therefore focuses on the *Strategic Independence* scenario, only. The following analyses the demand for the five selected minerals in comparison to globally available reserves or current extraction flow, and in comparison between regions.

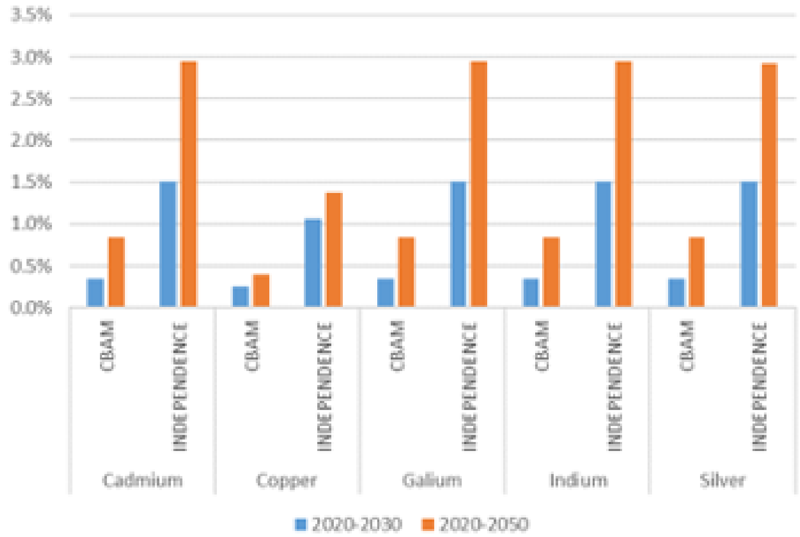

Figure 3-4: Percentual differences in the cumulative extraction of minerals between *CBAM* and *Strategic Independence* in relation to the *NDC_LTT* scenario in the Europe-27 region.

Global wind and solar capacity additions were 262 GW over 2022 (IRENA, 2023). GCAM assumes higher efforts for the *Strategic Independence* scenario. New additions for the four regions here analysed are in the range of 147 (2015-2020) to 344 (2045-2050) GW/year, what generates a pressure which could even result in bottlenecks if demand cannot be supplied, along the supply chain of minerals in coming years, as shown in Figure 3-5 (cadmium), Figure 3-6 (copper), Figure 3-8 (gallium), Figure 3-9 (indium), and Figure 3-10 (silver).

The thrust of renewables expansion induced by policies in the four regions would increase demand to reach about 50% of global cadmium production levels by 2020 and ramp it up close to 2050 (58%). The shares indicate that 25% of cadmium worldwide would be needed in India to build the CIGS

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(copper-indium-gallium selenide) and CdTe (cadmium telluride) solar panels, while Europe's market share falls after 2035 to less than 5% by 2050. The EU's study on CRMs evaluates cadmium as critical raw material, which is used 1% for solar application, while 91% for batteries, so results presented here capture a small part of the total demand, only. China, South Korea, and Japan cover 61% of the processing stage, while Europe does around 9%. The import reliance in Europe is low, 8%.

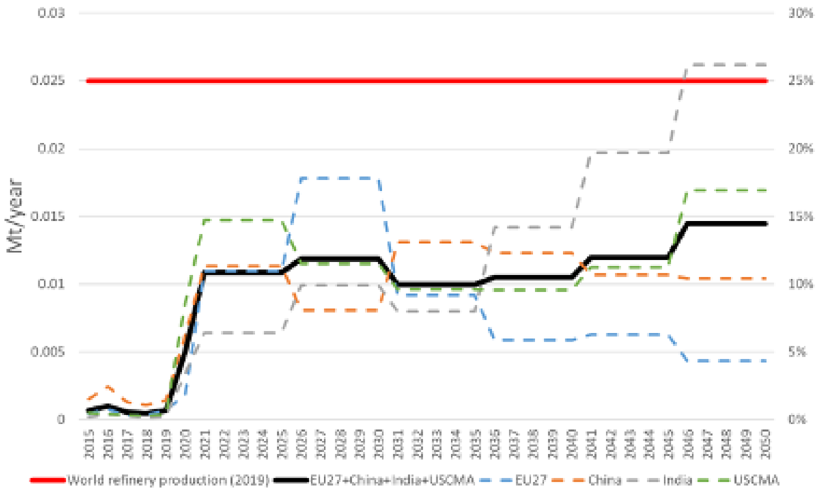

Figure 3-5: Annual world primary production of cadmium required for solar and wind technologies in India, Europe-27, China, and USCMA in the *Strategic Independence* scenario. The dashed lines mark the regional share related to the world refinery production in 2019. Units: megatons per year.

Copper is the third most-used metal globally. In the scenario, the four regions would accumulate 69% of the known reserves in 2022, with similar shares among them by 2050. All technologies need copper, as shown in Table 2. Europe would be the region that accumulates more copper by using 20% of the world known reserves estimated in 2020 from 2020 to 2050. The installation rate assumed in the scenario is several times higher than the historical data (until 2019), this difference creates the leap from 2019 to 2020 in Figure 3-6. Copper was included as strategic raw material in a study on critical raw materials of the EU Commission (Grohol and Veeh 2023), where it is pointed out that 28% of copper supply (extraction) is covered by Chile. Copper supply is well diversified but challenging to substitute due to the superior performance in electrical applications and a very long lifecycle.

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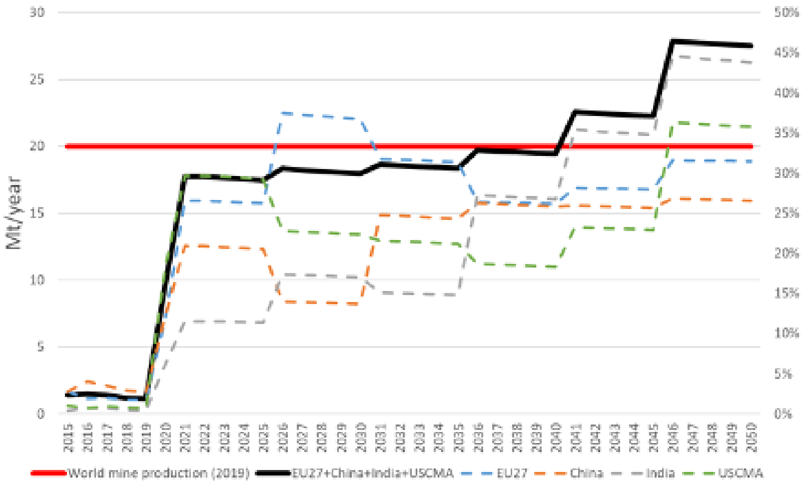

Figure 3-6: Annual world mine production of copper required for solar and wind technologies in India, Europe-27, China, and USCMA in the *Strategic Independence* scenario. The dashed lines mark the regional share related to the world refinery production in 2019. Units: megatons per year.

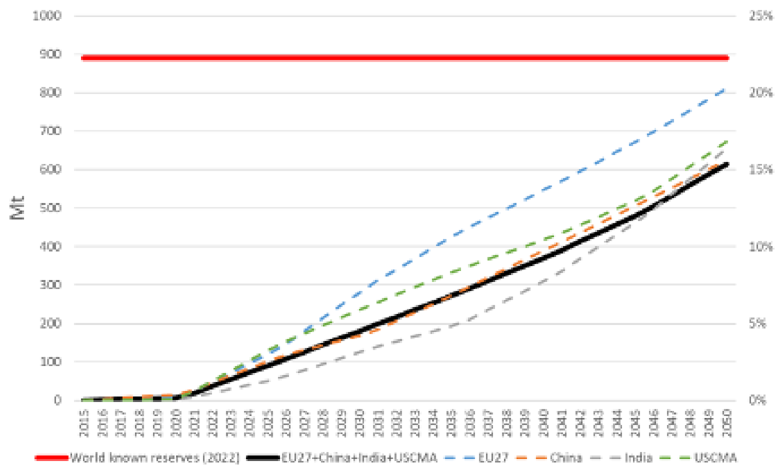

Figure 3-7: Cumulative extraction of copper required for solar and wind technologies in India, Europe-27, China, and USCMA in the *Strategic Independence* scenario. The dashed lines mark the regional share related to the world known reserves estimated in 2022. Units: megatons.

The calculation of Gallium and indium demands reveal inconsistent trends given the historical refinery production in 2019. The first year ahead the historical data (2020) already shows a demand beyond the limit. This means that, globally, the extraction of both minerals requires to be much higher than the current levels. Specifically, the four regions analysed would need a strong increase in the capacity of mineral refineries since the beginning of the scenario. This expansion is already on the table of the mining sector. The production capacity of gallium was 870 tonnes in 2022, while the refinery production of indium was 900 tonnes in 2022 (Schuyler Anderson, 2020). According to the EU's study on CRMs, gallium and indium are categorized as other non-ferrous metals. In 2023, China was the main supplier for Europe, covering 71% of the processed gallium. However, despite 60% of indium is used in Indium Tin Oxide in the World, its production in the European Union is higher than the consumption in this region, so below the threshold to consider indium as a critical raw material in 2023 (it was in the 2014's EU report).

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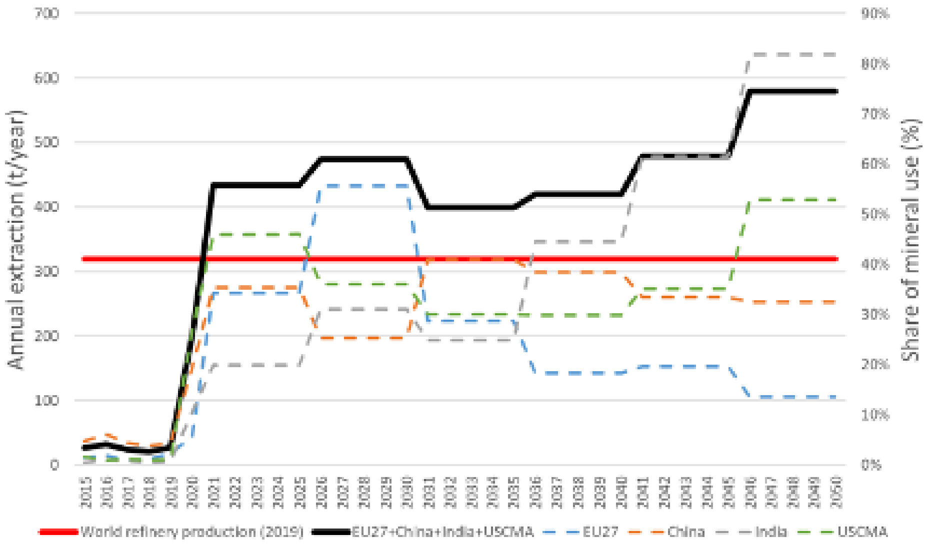

Figure 3-8: Annual extraction of gallium required for solar and wind technologies in India, Europe-27, China, and USCMA in the *Strategic Independence* scenario. The dashed lines mark the regional share related to the world refinery production in 2019.

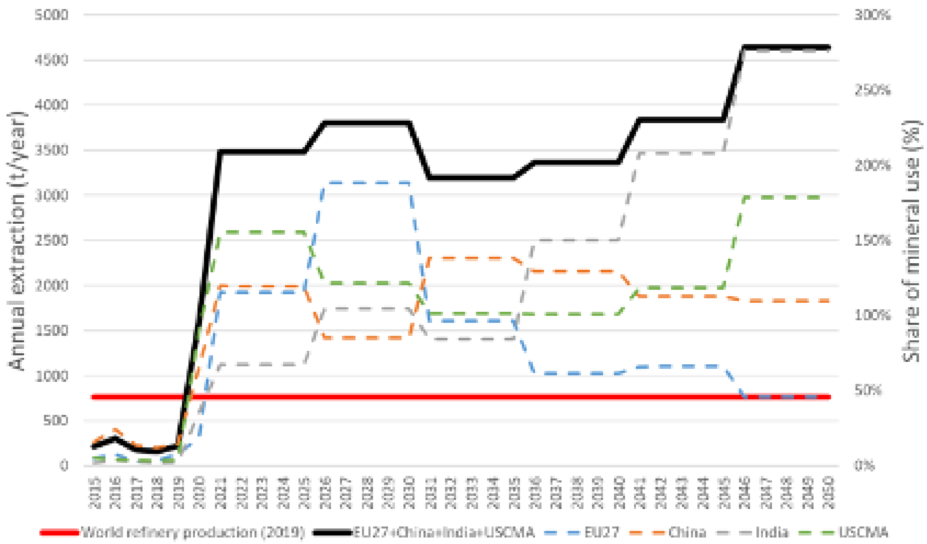

Figure 3-9: Annual extraction of indium required for solar and wind technologies in India, Europe-27, China, and USCMA in the *Strategic Independence* scenario. The dashed lines mark the regional share related to the world refinery production in 2019.

Finally, silver is employed in the construction of solar panels based on silicium and concentrated solar power plants. The estimated reserves in 2022 would be reached in 2040 just accounting the four regions we are analysing here (Figure 3-10), given the high production supply required. In the absence of new explorations, the reserves of silver would be consumed before 2038. In the EU's study on CRMs, silver is part of the platinum group metals, used in jewellery, photovoltaics, automotive industry, batteries, and medicine, among others. Mexico accounts 24.3% of the extraction share worldwide in 2023, and 52% with Peru, Chile, Bolivia and Argentina. This metal is not critical since the import reliance in extraction is only a 5%.

