IAM COMPACT

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

Enhancing Renewable Energy System Metrics: Security, Flexibility, and Sustainability

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1 Introduction

IAM COMPACT is a Horizon Europe research project, with the objective to support the assessment of global climate goals, the collective progress towards them, and the feasibility space in delivering on those goals. It aims to involve relevant stakeholders in the process to help promote acceptable, robust, sustainable transitions, as well as to enhance trust on both ends, yielding outputs intelligible in terms of real-world implications and actionable in terms of concrete policy recommendations.

Participatory approaches have been argued to bring a more diverse range of views into the IAM process, by building a better understanding of the social context and supporting more inclusive decision-making. In IAM COMPACT, we have designed a Policy Response Mechanism (PRM), a co-creation process that facilitates collaboration among modelling teams and with stakeholders. The PRM dynamically responds to changing policy priorities, aiming for policy relevance, knowledge exchange, and enhanced trust, by providing different layers of inputs and making modelling socially/politically realistic. Stakeholder engagement in IAM COMPACT is organised into themes (for stakeholders within the EU) and regions (for stakeholders outside the EU). The themes and regions were collaboratively determined within the project, with Bruegel coordinating the process. For the themes, the aim was to have a broad enough coverage to capture a range of issues, but also sufficiently selective to lead a clear research agenda later in the project. This policy brief is part of the theme *Optimal Transition*, which investigates how to best manage the energy transition in Europe, through national and European climate and energy targets, decarbonisation of electricity generation, and electrification of energy services.

Overall, 23 questions emerged from high-level exchanges with policy stakeholders (forming the Policy Steering Groups), which we grouped into proposals for seven modelling studies. These proposals were in turn grouped into four overreaching themes and discussed with a wider policy audience (forming the Core Working Groups) selected on geographical and sectoral criteria. The results of one of those studies is presented here, guided by the following research question:

> *What are the different cost, energy security, and resilience metrics and how do they compare for different scenarios?*

The consultative process helped us evaluate the relevance of policy issues, refine the scope of research questions, and establish a balanced group of stakeholders to participate. We conducted one workshop under each theme alongside the corresponding core working group to consult stakeholders on our scenario design and co-define desired outputs as well as a key set of joint input assumptions. During the workshop conducted under this theme, we sought feedback on the scenario design, inputs, and projections of two proposed modelling studies. The participating stakeholders, including representatives from the DG ENER, the Agency for the Cooperation of Energy Regulators (ACER), and the renewable energy industry, provided insights on the most policy relevant aspects of energy system security, resilience and flexibility. Suggestions were also offered to IAM COMPACT partners on specific metrics that could be used to assess model results along these criteria.

1.1 Methods and key findings

To address the research question, the European energy system is modelled with the EnergyPLAN tool, a deterministic hourly simulation model for modelling of complete energy systems i.e., heating and cooling (including district energy solutions), electricity and gas grids, transportation, and infrastructure. Three scenarios for the EU are analysed and compared; the European Commission's "Baseline 2050" and "1.5 Tech" scenarios based on PRIMES modelling, in addition to a 100% renewable "Smart Energy Europe" scenario.

The scenario outputs from EnergyPLAN are then utilized, through the integrated assessment models MARIO and

WILIAM, to further assess energy security and resilience, primary energy consumption and electricity generation, alongside upstream supply chain commodity linkages. Flexibility is explored through an assessment of peak electricity demands and residual electricity demands relative to dispatchable and variable generation capacity and the availability of energy storage. Resulting material demands and raw material prices for the different energy system scenarios are evaluated as an environmental effect.

Several key findings emerge:

1) **It is feasible to construct 100% renewable energy system scenarios without relying on energy imports** if this is a political priority. This finding arises from the Smart Energy Europe scenario.
2) The study demonstrates the need to expand the scope of scenario assessment criteria beyond cost and greenhouse gas optimisation, particularly by evaluating critical energy system dimensions like **energy system security, resilience, and flexibility.**
3) The design of future renewable energy systems must diligently consider the balancing of dispatchable and variable electricity generation and the available potential for flexible demands and energy storage. Hence, **the transition to renewable energy systems necessitates a diversification of the energy system**, both from an energy security, resilience, and flexibility perspective.
4) Energy scenarios for the EU should be discussed in terms of acceptable foreign energy and technology imports. This is critical for the development of future energy systems. This study found that **renewable energy systems are less reliant on foreign supply chains than fossil-fuel-based systems.**