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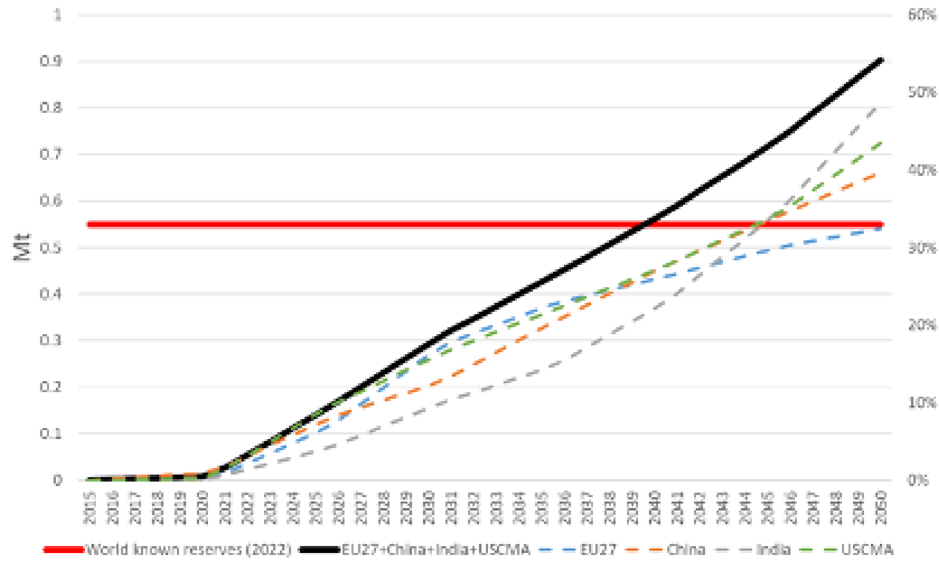

Figure 3-10: Cumulative extraction of silver required for solar and wind technologies in India, Europe-27, China, and USCMA. ***Strategic Independence*** **scenario. The dashed lines mark the regional share (%) related to the world known reserves estimated in 2022. Units: megatons.**

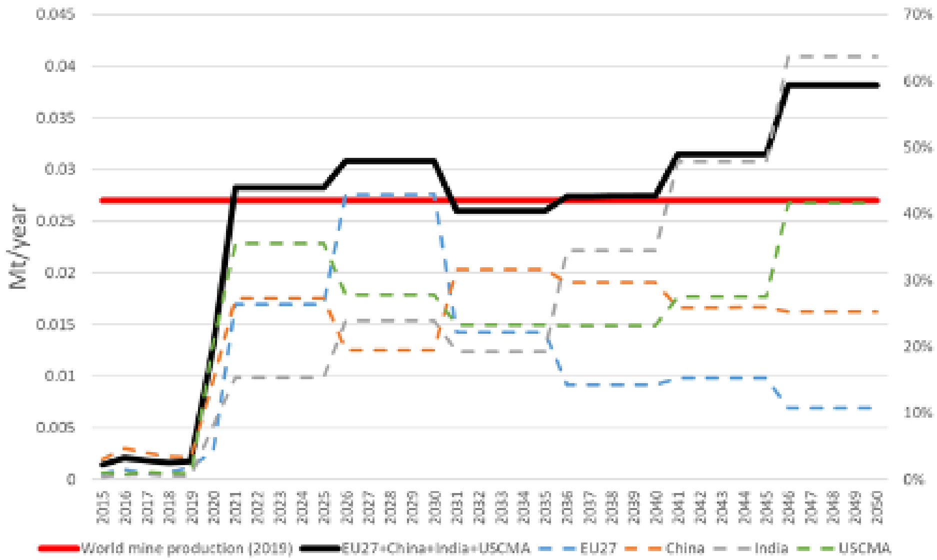

Figure 3-11: Annual world mine production of silver required for solar and wind technologies in India, Europe-27, China, and USCMA in the ***Strategic Independence*** **scenario. The dashed lines mark the regional share related to the world refinery production in 2019. Units: megatons per year.**

So, the obtained results show that there are sensitive concerns about the future supply of some materials to build an alternative energy system. We must highlight that in these simulations there is no feedback between the flow of information from GCAM to WILIAM concerning the results shown in this section; also there is no feedback on the relative scarcity of materials to PV sub-technologies. In all likelihood, facing a scarcity of gallium or indium, the market would increase the price of these minerals, producing a substitution that benefits monocrystalline and polycrystalline solar panels. Furthermore, the scarcity should depict a "S" shape curve indicating saturation in the phenomena rather than going directly to the limit. On the supply side, the market would surely invest in new exploratory projects looking for new mines and refinery processes. The relationship between primary extraction and by-products refinery is not represented as well. So, in the absence of these feedback, results must be taken

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with caution.

The fact that results suggest higher supply capacity is not new. The supply chain analysis made by the European Commission' Joint Research Centre in 2023 (Carrara et al. 2023) concludes that, in order to meet the EU's ambitious policy targets, this region will drive "an unprecedented increase in materials demand". Gallium, for example, is a relevant raw material in power amplifiers and photonic technologies, a mineral that is domestically supplied by less than 3%, and China has a monopolistic position in the production. Our results support the concern on minerals, specially about gallium.

Even results only cover some demand types (solar and wind technologies) and four regions, such deep energy transition would not be realistic if we look at the current annual production of cadmium, gallium and indium, and known reserves worldwide of copper and silver in 2022. There would be three ways to relax this pressure:

- Reduce the speed of the current planning of installing solar and wind technologies.
- Change the minerals used in the design of solar and wind technologies.
- Humanity may discover and exploit new ore deposits, assuming the impacts mining has.

Certainly, results are in line with the following sentence: "the global race to secure and access critical raw materials needed for widespread electrification continues to accelerate, adding urgency for the EU to respond to increased demand, protectionist trade policies by other actors, and the sustainability of critical raw minerals" (ASG, 2023).

The scarcity and spread of the analysed – and other – minerals is a severe risk. As discussed in literature (e.g. Rhodes 2019), conflicts and colonialism may persist triggered by rivalry in an unfair transition. China is, by far, in a better position of mining, where most of the known critical raw materials have been discovered (Figure 3-12). For example, China accounts 94% of gallium's reserves, while 66% of copper is placed in Chile and China.

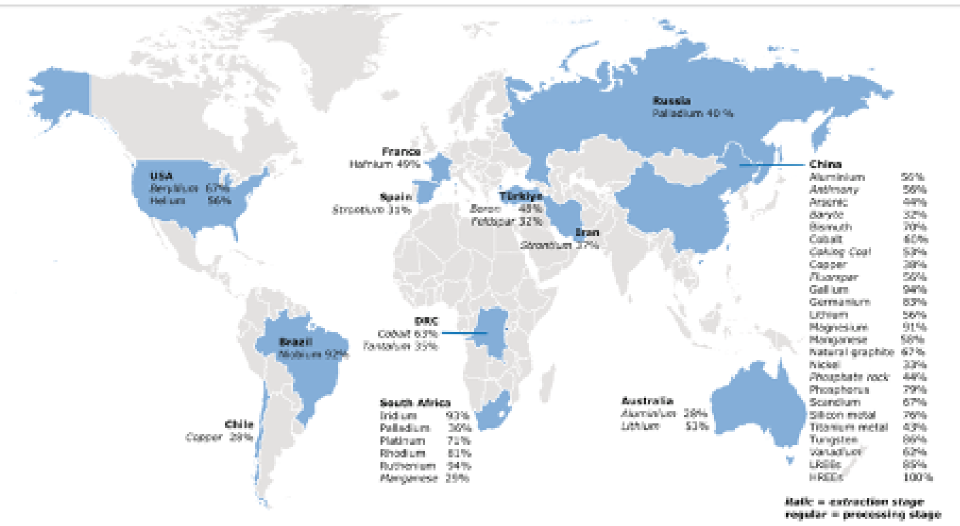

Figure 3-12: Countries accounting for largest share of global supply of critical raw materials. Source: Grohol and Veeh (2023).

3.4 Conclusions and Outlook

The findings of the impact assessment highlight the relevance of policies such as the NZIA and CRM Act. They put on the table two major issues. First, planning the economy, especially critical sectors, requires a deep understanding of the value chain. This includes, among others, the availability of physical resources. Second, the challenge of decarbonization is global and diplomacy would play a

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relevant role in the word "just" of a transition that should not forget the current inequalities of the material markets.

Our results visualize how a specific level of annual additions in the power system assumes the adaptation of the mining and refinery sector, as well as the pressure that may occur in the global market. By-products strongly rely on the mine production and refinery of certain metals, what makes their availability even harder. As shown, the capacity to supply of the analysed five metals would need to be increased to satisfy the consumption during the energy transition of the four world regions.

The CRM Act supports the provision of critical raw materials that are required for the Net-Zero Industry Act (NZIA). The targets of the NZIA will increase the domestic mining for critical raw materials significantly. For example, the document aims to define a regulatory environment to reach a goal of 10% of the EU's annual consumption for extraction and 40% for processing to build "strategic net-zero technologies". As results suggest, achieving the targets of the CRM Act becomes more ambitious through the NZIA, as the overall amounts required increase significantly. Hence both must be discussed in combination. Given the global scarcity of some CRMs, increasing the EUs mining capacities and improving its access to foreign CRMs is not a sufficient strategy for reaching the targets of the NZIA. A necessary complementary strategy would be to foster the development of net-zero technologies that use no or less of the most critical raw materials.

However, this analysis is subject to uncertainty since there are relevant effects that were not already modelled:

- Dynamization of recycling rates.
- Efforts finding new mines (increasing the reserves).
- Technological improvements (increasing the capacity and ore grade exploitation and reducing the material intensity of renewables).
- Dynamization of the shares of sub-technologies through market response to material scarcity

These points, together with the introduction of sub-technologies of batteries and wind power, would enhance the impact assessment during the next modelling cycle of this project. Finally, the leaps introduced when dealing from discrete to continuous simulations may be solved through linearization of scenarios, as part of the protocol bilaterally agreed by partners.

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4 Energy balance in upscaling renewable energy sources by 2050 in the Greek power sector

4.1 Introduction

Achieving carbon neutrality by 2050 will require a transition to a cleaner and sustainable power system with an increased penetration of renewable energy sources (RES) for decarbonising electricity generation. Nevertheless, this shift will have significant ramifications for the organisation and operation of the electricity sector. The increasing dependence on RES in the energy mix presents several difficulties for electric utilities because the power produced by wind and photovoltaic (PV) systems is influenced by weather conditions, which can lead to substantial fluctuations in instantaneous power generation. Hence, maintaining the balance between generation and demand will become even more challenging moving towards 2050, given that RES technologies will have a predominant role as the primary source of electricity (Van den Bergh & Delarue, 2020).

In this sense, accurate forecasting of renewable electricity generation is extremely challenging and balancing its variability requires a power system with a high degree of flexibility (Welsch et al., 2014). Flexibility requirements pertain to the capability of generating units to follow the load at any given moment. Due to the fluctuating production of wind and PV plants within a day and within an hour, ramping requirements on the dispatchable generation units increase. Furthermore, dispatchable power plants, such as conventional thermal and hydroelectric units, possess distinct technical constraints (e.g., ramping rates, minimum uptimes and downtimes, minimum stable output levels, etc.), hence intensifying the complexity of this issue (Krommydas et al., 2022).

So far, long-term energy models have sufficiently addressed the question whether the future installed generation capacity will be adequate to meet the projected electricity demand. However, in various instances, applied long-term energy system optimisation models have not considered whether the system's planned resources can operate with adequate flexibility, as they usually lack a high level of temporal resolution. Moreover, their primary focus does not involve extensively analysing the short-term variability of supply and demand. As a result, this leads to sub-optimal power plant dispatch and investment decisions. To overcome the limitations of current long-term energy system optimisation models in accurately representing operational characteristics, it is possible to interlink them with short-term power system models. This integration allows for the calculation of future power plant capacity mixes and improves the accuracy of electricity dispatch projections (Fernandez Vazquez et al., 2024).

The work outlined in this section has been carried out as a component of the IAM COMPACT PRM-1, under Theme 2: "Electrification" (see **Deliverable 2.2 "Scoping Relevant Research Questions**"). The topic of future flexibility requirements of the low-carbon electricity system, including the impact of flexibility solutions on capacity needs and the technologies that are best placed to provide flexibility by replacing the flexibility provided by conventional power plants, was recognised as an issue of high concern for high-level policymakers, from national governments to the European Commission (EC). Consequently, the following research question (RQ) was selected for this study:

RQ: "What are the capacity and flexibility requirements for the future electricity system to meet carbon neutrality?"

To answer this RQ, a working approach involving two power system models has been developed. Here, we present the soft-linking process between the models and the results from their combined application. Furthermore, a short discussion and an outlook on next steps for potential improvements of this model application is provided.

4.2 Working approach

We follow a soft-linking process between a long-term energy system optimisation model with a short-term power system model to assess the capacity and flexibility requirements of the Greek electricity system. For this purpose, two (2) scenarios that follow the same emission trajectory but deploy different technological configurations are defined and modelled by the long-term energy system optimisation model (see **Section 4.2.3**). As a first step, the long-term scenarios enable us to design different future power sector technological configurations that lead to carbon neutrality, thus identifying the capacity requirements. Afterwards, the short-term assessment makes the exploration of flexibility requirements for the identified technological configurations possible. The models used, case study specifications, and the scenario design are outlined in the subsections below before the steps of the analysis and the data flow between models are described.

4.2.1 Models used

4.2.1.1 OSeMOSYS-GR

The **O**pen **S**ource **e**nergy **MO**delling **SYS**tem (OSeMOSYS) is an open-source energy system model generator used to determine the most economically efficient pathway by minimising the discounted cost of the system while optimising the capacity and generation of each technology to meet final energy demand (Howells et al., 2011). Here, we use OSEMOSYS-GR, a model developed in the context of IAM COMPACT as part of the Technoeconomics of Energy Systems laboratory (TEESlab) modelling (TEEM) suite to accurately model the Greek power system towards 2050. Each modelled year is split in 48 time slices, i.e., four (4) different day-types (night, morning, noon, afternoon) for twelve (12) different days, one for each month of the year. The four (4) day-types were considered to have an equal length, i.e., six (6) hours per day. In OSEMOSYS-GR, the electricity supply system is represented by importing and extraction technologies, fossil-fired power plants using lignite, natural gas, oil, RES technologies (i.e., hydro, wind onshore and offshore, solar PV, biomass, geothermal), electricity storage (i.e., battery and pumped hydro), hydrogen production and consumption (namely electrolysers and fuel cells), transmission, and distribution systems, as well as interconnections with neighbouring countries.

4.2.1.2 FlexTool

FlexTool is a user-friendly, data-driven tool developed by the International Renewable Energy Agency (IRENA), which performs power systems' flexibility assessment based on national capacity investment plans and forecasts (Taibi et al., 2018). It is an optimisation tool capable of solving the hourly economic dispatch problem of a specific power system for one year aiming at identifying flexibility gaps and exploring optimal investments that support system flexibility in the long term. It considers the hourly demand profile and capacity factor for PV and wind, fuel costs, power plants' start-up costs, fixed and variable operational and maintenance (O&M) costs, CO_2 emission factors, etc., and minimises the total system's cost. The costs accounted for are related to O&M, fuel usage, CO_2 emissions, and start-up of units, as well as penalties for loss of load, insufficient upward reserves, insufficient capacity margin, and curtailment of variable renewable energy (VRE). Its outputs are different flexibility indicators, such as curtailment, loss of load, capacity inadequacy, etc.

4.2.2 Case study specifications

Greece has limited capacity for interconnections and heavy reliance on imported fuels for electricity production (Stavrakas et al., 2021). The country has set ambitious climate and policy goals, including the decarbonisation of its power sector by expanding RES capacity and decommissioning its lignite power plants by 2028 (Kleanthis et al., 2022). Natural gas has been considered as an intermediate transition fuel to help phase-out lignite-fired generation before 2021 (Hellenic Ministry of Environment and Energy, 2019). The 2022 energy crisis pushed back the Greek lignite phase out plan and forced the Greek government to re-evaluate the role of natural gas in the national energy system. However, Greece will progressively depend on rising volumes of RES to meet its electricity demand. According to the revised draft National Energy and Climate Plan (NECP), the target is to have a cumulative capacity of 69 GW of variable renewable energy (VRE), i.e., wind onshore, wind offshore, and solar PV, technologies by 2050 (Hellenic Ministry of Environment and Energy, 2023a), a twelvefold increase compared to the installed capacity in 2020. More details with regards to the energy transition in the Greek power sector can be found in **Deliverable 4.9** "**European sub-national deep dives**".

4.2.3 Scenario design

In the long-term scenarios simulated by OSeMOSYS-GR, we explore least-cost energy mixes that lead to a carbon-neutral power sector considering Greece's recent climate commitments and key data projections, such as the electricity demand projection, as these have been partially articulated in the draft Greek National Energy and Climate Plan (NECP) (Hellenic Ministry of Environment and Energy, 2023b). In the short-term assessment with FlexTool, hourly electricity demand time series were derived based on the annual electricity demand projections of the NECP for 2030, 2040, and 2050 (Figure 4-1).

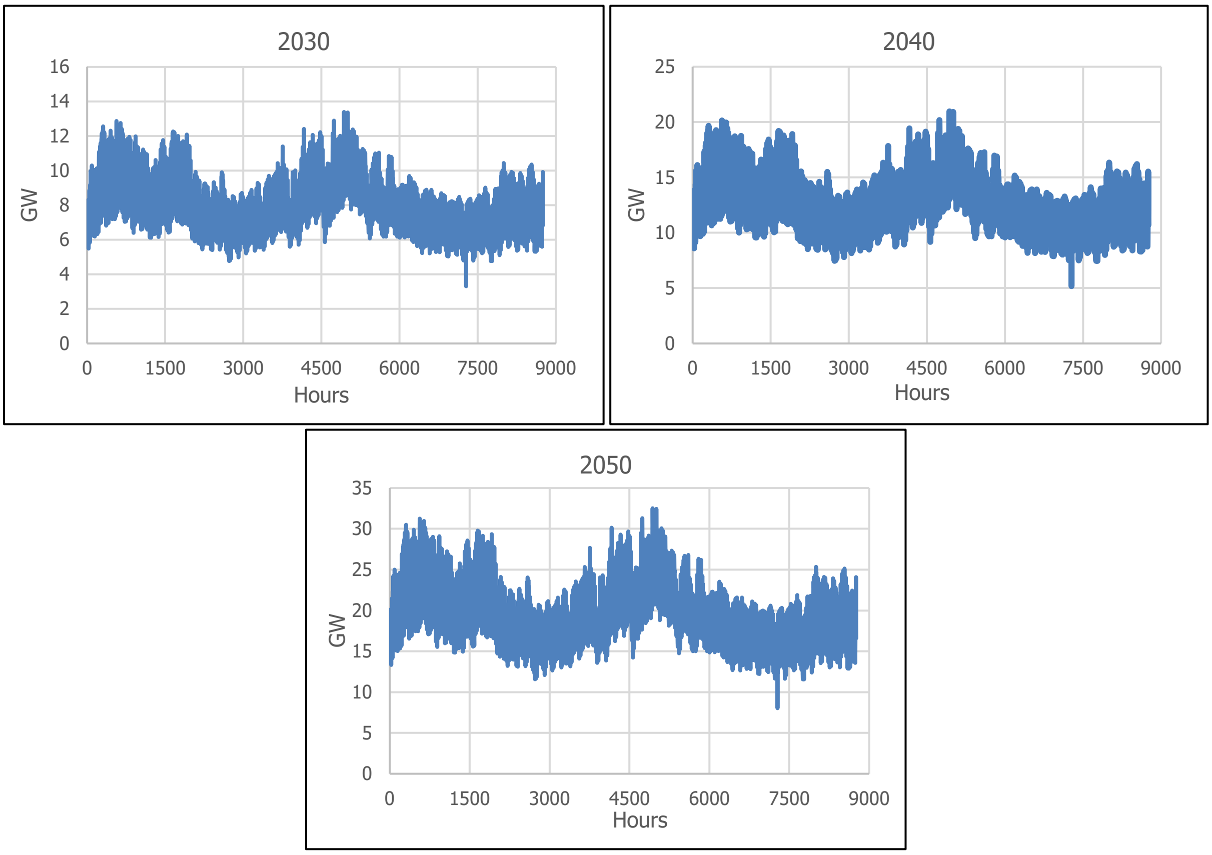

Figure 4-1: Hourly electricity demand series based on the annual electricity demand projections of the National Energy and Climate Plan of Greece for 2030, 2040, and 2050.

For this modelling application, we define two (2) different transition scenarios that both reach carbon neutrality by 2042 but differ in terms of the technology configurations required to attain carbon neutrality. Both scenarios take into account the decision to phase out lignite by 2028, according to the current national energy planning (Hellenic Ministry of Environment and Energy, 2019). Considering the uncertainty of the future of natural gas in the Greek energy system, we analyse scenarios with different dependence on natural gas for electricity generation. Therefore, we include a scenario in which natural gas contributes to the electricity mix until 2050 with the use of Carbon Capture and Storage (CCS) and

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another in which natural gas is phased out endogenously due to the fast adoption rate of green technologies. With regards to net electricity imports (i.e., imports minus exports) from the neighbouring countries, it is assumed that complete electricity independence (i.e., zero net electricity imports) is achieved by 2050. This scenario design leads to differences in the technological configurations required to attain carbon neutrality. The transition scenarios studied are simulated with OSeMOSYS-GR:

- "**Early Neutrality 1**": Carbon neutrality by 2042 focusing on VRE technologies as well as energy storage, namely batteries and pumped hydro for electricity and electrolysers for hydrogen. Achievement of endogenous gas phase-out before 2042.
- "**Early Neutrality 2**": Carbon neutrality by 2042 with the use of CCS for natural gas and biomass power plants and use of VRE and energy storage technologies.

4.2.4 Steps of the analysis and data flow

Although OSeMOSYS is valuable for assessing and suggesting potential future energy system development scenarios in the long term, its capacity to accurately depict the system's behaviour in the short term is restricted. On the other hand, FlexTool is capable of precisely depicting the behaviour of the system and its components, because it can analyse system's operations using a time step of one hour or less, which effectively handles the issue of variability in VRE electricity generation. However, its primary emphasis is on analysing the system only under specific conditions. The observed properties of these tools have revealed a complementarity that may be utilised to evaluate the development of power systems more effectively.

This study presents a soft-linking process between OSeMOSYS-GR and FlexTool. It employs a three-step methodology by using the unique features of each model and utilising the proposed soft-linking process:

1. The long-term model is used to run the two different transition scenarios, as presented in **Section 4.2.3**. Each scenario was simulated in OSeMOSYS-GR over the time period 2021-2050. This is done to establish a set of baseline results and to evaluate the system's behaviour in the future.
2. The long-term output data are converted into short-term input data. Installed capacities by technology deriving from OSeMOSYS-GR are inputted to FlexTool. Key input parameters such as the total electricity demand, net imports, RES capacity factors, carbon emission penalties, and yearly fuel prices are harmonised between the models.
3. The short-term model is used to conduct periodic feasibility analysis of scenarios. The model is run at different years for each long-term development scenario. The years 2030, 2040, and 2050 are simulated to assess the system's performance at various stages. Key indicators employed to evaluate the feasibility of the scenarios are the loss of load and curtailment.

4.3 Results

In this section, we first summarise the modelling results from the simulations of the long-term development scenarios for the Greek power system with OSeMOSYS-GR, including CO_2 emissions, power and storage capacity additions, and electricity dispatch. More details with regards to the long-term decarbonisation pathways of the Greek power sector can be found in **Deliverable 4.9 "European sub-national deep dives**". Second, we provide the results of the flexibility assessment, particularly the hourly electricity dispatch per technology during the weekly operation of the Greek power sector as well as the quantifications of the key flexibility indicators.

4.3.1 Power and storage capacity additions (OSeMOSYS-GR)

Our findings indicate that the "Early Neutrality 1" scenario can only be realised through the faster

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adoption of green technologies when compared to the "Early Neutrality 2" scenario (Figure 4-2). Specifically, in the "Early Neutrality 1" scenario, the high adoption rate of VRE and energy storage technologies allows the completion of the degasification by 2037. By 2030, 24 and 22.8 GW of VRE technologies will be installed in the "Early Neutrality 1" and "Early Neutrality 2" scenarios, respectively. By 2040, VRE capacity will increase to 50.6 and 45.9 GW, accordingly, while energy storage technologies will reach 27.8 and 21.6 GW, respectively. By 2050, VRE and energy storage capacity will increase to 70.4 and 47.4 GW in the "Early Neutrality 1" scenario, and 60.5 and 29.3 GW in the "Early Neutrality 2" scenario. The difference between the installed VRE and energy storage capacities among the two scenarios highlights the importance of the baseload capacity to the operation of the power system.

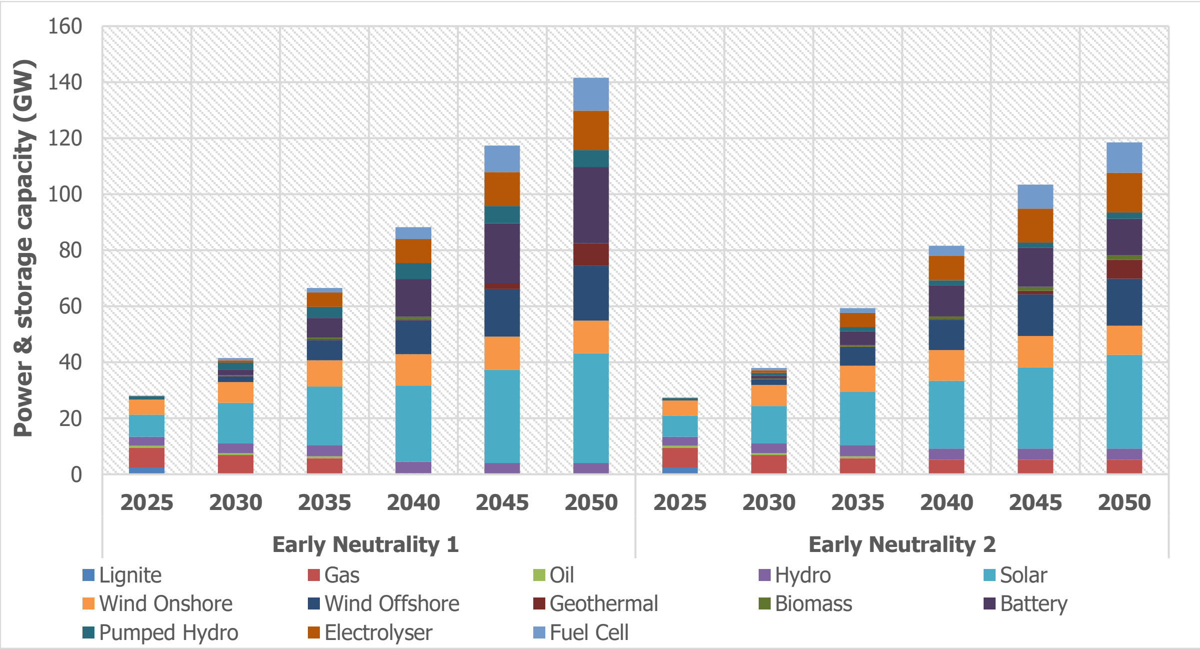

Figure 4-2: Total power and storage capacity mixes under the "Early Neutrality 1" and "Early Neutrality 2" CO_2 emissions (OSeMOSYS-GR)

Between 2025 and 2030, we observe a steep emission reduction in both scenarios (Figure 4-3). In 2025, lignite will maintain a large share of the total CO_2 emissions (39.5% in the "Early Neutrality 1" scenario and 36.5% in the in the "Early Neutrality 2" scenario). However, in 2025 and 2030, natural gas will become the predominant source of CO_2 emissions (54.6% and 84.5% in the "Early Neutrality 1" scenario and 58.1% and 84% in the "Early Neutrality 2" scenario). The main drivers of emission reduction between 2025 and 2030, are the rapid growth of VRE capacity and the lignite phase-out by 2028. In 2035, there is a sudden drop in the CO_2 emissions from natural gas and biomass in the "Early Neutrality 2" scenario, owing to retrofitting CCS to the existing natural gas and biomass power plants. It should be noted that the use of CCS in the "Early Neutrality 2" scenario will not eliminate carbon emissions on its own, considering that the CCS units can only capture ~90% of the CO_2 of combustion flues. This means that carbon dioxide removal technologies should also be implemented to absorb the remaining carbon emissions of the power sector.

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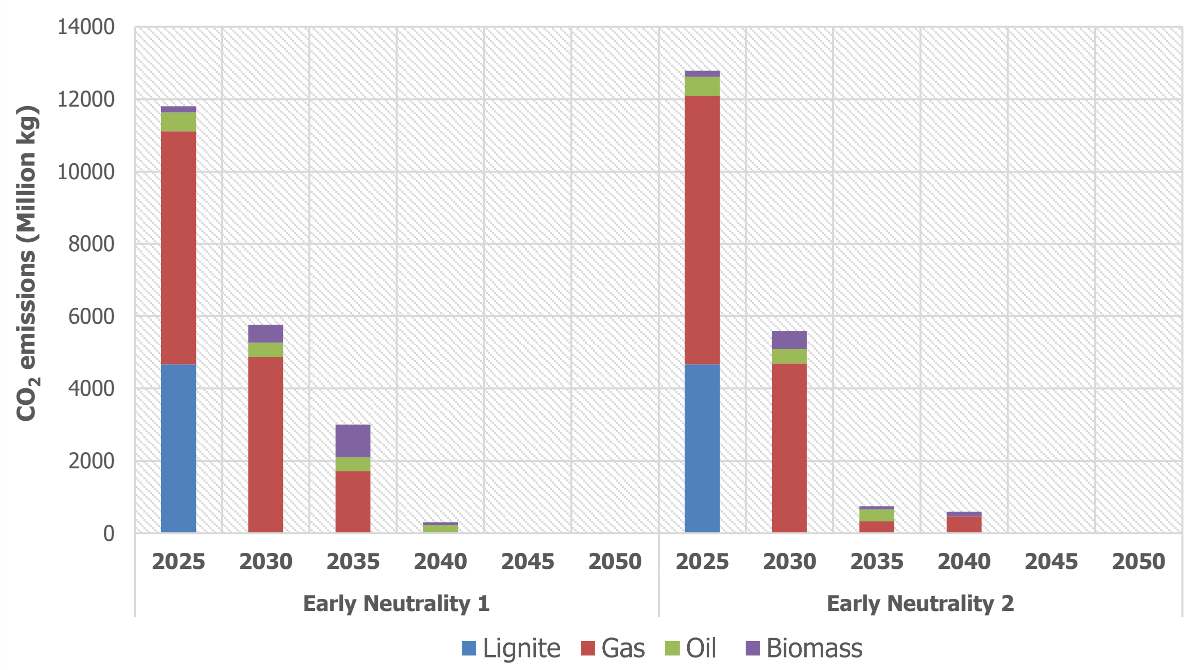

Figure 4-3: Total annual CO_2 emissions under the "Early Neutrality 1" and "Early Neutrality 2" scenarios.