1.2 Models

EnergyPLAN is a tool for simulation of the entire energy system including all sectors, i.e., heating, cooling, industry, transportation, as well as electricity and gas grids. Hourly temporal resolution allows for detailed modelling of variable renewable energy generation in addition to weekly and seasonal differences in electricity and heat demands. EnergyPLAN is a deterministic model based on analytical programming, making calculations fast even for complex energy systems. EnergyPLAN optimises the operation of the energy system rather than the investments, which is instead done exogenously by the user. In this study, EnergyPLAN is used to model the EU as an aggregated energy system and optimise the operations of technologies. The modelled scenarios are then further evaluated in unison with the MARIO and WILIAM models.

MARIO is a versatile modelling framework for input-output analyses and model handling. It comes with a set of useful features for performing economic-environmental impact assessments and footprinting analyses. MARIO can be used for macroeconomic and environmental policy analyses both as a stand-alone tool and to complement other modelling tools' results as in the case of this study. Results from EnergyPLAN scenarios, in terms of the new addition of PV and wind power (offshore and onshore) capacities and other new electricity generation capacities, are implemented as "shock" analyses. Simulated economic shocks trigger new production levels by all underlying supply chains, resulting in new economic and environmental impacts. Moreover, MARIO is used to calculate the so-called backward linkages of the technologies, indicating how each commodity (electricity produced by different energy sources) relies on upstream supply chains and whether these are based within or outside the EU.

The Within Limits Integrated Assessment Model (WILIAM) is a novel Integrated Assessment Model rooted in system dynamics, enabling the capture of intricate feedback loops and non-linear relationships among social, economic, and environmental variables. Comprising 8 modules: demographics, society, economics, finance, energy, materials, land and water, and climate, WILIAM takes a granular approach, with disaggregation into 62 sectors. Covering 9 regions and 35 countries, including the EU27, the model incorporates Input-Output Analysis for its sectoral breakdown and production sub-module. Notably, WILIAM includes mining & manufacturing of minerals sectors, encompassing iron, while steel is encompassed within the Manufacture of metal products sector. Its production and international trade sub-modules ensure that all the upstream and downstream supply chain effects are fully captured. Armington-elasticities are also applied to the international trade sub-module, resulting in different import shares from one region to others, and allowing spill-over effects across countries and regions.

2 Scenario Design

Three different scenarios for the future energy system of the EU were developed and evaluated for this study. The scenarios are modelled in EnergyPLAN as an aggregated energy system, i.e., without any geographical distinction. The aggregated approach to system modelling allows for significant modelling of sector integration measures and energy technologies at an hourly temporal resolution but also means that network, transmission, and interconnection restrictions cannot be represented. The scenarios evaluated in this study were first presented in Thellufsen et al. 2023[1] for a comparison of the role of sector integration in the PRIMES "A Clean Planet for All" scenarios to a scenario developed based on Smart Energy System Principles.

The scenarios included in this study are:

- **"Baseline 2050":** *Baseline 2050* was developed as part of the "A Clean Planet for All" strategy to reflect the EU decarbonisation trajectory towards 2050 based on agreed and proposed policies by the Commission, reflecting macro-economic projections, fuel price projections, and technology assumptions.
- **"1.5 Tech":** The *1.5 Tech* scenario was also developed as part of the "A Clean Planet for All" strategy, representing a climate-neutral scenario and a pathway to stay within the 1.5°C ambition of the Paris Agreement. This requires significant electrification and deployment of e-fuels and hydrogen, carbon capture and storage solutions largely for bioenergy, alongside strong penetration of variable renewable electricity for a decarbonized power sector.
- **"Smart Energy Europe":** *Smart Energy Europe* is developed as a 100% renewable energy system alternative based on the same technology catalogue as the PRIMES scenarios but designed according to Smart Energy System principles. Specifically, 1) energy efficiency first, 2) updated heating systems and expansion of district heating, 3) electrification of transport, 4) e-fuels for heavy parts of transport, 5) replacing remaining fossil fuel demands in industry and power generation (share that cannot be electrified) with biogas and biomass.

  The scenarios are evaluated considering energy system security, resilience, flexibility, costs and prices and environmental effects through different analyses.

[1]Jakob Zinck Thellufsen, Henrik Lund, Peter Sorknæs, Steffen Nielsen, Miguel Chang, Brian Vad Mathiesen, Beyond sector coupling: Utilizing energy grids in sector coupling to improve the European energy transition, Smart Energy, Volume 12, 2023, 100116, ISSN 2666-9552, https://doi.org/10.1016/j.segy.2023.100116.