4.3.2 Electricity dispatch (OSeMOSYS-GR)

Modelling results also show that RES, electricity storage, and fuel cell technologies cover 70.2% and 69.5% of the total gross electricity generation in the "Early Neutrality 1" and "Early Neutrality 2" scenarios by 2030 (Figure 4-4). These shares increase to 93.7% and 88.3% by 2040, respectively, and to 100% and 94.8% by 2050. Fossil fuels and net electricity imports cover the remaining shares of the total gross electricity generation (net electricity imports are assumed to be zero in 2050). Therefore, in the "Early Neutrality 2" scenario, the use of CCS will allow natural gas to contribute with a 5.2% share to the electricity mix in 2050.

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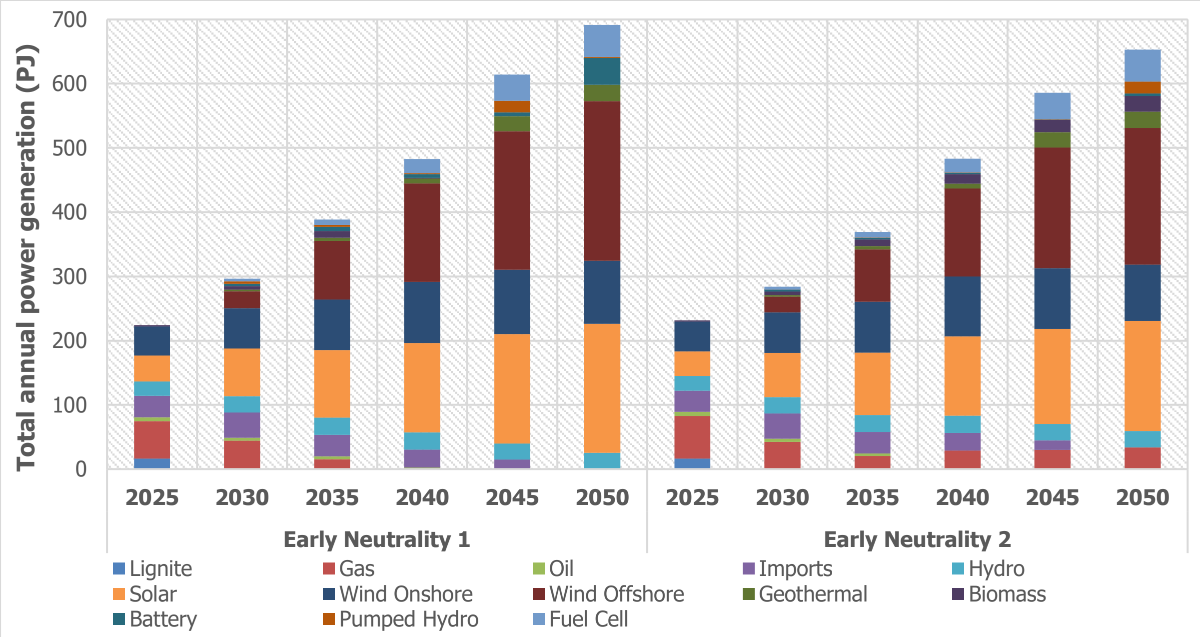

Figure 4-4: Total annual power generation mixes under the "Early Neutrality 1" and "Early Neutrality 2" scenarios.

4.3.3 Flexibility assessment (FlexTool)

Figure 4.5 illustrates the electricity production per technology for one week (hours 1-168) and one additional day (hours 756-779) in the "Early Neutrality 1" scenario for 2030, 2040, and 2050. We see that curtailment is reduced towards 2050 due to the increased capacity of electricity storage (i.e., pumped hydro and batteries) and electrolysers, which use electricity from VRE to charge and convert it to hydrogen, respectively, thus providing additional flexibility to the hourly operation of the system. Specifically, curtailment amounts to 5.6% of total electricity produced from VRE in 2030 and drops to 0.2% in 2040 and 0% in 2050 (Table 4-1). Furthermore, a total of 7.5 TWh of net electricity imports will be required in 2030 to avoid potential losses of load, which then decrease to 5.65 TWh in 2040 and 0 TWh in 2050, meaning that achieving electricity independence from neighbouring countries can be achieved by 2050. In 2030, natural gas and hydro power plants are the primary baseload sources of electricity generation, with PV and wind power plants combined with electricity storage serving as complementary sources to meet demand. However, in 2040 and 2050, geothermal and fuel cells progressively play the role of the primary baseload sources of electricity generation due to the forced shutdown of natural gas power plants, while VRE combined with storage become the predominant source of electricity.

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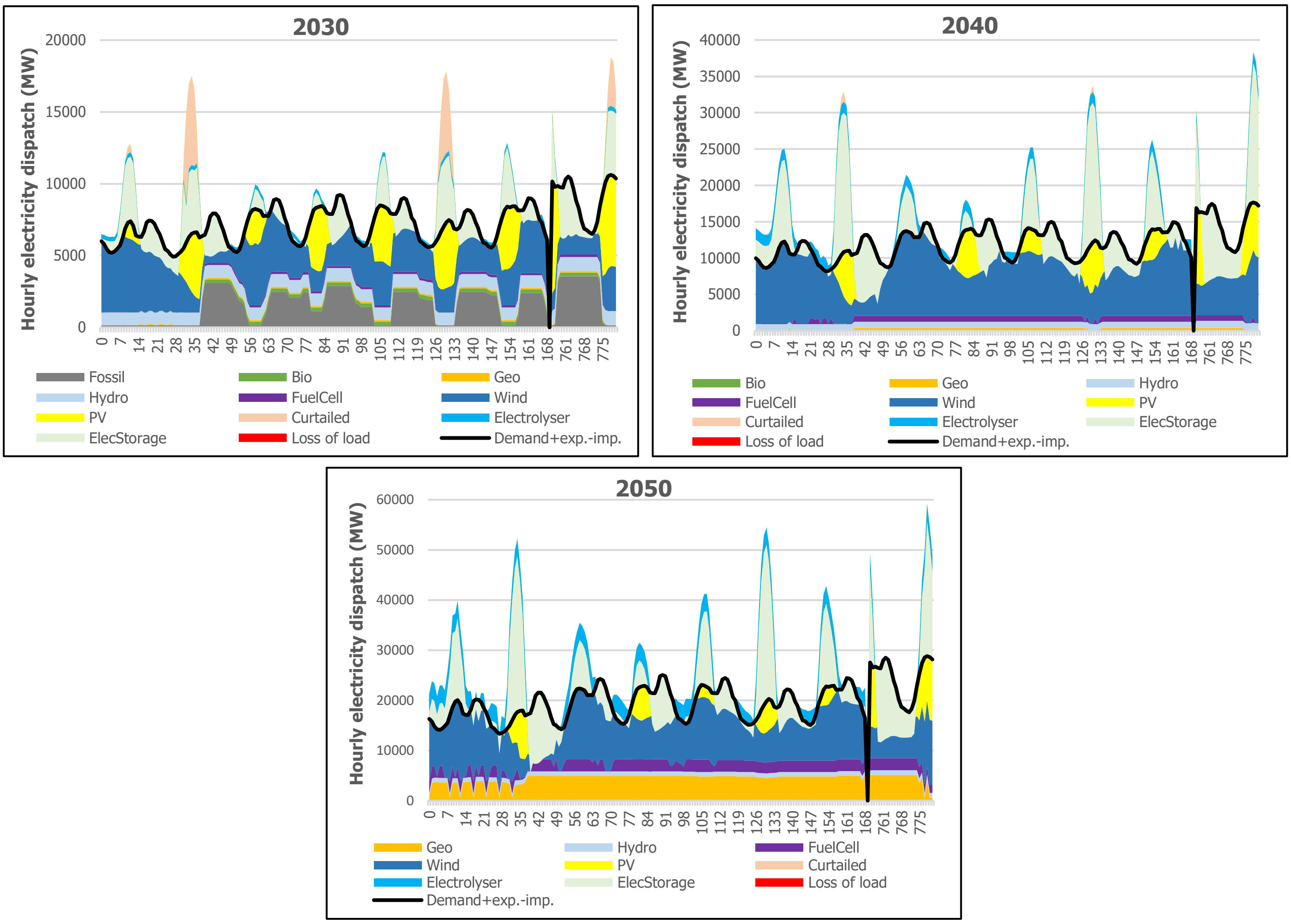

Figure 4-5: Hourly electricity dispatch per technology during the weekly operation of the Greek power sector in 2030, 2040, and 2050 under the "Early Neutrality 1" scenario.

Respectively, Figure 4-6 shows the power generation per technology for one week and one additional day in the "Early Neutrality 2" scenario for 2030, 2040, and 2050. Again, curtailment will decrease towards 2050 due to the growing electricity storage and electrolyser capacity. However, in this scenario, curtailment will be higher compared to the "Early Neutrality 1" scenario, i.e., 10.8% in 2030, 1.7% in 2040, and 0.5% in 2050 (Table 4-1), since electricity storage technologies will not reach the same capacity levels. In addition, a total of 10 TWh of net electricity imports will be required in 2030 to prevent loss of load (2.5 TWh more than that needed in the "Early Neutrality 1" scenario), which then will be reduced to 5 TWh in 2040 (0.65 TWh less than the "Early Neutrality 1" scenario) and 0 TWh in 2050. The slightly higher electricity independence after 2040 will be due to the more diversified electricity mix, as both fossil and biomass power plants will be retrofitted with CCS, and thus will be able to continue to operate regularly. In this scenario, geothermal and fuel cells play a somewhat lesser role with regards to baseload electricity generation in 2040 and 2050, while VRE combined with storage will once more be the most important technologies for covering electricity demand.

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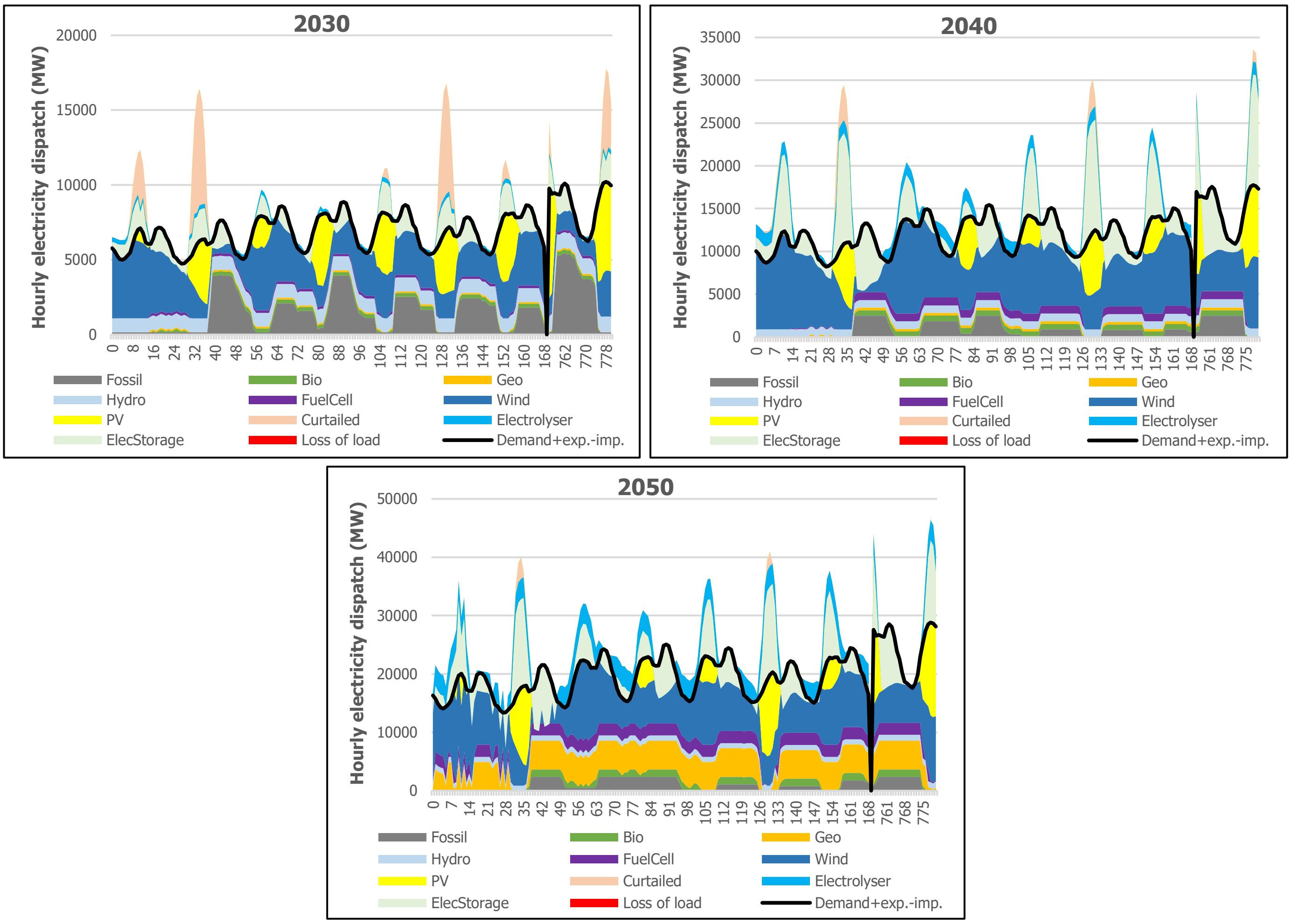

Figure 4-6:Hourly electricity dispatch per technology during the weekly operation of the Greek power sector in 2030, 2040, and 2050 under the "Early Neutrality 2" scenario.

Table 4-1 provides a summary of the key flexibility indicators derived from each of the short-term scenarios simulated in FlexTool. When comparing the flexibility indicators, we find a noticeable difference in net imports in 2030 (2.5 TWh less in the "Early Neutrality 1" scenario compared to the "Early Neutrality 2" scenario). This difference is mainly owing to the slower capacity growth of batteries and pumped hydro in the "Early Neutrality 1" scenario which also lowers the amount of VRE electricity that can be absorbed by the system, thus resulting to higher curtailment. In 2040, the discrepancy in net imports is much lower and in favour of "Early Neutrality 2" scenario, due to the operation of natural gas and biomass plants that mitigate the lower flexibility provided by batteries and pumped hydro. Along with curtailment and required net imports to prevent loss of load, the peak net load achieved in each scenario is presented. As can be seen, the peak net load is mostly affected by the net imports requirements until 2040, i.e., the scenarios with higher required net imports achieve lower peak net loads, while in 2050, when there are no net imports in both scenarios, only electricity from VRE has an effect on peak net load, particularly in the "Early Neutrality 1" scenario in which more electricity from VRE will be generated. Finally, it should be noted that the required net imports derived from FlexTool scenarios were lower than those assumed in both long-term scenarios derived from OSeMOSYS-GR (i.e., 10.9 TWh in 2030, 7.7 TWh in 2040, and 0 TWh in 2050). These variances are primarily owing to the capability of FlexTool to accurately assess the dispatch of power generation and storage

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technologies in an hourly resolution, capturing aspects such as technical minimums of dispatchable power plants, ramping constraints, minimum uptimes/downtimes. In this regard, we find that somewhat less electricity generation than that provided by OSeMOSYS-GR is actually required to cover the electricity demand projection 2030 and 2040, while the two tools converge on the electricity generation requirements in 2050.

Table 4-1: Quantifications of the key flexibility indicators for the Greek power sector in 2030, 2040, and 2050 under the "Early Neutrality 2" scenario.

FlexTool short-term scenarios	Flexibility indicators		
	Peak net load (MW)	Required net imports to prevent loss of load (TWh)	Curtailment (% of VRE gen.)
Early Neutrality 1, 2030	8127.6	7.5	5.58
Early Neutrality 2, 2030	7713.5	10	10.84
Early Neutrality 1, 2040	11524.8	5.65	0.16
Early Neutrality 2, 2040	12086.3	5	1.69
Early Neutrality 1, 2050	20197.8	0	0
Early Neutrality 2, 2050	21209.4	0	0.51

4.4 Conclusions and Outlook

The work conducted established the soft-linking process between two (2) power system models and presented the long-term decarbonisation pathways and the short-term flexibility requirements for a green transition in the Greek power sector. Our findings imply that the exploration of long-term decarbonisation pathways should combine long-term capacity planning with short-term operational assessment to provide more accurate representations of the future power system behaviour. From the results above, we can suggest that the Greek power sector will be able to always supply demand in both "Early Neutrality 1" and "Early Neutrality 2" scenarios and there will be no issues relating to loss of load. However, there are some issues concerning curtailment, especially in the short term: To address curtailment, EV charging may be implemented in the electricity grid along with battery storage, to allow users the flexibility to charge their vehicles at any schedule. Furthermore, the flexibility assessment results suggest adaptations of the capacity and electricity mixes. Apart from the minor changes in net electricity imports, the short-term results signify a need for further exploration of the potential of RES and storage technologies in terms of electricity generation. In this regard, consultation with Greek experts should take place to co-create additional long-term scenarios for the transition to a fully renewable-based power sector.

5 Consumer adoption of small-scale PV towards the achievement of the 2030 national targets in the Greek residential sector

5.1 Introduction

For almost two decades, the European Union (EU) has played a prominent role in combating the climate crisis on a global scale. The EU has strengthened its efforts to become the world's first climate neutral continent by 2050 (Süsser et al., 2022). To attain this objective, it is crucial to undertake decarbonisation of the energy sector, while to achieve more precise objectives, it is important to study the energy sector by dividing it into subsectors. The residential sector is one of the energy subsectors being analysed in this section, since it has a 25% share of the total EU GHG emissions (Jakučionytė-Skodienė et al., 2022). In this context, it is important that Member States implement decentralised technologies to modify the grid in order to accomplish the goals of a clean transition. Small-scale solar photovoltaic (PV) systems are an essential technology in this context, also towards the achievement of the respective national targets in the residential sector.

In relation to the 2023 data, the residential sector accounts for a mere 20% of the overall solar PV installed capacity in the European Union (IRENA, 2023; Research and Markets, 2023). Within this context, Greece has the potential to play a significant role in the adoption of solar PV technology in the residential sector, thanks to its abundant solar irradiation levels, with an average of 1,639 kWh/m^2. However, Greece has not yet effectively harnessed the full potential of solar power integration (Chatzisideris et al., 2017). According to the Renewable Energy Sources Operator & Guarantees of Origin, Greece has currently a total installed PV capacity of 5,557 MW with only 352 MW (6.33%) coming from small-scale installations of up until 10 kWp in the residential sector (DAPEEP, 2022; IRENA, 2023). As stated in the revised draft NECP, the objective for small-scale solar PV systems is to reach 1 GW by 2030, which, considering the current state, clearly highlights the importance that more measures have to be taken.

Policy schemes undoubtedly exert a significant influence on the energy transition by promoting varying degrees of decarbonisation in the residential sector. Nevertheless, the current research literature on the impact of various policy schemes on consumer behaviour is still in a nascent stage (Shakeel et al., 2023). A very generous feed-in tariff (FiT) policy scheme used to exist in Greece, which led to an unprecedented increase in solar PV capacity during the period 2009-2013. During that time, tariffs for installations under than, or equal to, 10 kW_p ranged from 0,45 €/kWh to 0,294 €/kWh, respectively (Kërçi et al., 2022; Stavrakas et al., 2019). However, such extremely high-level tariffs were not economically viable, and the scheme was gradually abolished, leading to a complete stagnation of the PV market. In recent years, concerted regulatory endeavours have been undertaken to align with the standards established in other European markets that have transitioned from a high FiT status to a market-based environment. Notably, legislative measures, including the implementation of net-metering and a revised FiT scheme, have been enacted (Stavrakas et al., 2020).

Within this context, the scientific literature underscores the significance of comprehending consumer behavioural patterns regarding PV adoption to ensure the efficacy of future policies (Sommerfeld et al., 2017). Owing to the intricate interplay of numerous factors shaping a household's decision to embrace innovative energy technologies like small-scale PV systems, the application of agent-based modelling (ABM) techniques emerges as a fitting framework for simulating the adoption decision process within a diverse social system. This modelling approach is grounded in the individual preferences of system members, encapsulating their behavioural rules and interactions within the context of a social network. By considering the heterogeneity inherent in individual decision-making, ABM provides a robust platform

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for capturing the complexities and dynamics involved in the adoption of innovative energy technologies, such as PV, within a broader societal context (Ringler et al., 2016). The conceptualisation of a system as a collective of autonomous decision-making entities, called "agents," is a fundamental tenet of the ABM techniques. This modelling paradigm, characterised by its high flexibility, delves into the micro-level behaviour of these agents, accommodating the inclusion of detailed information pertaining to their decisions and interactions (Bonabeau, 2002). It also enables the explicit consideration of the intricate interplay between technological characteristics and human behaviour, presenting a richer and more nuanced perspective on the dynamics inherent in complex systems. Recognised for its adaptability and capacity to capture emergent phenomena, ABM approaches, thus, stand as a valuable tool in elucidating the multifaceted relationships between technological innovation, human behaviour, and overarching sustainability objectives (Taylor et al., 2016).

The study described in this section was conducted as part of the IAM COMPACT PRM-1, specifically under Theme 4: "Behavioural Change" (see **Deliverable 2.2** "**Scoping Relevant Research Questions**”). The topics of consumers’ decision-making process about the adoption of clean technologies in the framework of behavioural change, and the significance of comprehending how different policy schemes may affect and drive the potential decision-making process of consumers, were of utmost importance for high-level policymakers from national governments and the European Commission (EC). The novelty of this study contrary to other similar studies mainly lies on the incorporation of the uncertainty bounds that govern such decisions, taking into account the “sensitivity” of the parameters that shape the decision for implementing (or not) such investments (namely, small-scale solar PV system installations). Therefore, it is important to utilise a modelling framework that represents the decision-making process of consumers, when it comes to the adoption of small-scale PV systems, through a more “real-world” process. As a result, the following research question (RQ) is selected for this study:

RQ: “**How could consumers' decision-making behaviour affect the adoption of small-scale solar PV systems towards the achievement of the 2030 national targets in the Greek residential sector?**”

5.2 Working approach

In order to address the behavioural uncertainty that governs such decisions (namely, to implement the investment for the installation of small-scale solar PV systems in households), we employ an agent-based technology adoption model that enables the explicit consideration and quantification of the uncertainties that are associated with consumers’ behaviour and decision-making criteria. The objective is to investigate the adoption of small-scale PV systems in the Greek residential sector by 2030 under three (3) distinct policy scenarios. The description of the model, the scenarios’ design, and the model parameterisation are outlined in the subsections below.

5.2.1 Model used

The Agent-based Technology adOption Model (ATOM) is a modelling framework grounded in agent-based modelling principles. Evaluated against historical data and empirical observations for plausibility, ATOM systematically simulates the anticipated efficacy of diverse policy frameworks concerning the adoption of various technologies (such as small-scale solar PV systems, battery energy storage systems, and heat pumps) within the residential sector. This simulation is conducted within the specific geographic and socioeconomic context under investigation.

Beyond elucidating the anticipated impacts of technology adoption under targeted policy schemes, ATOM facilitates the explicit consideration and quantification of uncertainties inherent in agents' preferences and decision-making criteria, denoted as behavioural uncertainty. Within the model, agents are representative of consumers (more specifically, “average income” households), thus encapsulating

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the dynamics of decision-making at the individual and collective levels.

ATOM comprises three (3) primary modelling modules (Stavrakas et al., 2019), as also depicted in Figure 5-1:

I. A "calibration" module, which establishes the final set of the key parameters governing the decision-making process of the agents and their pertinent value ranges, based on historical data and past observations.

II. A "sensitivity analysis" module that quantifies uncertainties related to agents' characteristics and decision-making criteria rather than the more obvious uncertainties derived from the calibration module's results.

III. A "scenario analysis" module that examines the potential behaviour of technology adopters in different spatial, social, and economic contexts, considering different policy scenarios of interest through forward-looking simulations.

ATOM has the capability to derive realistic uncertainty bounds and ranges as well to systematically disentangle the overall model's uncertainty into its primary contributing sources; this trait highlights the novelty of ATOM compared to other existing ABM tools in the field. This capability comes from the incorporation of a variance decomposition framework and an uncertainty identification method, while in parallel addressing structural uncertainty. Consequently, ATOM facilitates the definition of uncertainty ranges, taking into account so the type, as much as the nature of the uncertainty, and additionally gives an answer to how this uncertainty is transmitted to the model's outputs over the time span under analysis.

Variance decomposition happens across all the three (3) main modules of ATOM: In the "calibration" module, users are able to specify initial values for agent-related parameters based on how realistic the model's outputs are in relation to historical data and past observations, thereby capturing input uncertainty. The "scenario analysis" module, then, produces forward-looking simulations for diverse behavioural profiles, ranging from potential consumers that are willing to invest in the technology under study, to consumers that are not willing to take risks, so they do not invest in the technology under study, capturing parametric uncertainty.

Finally, the propagation of both types of uncertainty happens during the simulation of ATOM, and respective contributions to the variance of the final model's outcomes is quantified. The remaining uncertainty is attributed to the structure of the model. It is noteworthy that the agent-related parameters' uncertainty is conducted individually for each one of the parameters. That allows the assessment of each agent-related parameter's sensitivity to the outcomes of the model through a sensitivity analysis that is based on the variance of each parameter and on the Sobol method (Mavromatidis, Orehounig, & Carmeliet, 2018).

The temporal resolution of the model is typically one (1) month since technology capacity additions are calculated and presented as such, however, it could also be one (1) year, or five (5) years, depending on the time horizon of interest for each application under study.

All the modules of ATOM are developed in Python, while the model is open access under the "GNU AFFERO GENERAL PUBLIC LICENSE" and is available on GitHub[14].