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3 Modelling Results

3.1 Energy security and resilience

One aspect of energy security, diversity, is evaluated through the Shannon Diversity Index. The Shannon Diversity Index is a measure of diversity, originally developed for measuring ecological diversity of species, but more recently also applied as a measure of energy system diversity. The resulting diversity index values can be used as a proxy measure of security, based on the principle that having access to more (different) energy sources and technologies improves the security of a system. Results for the three European scenarios can be seen in *Figure 1* and *Figure 2*.

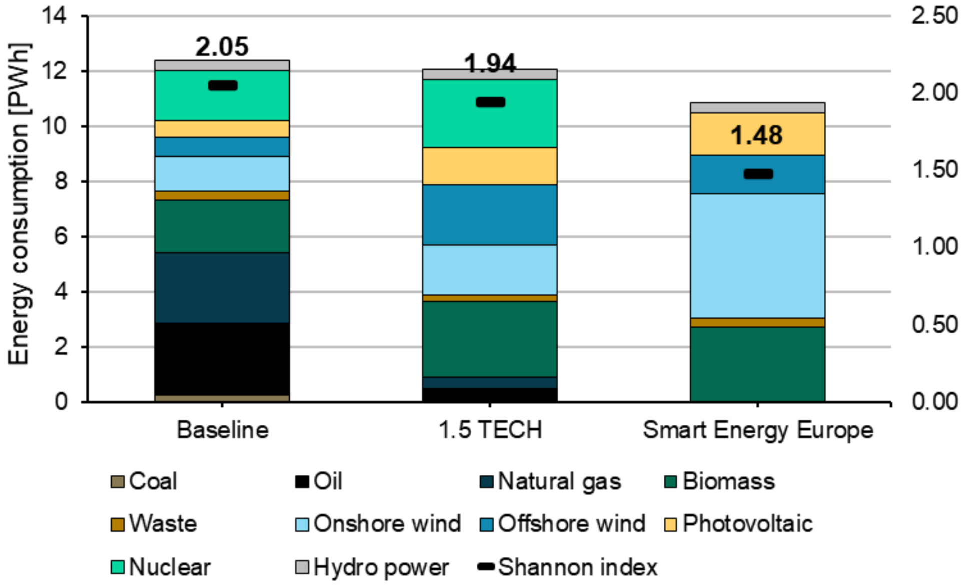

Figure 1: Primary energy consumption in 2050 and corresponding Shannon diversity index values.