[14] https://github.com/TEESlab-UPRC/ATOM

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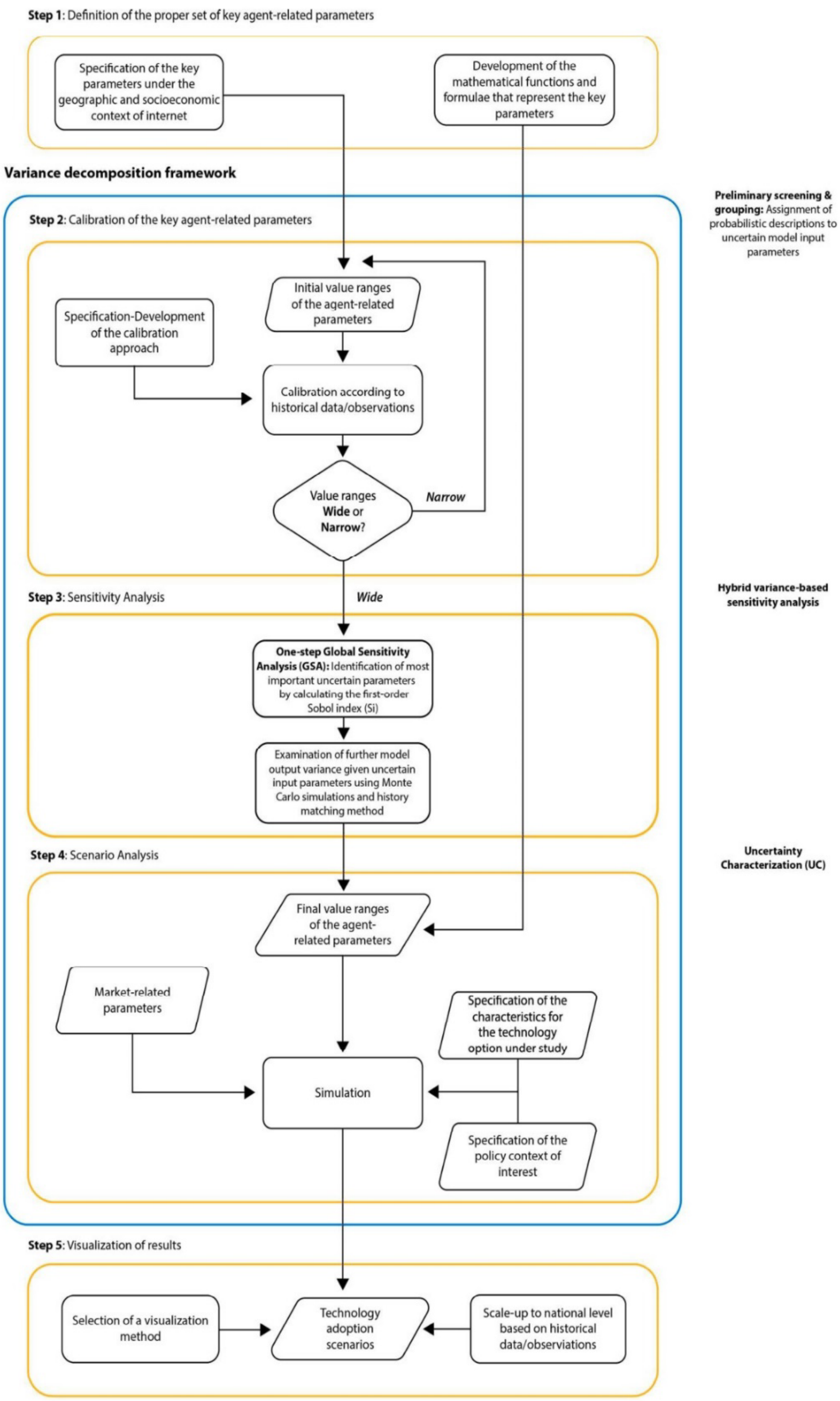

Figure 5-1. The architecture of ATOM as it currently stands (Stavrakas et al., 2019).

5.2.2 Scenario design and model parameterisation

We explore the diffusion of small-scale PV systems up to 10kWp in the residential sector in Greece under three (3) different policy scenarios, namely: **(i).** a FiT scenario, **(ii).** a net metering scenario, and **(iii).** a net metering with a battery energy storage system (BESS) scenario. Specifically, the national government has introduced in late 2021 the policy programme "Solar on Rooftops" under the Official

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Government Gazette OFG.2903/b/02.05.2023[15], which provides the characteristics of the subsidies that consumers can receive in order to invest in small-scale PV installations in their homes. Note that under this programme, prosumers are able to participate in the net metering scheme, since the government plans to gradually eliminate the fixed price that prosumers could select to be remunerated through the feed-in tariff scheme under Law 5037/2023.OFG 78/28.03.2023[16]. Policy specifications are described in more detail as follows.

Feed-in Tariff

This scenario is based on the "Solar Panels on Roof" programme, introduced in late 2021 in Greece, which offers consumers a fixed tariff of 87 €/MWh (Article 4/L.4414/2016.A'149[17]) for the electricity they sell to the grid, with a contract duration of 25 years. Under this policy scenario, the average subsidy for the PV installation cost is 500 €/kWp according to the "Solar on Rooftops" programme. The anticipated benefits $\mathrm{P}_{\mathrm{resid}}^{\mathrm{total}}$ (€) that comes from each consumer's investing decision, are calculated according to the following equation:

$$\mathrm{P}_{\mathrm{resid}}^{\mathrm{total}} = \mathrm{E}_{\mathrm{PV}} \cdot \mathrm{Tariff}$$

, where: E_{PV}: PV panel's electricity generated in total (kWh), and Tariff: The fixed price (€/kWh) as defined by the respective legislation.

Net metering

In this scenario, specifications of the net-metering scheme currently in place in Greece are assumed; the final electricity bill of consumers results from the difference between the consumed electricity and the PV-produced electricity, injected to the grid in a billing period. In case of excess electricity produced, it is credited to the next billing period for three (3) years when the final settlement takes place. The average subsidy assumed for the PV installation cost is the same as in the FiT policy scenario (500 €/kWp). The anticipated benefits $\mathrm{P}_{\mathrm{resid}}^{\mathrm{total}}$ (€) that comes from each consumer's investing decision, at the end of each netting period, are calculated according to the following equation (Stavrakas et al., 2019; Stavrakas & Flamos, 2022):

$$\mathrm{P}_{\mathrm{resid}}^{\mathrm{total}} = \mathrm{C}_{\mathrm{grid}} \cdot \min(\mathrm{E}_{\mathrm{PV}}, \mathrm{E}_{\mathrm{resid}}) + \mathrm{C}_{\mathrm{PV}} \cdot \mathrm{E}_{\mathrm{resid}_{\mathrm{PV}}}$$

, where: $\mathrm{C}_{\mathrm{grid}}$: Price for the electricity consumption (€/kWh), C_{PV}: Price for the electricity absorption from the PV panel (€/kWh), E_{PV}: PV panel's electricity generated in total (kWh), $\mathrm{E}_{\mathrm{resid}}$: Total electricity demand (kWh), and $\mathrm{E}_{\mathrm{resid}_{\mathrm{PV}}}$: Total electricity consumption from the PV panel (kWh). Note that this formula's results correspond to each netting period.

Net metering with a Battery Energy Storage System

Finally, in this scenario, and based on recent announcements, a policy scheme that combines the existing net metering's specifications with a support policy that subsidises the 90% of the investment costs of a BESS (800 €/kWh is assumed according to the most recent prices). Also, as it was assumed in the previous policy scenarios, a subsidy for the PV cost equal to an average of 500 €/kWp, is assumed under this policy scenario as well. The anticipated benefits $\mathrm{P}_{\mathrm{resid}}^{\mathrm{total}}$ (€) that comes from each consumer's investing decision, are calculated according to the following equation (Stavrakas et al., 2019; Stavrakas & Flamos, 2022):

[15] https://pvstegi.gov.gr/content/FEK-2023-Tefxos%20B-02903.pdf (in Greek).
[16] https://deddie.gr/media/31220/νομοσ-5037-2023-φεκ-α-78-28032023.pdf (in Greek).
[17] https://www.kodiko.gr/nomothesia/document/237723/nomos-4414-2016 (in Greek).

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$$P_{resid}^{total} = C_{grid} \cdot (E_{resid} - C_{grid}) + C_{PV} \cdot E_{resid_{PV}}$$

, where: C_{grid}: Price for the electricity consumption (€/kWh), C_{PV}: Price for the electricity absorption from the PV panel (€/kWh), E_{resid}: Total electricity demand (kWh), and $E_{resid_{PV}}$: Total electricity consumption from the PV panel (kWh). Note that this formula's results correspond to each netting period.

It is noted that in the respective legislations, different subsidies are provided for different categories of consumers, according to their annual income. For this study, we assume that all consumers have an annual income lower than, or equal to 20,000 €/year, the most common in Greece according to statistics from the Hellenic Statistical Authority (2023).

Agent-related parameters and calibration

When it comes to the proper parameterisation of the model's agent-related parameters and generating different behavioural profiles, which dictate the consumers' decision-making behaviour, ATOM is calibrated against historical data/observations. Considering the existing relative scientific literature, the set of the agent-related parameters that characterise consumers' decision-making behaviour with respect to investing in small-scale PV systems, the number of simulated agents can be differentiated from application to application, however, for this study, the number of simulated agents is 1,000, and each agent is a "neighbour" to five (5) other agents, with which can interact and affect their perspective about the profitability of a potential investment. Results are then upscaled to the national level based on a scalability factor, as derived from the historical data/observations. The agent-related parameters utilised in ATOM for this study were derived from the literature (Stavrakas et al., 2019), and they include:

- Agents' beliefs

Each agent has an initial private belief about the annual net cash flows of the investment in a PV panel of 300 Wp. This belief is expressed in the model as a normal (Gaussian) distribution. Beliefs of each agent are initially specified arbitrarily through two (2) probability distributions (one (1) for the mean value, and one (1) for the standard deviation). The arithmetical ranges of this parameter are finally determined through the calibration process.

- Social learning

This parameter expresses communication and interaction between the agents within a social structure. It affects consumers' decision-making on investing in an important way. Each agent receives quantitative data from other agents of its social circle, who have already invested. This data mainly lies on the profitability of the investment, which is modelled, in the context of the ATOM modelling framework, through the implementation of a net present value (NPV). Note that each agent interacts only with five (5) other agents to depict that this kind of investment is affected only by a narrow social circle (e.g., family, close friends, etc.).

- Resistance towards PV investments

This parameter is modelled as the weighted sum of the investment's profitability in terms of NPV and the difference between agents' number under study (1,000) with the number of agents that already have implemented the investment, in a given time period. The rationale behind this is that the larger the profitability, the shorter the payback period and, thus, the lower the resistance. The key parameters that affect this agent-related parameter are the capital expenditure (CAPEX) and the discount rate of the investment. Note that as the difference between the simulated agents' number and the number of agents that have implemented the investment decreases, the value of the resistance is decreased as well. This highlights the importance that the social circle of each agent has in their decision-making process.

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- Probability of investing

Agents have a threshold value about the "Resistance towards PV investments" parameter. When the resistance parameter value is lower than the threshold value, it is probable for an agent to take the decision to invest; not necessarily, though. In order to calibrate the model, we assume that when the agents decide to implement the investment, the installed capacity in which they will invest, is determined through an empirical probability distribution that is derived from the available past observations.

- Inertia to invest

In the model, inertia to invest is incorporated through the definition of a global parameter, which maintains a consistent value across all agents within the system. This parameter signifies the likelihood of an agent proceeding with an investment once its resistance threshold is surpassed. Notably, during the calibration process, inertia is held constant. This decision is motivated by the role of this parameter in regulating model scale. Altering its value, while maintaining the simulated agents' number constant, has repercussions on the ratio of adopters to the overall number of simulated agents at the conclusion of the simulated period. Such adjustments introduce issues with the attributability into the model, emphasising the need for a consistent inertia parameter value throughout the calibration phase to ensure model integrity and meaningful interpretation of results.

The final value ranges of the agent-related parameters are set through the calibration process. We used historical data from the period 2009-2013, when the FiT scheme was operational with the highest recorded fixed price, which had as a result the largest solar PV capacity addition in the residential sector. The value ranges of the agent-related parameters after calibration are presented in Table 5-1, while the reliability of the calibration results (fitness) is depicted in Figure 5-2, compared to the real historical data/observations for the given period.

Table 5-1. Final value ranges of the model's agent-related parameters after calibration.

Agent-related parameter	Description	Min	Max
Initial beliefs	Global distribution's shape parameter that designates the agents' mean value.	114	122
	Global distribution's shape parameter that designates the agents' standard deviation.	1.8	19
Social learning	Global distribution's scale parameter that designates the agents' mean value.	7.23	26.47
	Global distribution's scale parameter that designates the agents' standard deviation.	0	5
Resistance towards PV investment	Global distribution's shape parameter that designates profitability's weight to the agents' resistance.	4.32	4.48
	Global distribution's scale parameter that designates profitability's weight to the agents' resistance.	1.1	1.46
	Global distribution's shape parameter that designates installed base's weight to the agents' resistance.	10	13.45
	Global distribution's scale parameter that designates installed base's weight to the agents' resistance.	1	8
Probability of investing	Global distribution's shape parameter that designates the agents' upper limit of resistance.	36.43	39.38
	Global distribution's scale parameter that designates the agents' upper limit of resistance.	1.81	7.75
Inertia to invest	No change in this parameter due to the impact that it will has in the model's outcomes (kept constant).	0.01	

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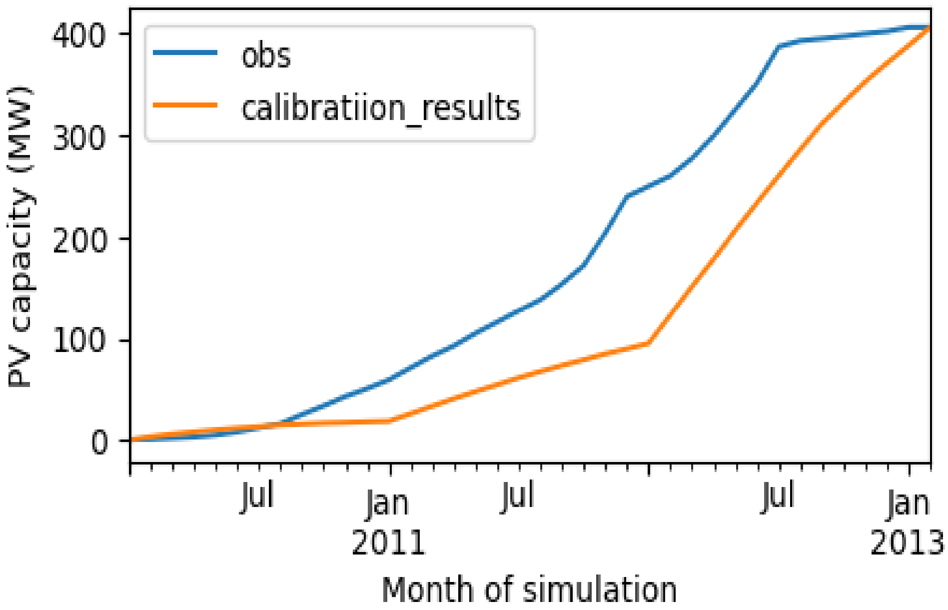

Figure 5-2. Calibration results from the application of ATOM compared to the historical data during the period 2009-2013, when the first FiT policy scheme was in place in Greece.

It is apparent that the curve representing the calibration results does not completely align with the curve representing the historical data. Nevertheless, within the mathematical framework of the history matching method, it is impossible for the two (2) curves to completely coincide. Consequently, we consider the results to be reliable when the two (2) curves exhibit minimal distance from each other across multiple runs of the calibration module.

Market-related parameters

The market-related parameters used in ATOM for the forward-looking simulations to explore diffusion of small-scale PV systems in the residential sector of Greece by 2030, under the three (3) policy scenarios under study, are presented in Table 5-2 (IEA, 2023; Michas et al., 2020; Stavrakas et al., 2019).

Table 5-2. Market-related parameters used in ATOM for this study.