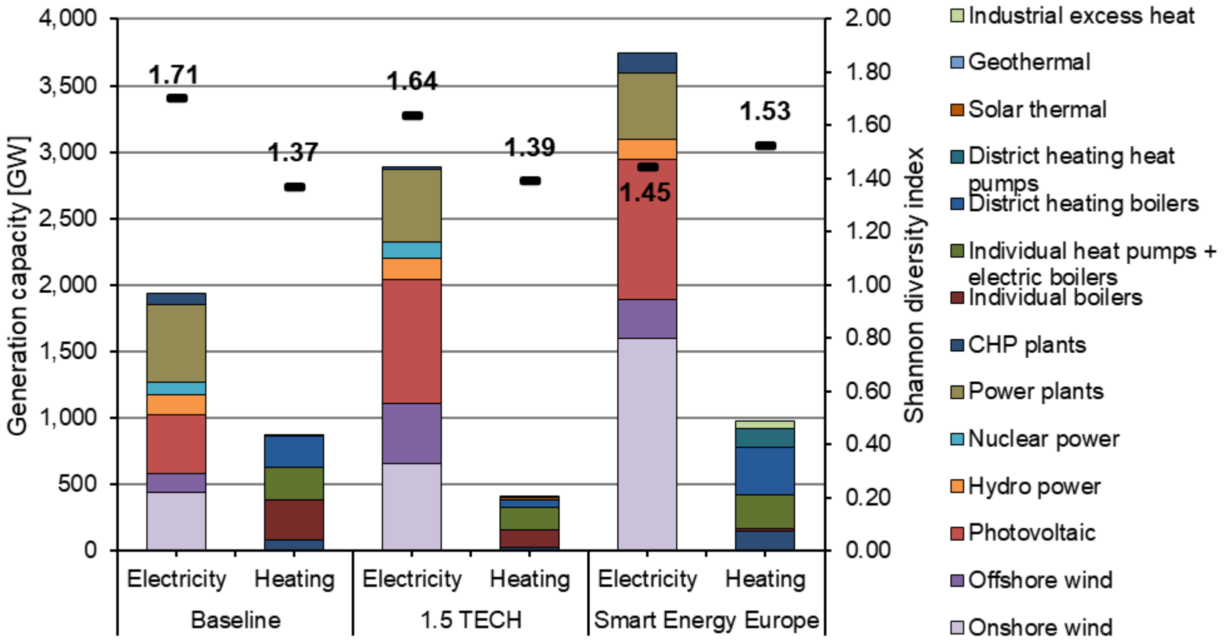

Figure 2: Electricity and heat generation capacities in 2050 and Shannon diversity index values.

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The transition to renewable energy, and phase-out of fossil fuel types, inherently reduces the number of fuels available to a system, which leads to lower observed diversity index values for the primary energy consumption in the *1.5 Tech* and *Smart Energy Europe* scenarios. On the contrary, the large amounts of renewable energy produced are fully available within the EU and not subject to potential import issues or politically enforced limitations. Furthermore, renewable energy technologies are naturally geographically distributed, more so than traditional fossil-fuel-based power plants and fuel depots, overall increasing the security of renewable energy systems.

As mentioned previously, the integrated assessment model MARIO is used to calculate the backward linkages of electricity produced by different energy sources through the application of the Ghosh model based on the energy generation characteristics of a system. These linkages provide an indication about how each commodity (i.e., electricity produced by different energy sources) relies on upstream supply chains and whether these latter are based within or outside the EU borders.

The results serve as a proxy of how the power sector in the EU is dependent on foreign industrial activities. The modelling of dependency values (backward linkages[2]) of renewable electricity generating technologies was found to closely resemble those linked to other fossil sources, see *Figure 3*. Geothermal, nuclear, hydro and other less common sources exhibit the lowest values of backward linkages, excluding photovoltaics and wind power. When compared to their fossil counterparts, photovoltaics and wind power show a comparable share in non-European economies, with photovoltaics having a similar share and wind power having a lower share. While the dependency on upstream supply chains for these two renewable technologies is comparable to that of fossil fuels, the notable difference lies in the predominantly European nature of the supply chains they rely on.

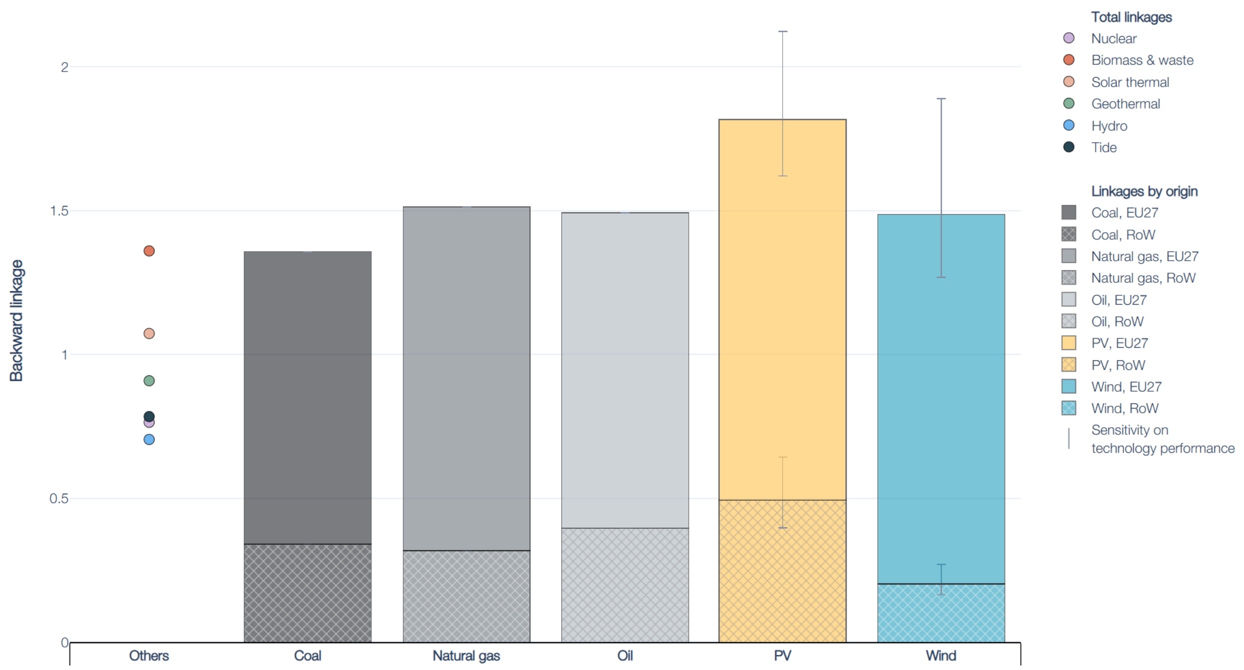

Figure 3: Backward linkages of electricity generation sources in EU27 in 2050.

However, this modelling of backward linkages and supply chain dependency does not account for the evolution of the dependency: currently, the European energy system heavily relies on primary resources like imported

[2] Backward linkage is a measure for how interconnected an industry (in this case energy technologies) is to inputs from other industries to produce an output (in this case electricity). It is calculated as a summation of an input-output matrix where a high backward linkage is a result of a production reliant on many other industries.

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natural gas. In transitioning to renewable energy, photovoltaics and wind power, interconnection will be essential for building new generation capacity. Nevertheless, once the plant is installed, operational dependency diminishes, as these technologies are characterized by very low operating costs and no fuel inputs. This issue gains even more significance as these technologies become more widespread in the economy. This modelling of backward linkages reflects today's economy and hence changes in trade patterns and thereby also supply chains would impact these results.

3.2 Flexibility

Energy system flexibility is essential in renewable energy systems with large shares of variable electricity generation. For the evaluation of flexibility for the modelled scenarios, flexibility is considered for the energy supply, demand, and storage side of the energy systems, for a holistic understanding of all potential flexibility sources.

Figure 4 shows the electricity demands of the modelled European energy systems. Across the *Baseline*, *1.5 Tech*, and *Smart Energy Europe* scenarios, the non-flexible electricity demand[3] is of similar size. However, in terms of flexible electricity demands (mainly electrolysis, large-scale heat pumps and electric boilers, and electric vehicles) the *1.5 Tech*, and to an even larger extent the *Smart Energy Europe* Scenario, has a significantly larger potential for flexibility. Most of this demand (and thus flexibility) is connected to the electrification of transport, either directly through electric vehicles or in hydrogen production for fuels and gas and to a lesser extent, in the electrification of the heating sector.

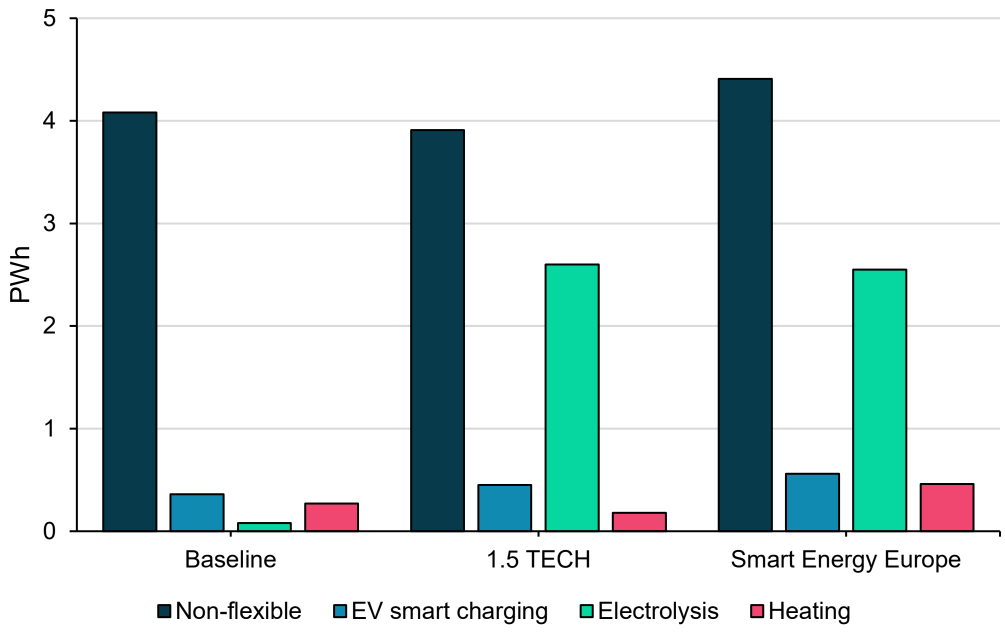

Figure 4: *Electricity demands in the scenarios for EU in 2050.*

Storage is crucial to ensure the flexibility of the system, especially in the utilisation of flexible demands and flexible production units. *Figure 5* shows storages included and utilized in the modelled scenarios.