Market-related parameters	Feed-in Tariff	Net Metering	Net metering with Battery Energy Storage System
Initial PV Cost (€/Wp)	0.833	0.833	0.833
PV Price Annual Change Factor (%)	-1.28	-1.28	-1.28
Initial FiT Value (€/MWh)	87	-	-
FiT Annual Change Factor (%)	False	-	-
Initial Electricity Price (€/kWh)	0.1595	0.1595	0.1595
Regulated Charges (€/kWh)	0.0508	0.0508	0.0508
Electricity Price Annual Change Factor (%)	N/A	N/A	N/A
Annual Electricity Demand (kWh)	-	4,162	4,162
Battery Efficiency (%)	-	-	92
Inverter Efficiency (%)	-	-	96
Initial Battery Cost (€/kWh)	-	-	800
Battery Cost Annual Change Factor (%)	-	-	-2.91
Battery Subsidy Percentage (%)	-	-	90

5.3 Results

We present the forward-looking simulation results, as derived from ATOM, for each policy scenario under study. Simulation results project future outcomes from 2024 to 2030. The figures below illustrate the various pathways on the small-scale PV capacity addition (in MW) under the three (3) policy scenarios. Uncertainty of the adoption rate for each scheme is represented using error bars, which are coloured light orange, visualising the overall uncertainty range in consumers' adoption behaviour, from consumers eager to invest to consumers who are completely risk-averse, also depicting average projections (i.e., the most probable scenario for each policy scheme).

The most significant positive influence on the increase in small-scale PV capacity by 2030, in the Greek residential sector seems to be once again achieved by implementing a FiT policy programme (Figure 5-3). In this policy scenario, the impact of government choices is reduced as consumers' decision-making behaviour is mostly influenced by market-related factors. An important factor in their decision-making process is the set tariff amount that consumers get as compensation for the electricity they supply to the grid. Therefore, in this situation, the fixed price of payment must accurately represent the societal perspective on how customers should be reimbursed. The determination of a fixed price should be based on sensible criteria that consider market trends, PV costs, and power prices. Results indicate that it is possible to achieve a solar PV capacity increase of around 250 MW by 2030 under the FiT scenario (with a fixed price equal to 87 €/kWh). The range of uncertainty in consumers' expected decision-making behaviour is relatively small since it spans from 240 MW (in the most pessimistic scenario) to 260 MW (in the most optimistic scenario).

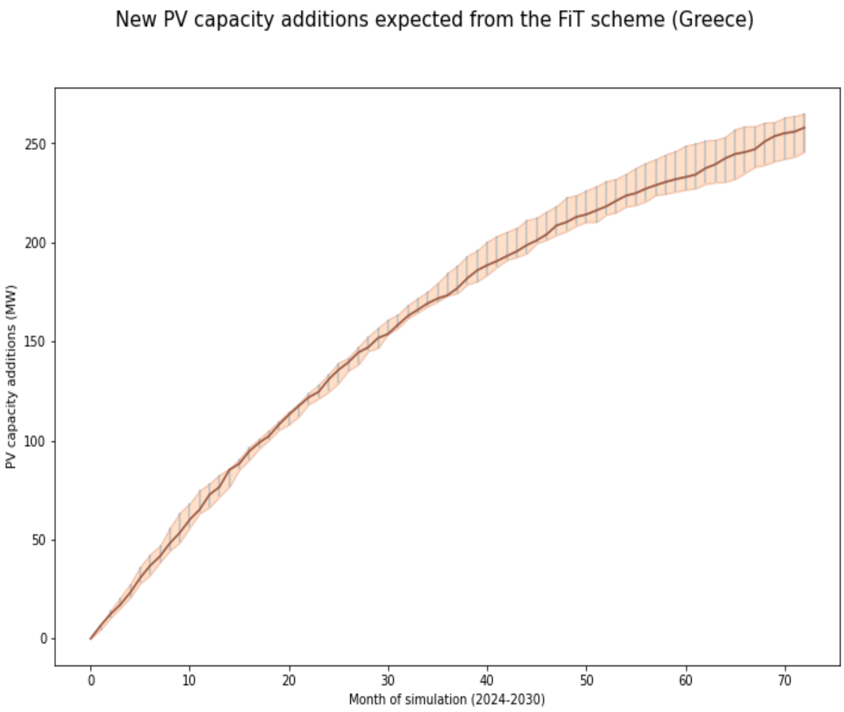

Figure 5-3: Forward-looking simulation results on the small-scale PV capacity addition expected by 2030 in the Greek residential sector under the existing feed-in tariff policy scheme. Uncertainty in consumers' adoption behaviour is captured through error bars.

Compared to the FiT scenario, the impact of the net metering policy scheme, currently in place (Figure 5-4) on the expected small-scale PV capacity addition by 2030, is more than two (2) times lesser, estimated at approximately 100 MW in the most probable scenario. In the context of the net metering scheme, consumers lack the incentive to generate surplus electricity as they do not receive compensation for it during the netting periods. Hence, it appears that the existing net metering scheme

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has a lesser influence on the acceptance of the technology in comparison to the implementation of a FiT policy scheme. On the other hand, it is noteworthy that consumers' decision-making behaviour under the net metering scheme is marked by less uncertainty compared to the FiT scenario. Uncertainty ranges from around 95 MW in the most pessimistic scenario to around 105 MW in the most optimistic scenario.

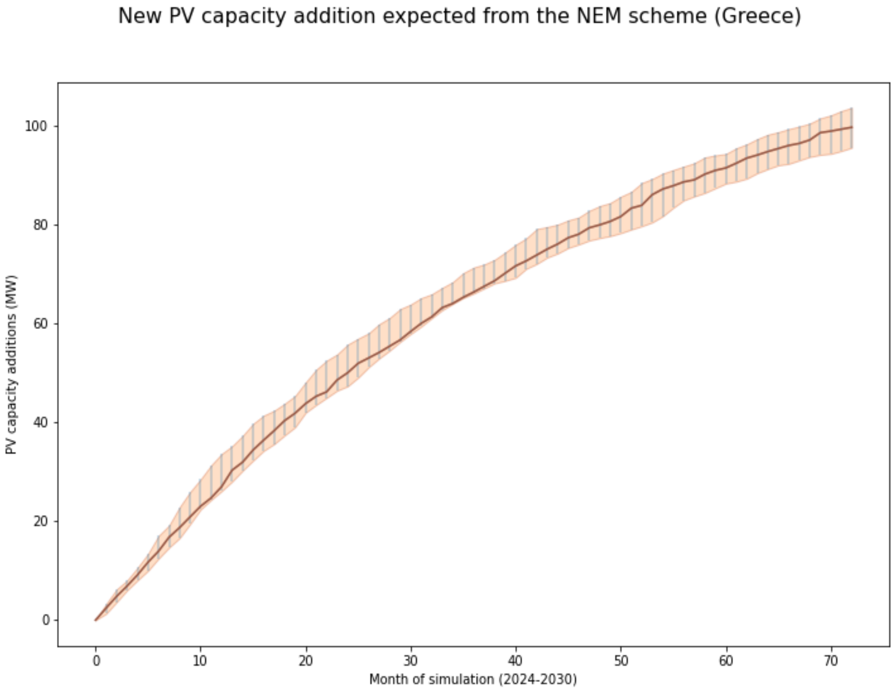

Figure 5-4: Forward-looking simulation results on the small-scale PV capacity addition expected by 2030 in the Greek residential sector under the current net-metering policy scheme. Uncertainty in consumers' adoption behaviour is captured through error bars.

Finally, combining the existing net metering policy with a support scheme that subsidises 90% of the investment in a BESS (Figure 5-5) seems to have an even weaker influence on consumers' decision to invest in small-scale solar PV systems compared to the existing net metering scheme. This combined approach is expected to result in an approximate increase of 63 MW in capacity by 2030, under the most probable scenario. In addition, consumers' decision-making in this case appears to be even more uncertain, compared to the net metering scenario. This is likely due to the relatively high costs of storage technologies, which impact consumers' perceptions of the profitability of their investment. Consumers who are very cautious about taking risks have an ambiguous understanding of the investment's profitability over time, and as a result, their opinions and reluctance to invest remain unchanged. The uncertainty range in this situation spans from 59 MW (in the most pessimistic scenario) to 72 MW (in the most optimistic scenario).

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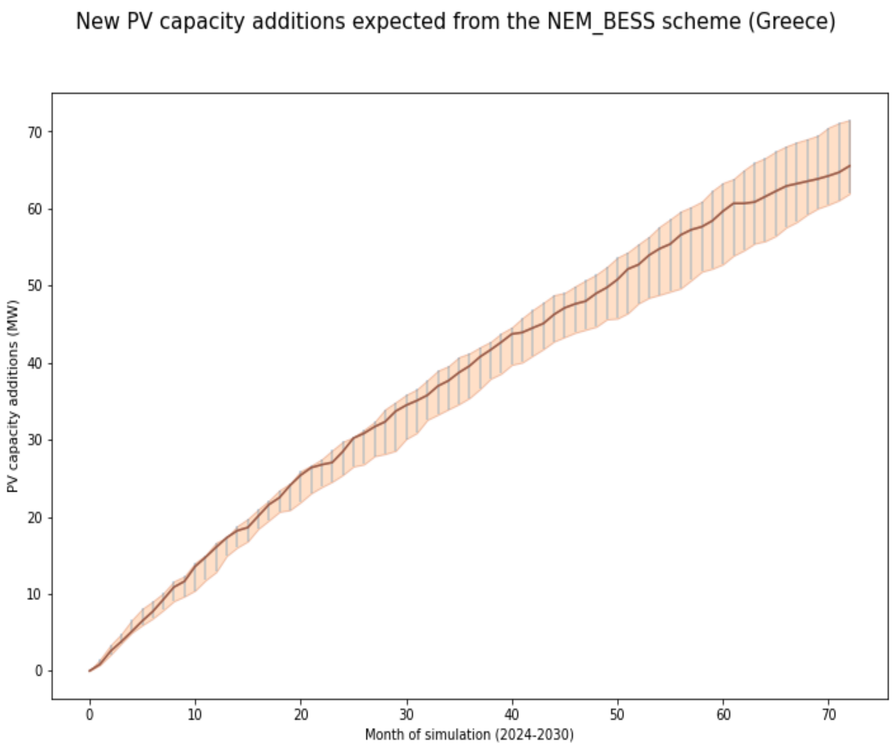

Figure 5-5: Forward-looking simulation results on the small-scale PV capacity addition expected by 2030 in the Greek residential sector under the existing provision for net-metering policy scheme that subsidises a battery energy storage system. Uncertainty in consumers' adoption behaviour is captured through error bars.

Furthermore, we calculate the carbon emission reduction due to the increase in the small-scale PV capacity by 2030 in the Greek residential sector for the three (3) policy scenarios under study (Figure 5-6). Model calculations are based on the average power sector carbon intensity in Greece according to the country's energy mix, which is around 342.4 gCO_2/kWh for 2023 (IEA, 2023), dropped substantially from 791.6 gCO_2/kWh that was on 2005 when the country's electricity production was dominated by lignite (around 60% of the total electricity production according to statistics from "Our World in Data"). As expected, results indicate that the largest carbon emission reduction is achieved under the FiT scenario with almost 120,000 $tnCO_2$, while around 40,000 $tnCO_2$ could be reduced under the existing net metering scheme, and approximately 35,000 $tnCO_2$ could be reduced under the existing net metering scheme with a provision on subsidising a BESS.

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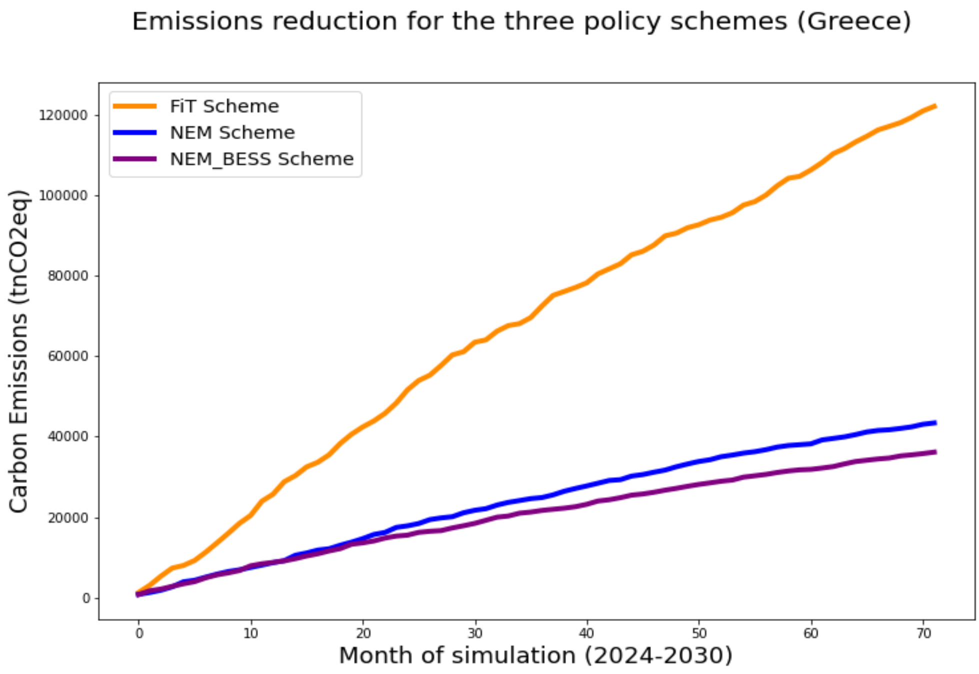

Figure 5-6: Carbon emission reduction due to the increase in the small-scale PV capacity by 2030 in the Greek residential sector, for the three (3) policy scenarios under study.

Last but not least, we compare simulation results on the trajectories of the expected small-scale PV capacity addition by 2030 in the Greek residential sector, for the three (3) policy scenarios under study, with the NECP's trajectory target (1 GW of small-scale PV installed capacity by 2030 in the residential sector). Figure 5-7 presents this comparison; it is noteworthy that none of the three (3) policy schemes under study are able to achieve this target if no additional supportive measures are taken, e.g., an even more generous fixed price than the one under study, or a net metering scheme with compensation provisions for consumers', etc.

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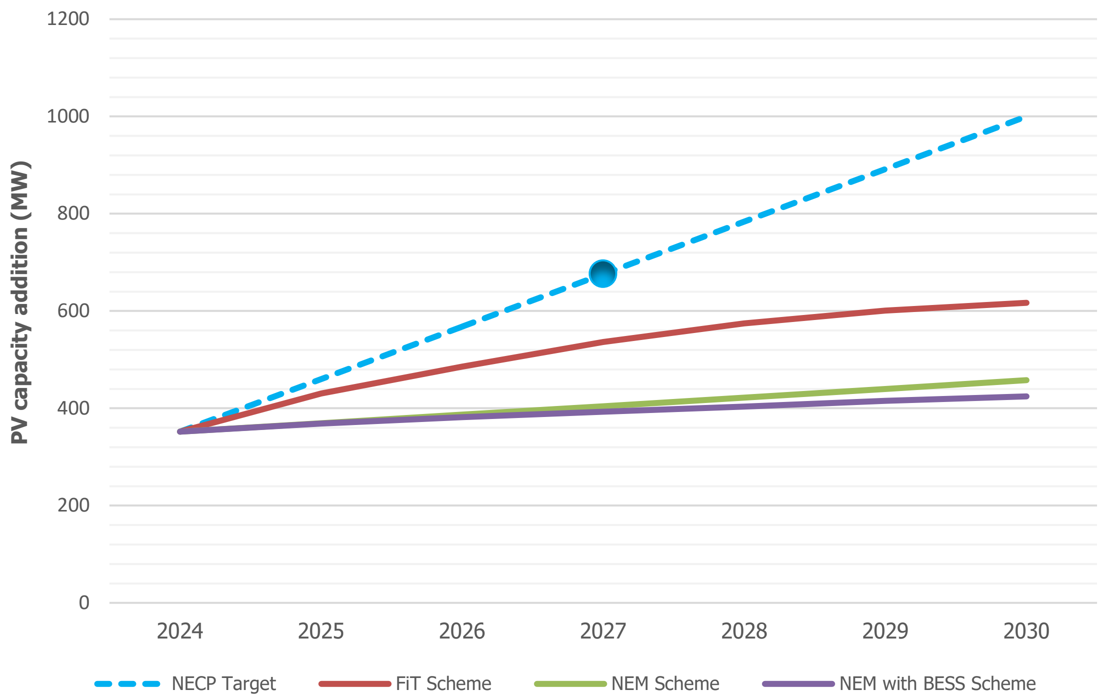

Figure 5-7: Comparison of simulation results on the trajectories of the expected small-scale PV capacity addition by 2030 in the Greek residential sector, for the three (3) policy scenarios under study, with the National Energy and Climate Plan's target trajectory.

5.4 Conclusions and Outlook

When it comes to the increase of the small-scale PV capacity by 2030 in the Greek residential sector, our results showed that policy schemes recently introduced under the "Solar on Rooftops" programme, i.e., a FiT policy scheme with a fixed price of 87 €/MWh, a net metering scheme where consumers receive no remuneration for the excess electricity produced, and a net metering scheme combined with a BESS subsidisation of 90%, are not able to achieve the capacity addition necessary to meet the target of 1 GW set by the Greek NECP. This implies that in order to achieve the current target, or even go beyond and reach a more ambitious target (recently, the President of the HELlenic Association of Photovoltaic COmpanies (HELAPCO) announced that Greece could be more ambitious in target planning when it comes to the small-scale PV capacity installed in the residential sector, suggesting a target of 2 GW by 2030), updates in the current policy planning and contingency actions that provide stronger incentives to consumers are necessary.

Simulation results suggest that one of the main drivers motivating consumers to embrace small-scale solar PV systems is profitability, and particularly through a higher fixed price in the case of a FiT policy scheme, or adjusted taxes, market regulations, and financial support measures that steer energy prices towards fostering a just energy transition. This entails promoting system flexibility through decentralised energy systems that generate electricity at a local level, thereby reducing the risk of having unused and unprofitable assets. Policymakers should advocate more robust financial incentives, such as tax exemptions for prosumers, to highlight the significant profits on such investments. Regulatory support, encompassing streamlined processes and clear guidelines is also pivotal in facilitating wider adoption. Finally, more research should be conducted in order to highlight how the capital costs of such investments could affect the decision-making process of consumers/households, adding to the existing knowledge about the factors that affect the most the implementation of investments like the installation of small-scale solar PV systems in households.

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ANNEX

Harmonised steel technology data for Study on EU Steel Industry

Process	Process long name	energy for crude steel production: electricity	natural_gas	coal	hydrogen	biomass	biomethane	char_coal	off_gas
Unit		GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product
BF_BOF	Blast furnace / blast oxygen furnace	0.000	0.584	21.145	0.000	0.000	0.000	0.000	-1.911
BF_BOF_CCS_73%	Blast furnace / blast oxygen furnace + CCS (at coke ove, hot stoves, Power Plant)	3.009	0.584	21.145	0.000	0.000	0.000	0.000	-1.911
BF_BOF_CCS_86%	Blast furnace / blast oxygen furnace + CCS (at coke ove, hot stoves, Power Plant and sinter pl	3.658	0.584	21.145	0.000	0.000	0.000	0.000	-1.911
BF_BOF_BECCSmin	Blast furnace / blast oxygen furnace with bioenergy + CCS	3.017	0.000	14.110	0.000	0.000	0.584	6.458	-1.911
BF_BOF_BECCSmax	Blast furnace / blast oxygen furnace with bioenergy + CCS	3.025	0.000	12.959	0.000	0.000	0.584	7.619	-1.911
SR_BOF	Smelting reduction / blast oxygen furnace	1.647	0.000	13.784	0.000	0.000	0.000	0.000	-0.771
SR_BOF_CCS	Smelting reduction / blast oxygen furnace + CCS	2.521	0.000	13.784	0.000	0.000	0.000	0.000	-0.771
DRI_EAF_NG	Direct reduction of iron with natural gas + Electric Arc furnace	1.574	11.364	0.080	0.000	0.000	0.000	0.000	0.000
DRI_EAF_NG_CCS	Direct reduction of iron with natural gas + Electric Arc furnace + CCS (at shaft kiln)	2.236	11.364	0.080	0.000	0.000	0.000	0.000	0.000
DRI_EAF_coal	Direct reduction of iron with gasified coal + Electric Arc furnace	3.951	0.000	21.480	0.000	0.000	0.000	0.000	0.000
DRI_EAF_coal_CCS	Direct reduction of iron with gasified coal + Electric Arc furnace + CCS	9.323	0.000	21.480	0.000	0.000	0.000	0.000	0.000
DRI_EAF_BECCS	Direct reduction of iron with bioenergy + Electric Arc furnace + CCS (at shaft kiln)	3.356	0.000	0.000	0.000	13.905	0.000	0.352	0.000
DRI_EAF_H2	Direct reduction of iron with hydrogen + Electric Arc furnace	2.231	0.000	0.000	8.958	0.000	0.000	0.575	0.000
DRI_SAF_BOF_NG	Direct reduction of iron with natural gas + smelter + Blast oxygen furnace	2.133	10.704	0.110	0.000	0.000	0.000	0.000	0.000
DRI_SAF_BOF_H2	Direct reduction of iron with hydrogen + smelter + Blast oxygen furnace	2.133	0.000	0.000	8.197	0.000	0.000	1.550	0.000
DRI_SAF_BOF_BECCS	Direct reduction of iron with bioenergy + smelter + Blast oxygen furnace + CCS (at shaft kiln)	5.539	0.000	0.000	0.000	13.984	0.000	0.612	-1.096
AEL_EAF	Alkaline electrolysis + Electric Arc furnace	14.508	0.000	0.000	0.000	0.000	0.000	0.407	0.000
MOE	Molten oxide electrolysis	16.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EAF_scrap_fossil	Electric Arc furnace (scrap only), fossil and finishing with NG	2.233	0.442	0.405	0.000	0.000	0.000	0.000	0.000
EAF_scrap_bio	Electric Arc furnace (scrap only), bioenergy and finishing with NG	2.674	0.000	0.000	0.000	0.000	0.000	0.407	0.000
EAF_scrap_fossil	Electric Arc furnace (scrap only), fossil and electrical finishing	2.233	0.442	0.405	0.000	0.000	0.000	0.000	0.000
EAF_scrap_bio	Electric Arc furnace (scrap only), bioenergy and electrical finishing	2.674	0.000	0.000	0.000	0.000	0.000	0.407	0.000

Process	energy for finishing: electricity	natural_gas	hydrogen	biomass	biomethane	off_gas	CO2 Transport & storage (T&S) costs 2020	2030	2050	CO2 emissions: captured	emitted
Unit	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	GJ / t finished steel product	$/ t CO2 T&S	$/ t CO2 T&S	$/ t CO2 T&S	t CO2 captured / t steel product	t CO2 emitted / t finished product
BF_BOF	0.473	0.698				1.911	50	45	25	0	2.07
BF_BOF_CCS_73%	0.473	0.698				1.911	50	45	25	1.48	0.59
BF_BOF_CCS_86%	0.473	0.698				1.911	50	45	25	1.84	0.23
BF_BOF_BECCSmin	0.473				2.609	1.911	50	45	25	1.48	-0.13
BF_BOF_BECCSmax	0.473				2.609	1.911	50	45	25	1.49	-0.24
SR_BOF	0.473	1.839				0.771	50	45	25	0	1.37
SR_BOF_CCS	0.473	1.839				0.771	50	45	25	0	0.24
DRI_EAF_NG	0.473	2.609					50	45	25	0	0.79
DRI_EAF_NG_CCS	0.473	2.609					50	45	25	0.42	0.37
DRI_EAF_coal	0.473	2.609					50	45	25	0	2.28
DRI_EAF_coal_CCS	0.473	2.609					50	45	25	1.92	0.36
DRI_EAF_BECCS	0.516			3.728			50	45	25	0.87	-0.86
DRI_EAF_H2	0.473		2.609				50	45	25	0	0.01
DRI_SAF_BOF_NG	0.473	2.609					50	45	25	0	0.78
DRI_SAF_BOF_H2	0.473		2.609				50	45	25	0	0.04
DRI_SAF_BOF_BECCS	0.516			2.632		1.096	50	45	25	0.92	-0.87
AEL_EAF	3.082						50	45	25	0	0.01
MOE	3.082						50	45	25	0	0.00
EAF_scrap_fossil	0.473	2.609					50	45	25	0	0.22
EAF_scrap_bio	0.473	2.609					50	45	25	0	0.15
EAF_scrap_fossil	3.082						50	45	25	0	0.07
EAF_scrap_bio	3.082						50	45	25	0	0.01

Process	Process long name	Materials: material cost (non energy cost) 2020	2030	2050	CAPEX 2020	2030	2050	OPEX (fix) 2020	2030	2050	Lifetime	TRL	Exp. readine:	Capacity facor
Unit		$/t finished steel product	$/t finished steel product	$/t finished steel product	$/t capacity (un-discounted costs)	$/t capacity (un-discounted costs)	$/t capacity (un-discounted costs)	$/t finished steel product	$/t finished steel product	$/t finished steel product	years	-	year	-
BF_BOF	Blast furnace / blast oxygen furnace	295.2	297.4	305.0	245	245	245	39	39	39	25	9	-	0.8
BF_BOF_CCS_73%	Blast furnace / blast oxygen furnace + CCS (at coke ove, hot stoves, Power Plant)	0.0	299.6	306.1		574	574		69	69	25		2030	0.8
BF_BOF_CCS_86%	Blast furnace / blast oxygen furnace + CCS (at coke ove, hot stoves, Power Plant and sinter pl	0.0	300.6	308.2		899	899		72	72	25	6	2030	0.8
BF_BOF_BECCSmin	Blast furnace / blast oxygen furnace with bioenergy + CCS	0.0	299.6	306.1		574	574		75	75	25		2030	0.8
BF_BOF_BECCSmax	Blast furnace / blast oxygen furnace with bioenergy + CCS	0.0	300.6	308.2		574	574		75	75	25	6	2030	0.8
SR_BOF	Smelting reduction / blast oxygen furnace	307.2	307.2	307.2	732	525	386		90	71	25	6	2030-2035	0.8
SR_BOF_CCS	Smelting reduction / blast oxygen furnace + CCS	0.0	307.2	307.2		660	521		97	77	25	6	2030-2035	0.8
DRI_EAF_NG	Direct reduction of iron with natural gas + Electric Arc furnace	401.6	408.1	421.1	829	829	829	59	59	59	25	9	-	0.8
DRI_EAF_NG_CCS	Direct reduction of iron with natural gas + Electric Arc furnace + CCS (at shaft kiln)	0.0	409.2	422.2		863	863	61	61	61	25	7	>2025	0.8
DRI_EAF_coal	Direct reduction of iron with gasified coal + Electric Arc furnace	401.6	408.1	421.1	829	829	829	59	59	59	25	9	-	0.8
DRI_EAF_coal_CCS	Direct reduction of iron with gasified coal + Electric Arc furnace + CCS	0.0	409.2	422.2		953	953		61	61	25	8	>2025	0.8
DRI_EAF_BECCS	Direct reduction of iron with bioenergy + Electric Arc furnace + CCS (at shaft kiln)	0.0	409.2	412.4	43	974	974		61	61	25	8	>2025	0.8
DRI_EAF_H2	Direct reduction of iron with hydrogen + Electric Arc furnace	0.0	412.4	415.7	43	829	829		59	59	25	8	2025	0.8
DRI_SAF_BOF_NG	Direct reduction of iron with natural gas + smelter + Blast oxygen furnace	369.0	373.4	376.6	1051	1051	1051	66	66	66	25	8	2025	0.8
DRI_SAF_BOF_H2	Direct reduction of iron with hydrogen + smelter + Blast oxygen furnace	362.5	377.7	381.0	1051	1051	1051	66	66	66	25	7-8	2025	0.8
DRI_SAF_BOF_BECCS	Direct reduction of iron with bioenergy + smelter + Blast oxygen furnace + CCS (at shaft kiln)	0.0	379.9	384.2		1146	1146		68	68	25	7	>2025	0.8
AEL_EAF	Alkaline electrolysis + Electric Arc furnace	0.0	315.8	315.8		1153	1153		78	78	25	3-4	2040	0.8
MOE	Molten oxide electrolysis	0.0	265.9	265.9		937	937		69	69	25	4	2035	0.8
EAF_scrap_fossil	Electric Arc furnace (scrap only), fossil and finishing with NG	353.8	360.3	360.3	261	261	261		45	45	25	9	-	0.8
EAF_scrap_bio	Electric Arc furnace (scrap only), bioenergy and finishing with NG	353.8	360.3	360.3	261	261	261		45	45	25	8	<2025	0.8
EAF_scrap_fossil	Electric Arc furnace (scrap only), fossil and electrical finishing	353.8	360.3	360.3	261	261	261		45	45	25	9	>2035	0.8
EAF_scrap_bio	Electric Arc furnace (scrap only), bioenergy and electrical finishing	353.8	360.3	360.3	261	261	261		45	45	25	8	>2035	0.8

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