[3] Non-flexible electricity demand includes electricity consumption in households (e.g., for lighting, cooking, etc.), industrial electricity demands, electricity for household heating solutions (heat pumps and electric boilers), and electricity demands for rail and other heavy transport forms.

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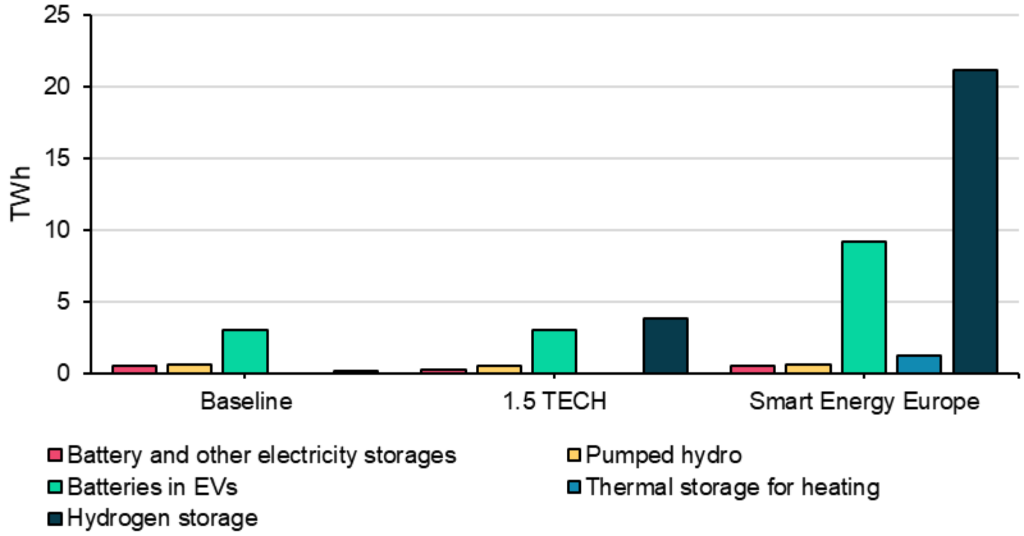

Figure 5: Storage capacities in the scenarios for the EU in 2050.

In general, electricity storage is expensive, which also is evident in the three European scenarios as relatively limited electricity storage is included, of which dammed hydro has the largest utilisation. However, indirect electricity storage in the form of electric vehicles is important, as a significant flexibility potential can be realised through smart charging. Hence, there is a large utilisation of electricity storage in electric vehicles in all three scenarios, particularly in the *Smart Energy Europe* scenario. *Smart Energy Europe* also has a significant amount of thermal storage, to be used in connection to district heating systems. This allows for the flexible use of heat pumps and electric boilers in the district heating grid. Finally, hydrogen storage plays an important role in the flexibility of electrolysis, which is why it is the biggest storage both in the *1.5 Tech* and *Smart Energy Europe* scenario. By having sufficient hydrogen storage, it is possible to utilise electrolysers flexibly and handle large quantities of renewable energy. *Smart Energy Europe* has a significantly larger implementation of hydrogen storage than the *1.5 Tech* and the *Baseline* scenarios due to an ambition of being entirely self-sufficient. The main reason is that *Smart Energy Europe* is completely self-sufficient, in contrast to the *1.5 Tech* and the *Baseline* scenario are dependent on imports of natural gas from other regions (e.g., Russia) outside the EU.

3.3 Costs and Environmental Impacts

For costs and environmental impacts, the analyses focus on the material demand and consumption for each modelled scenario and the resulting raw material prices, both as modelled in WILIAM.

The significant electrification and the deployment of e-fuels and hydrogen have led to transformative changes in both material demand and material prices. In the *1.5 Tech* scenario, a heightened material demand is observed, in contrast to the *Smart Energy Europe* scenario, easing pressures on materials consumption. By prioritising efficiency measures across energy sectors, the *Smart Energy Europe* scenario mitigates the need for extensive material consumption in the energy transition process. The strategic update of heating systems and the expansion of district heating in the scenario contribute to a more efficient use of materials in the energy sector. This optimisation minimises the demand for specific materials associated with traditional heating systems, thus easing pressures on material resources.

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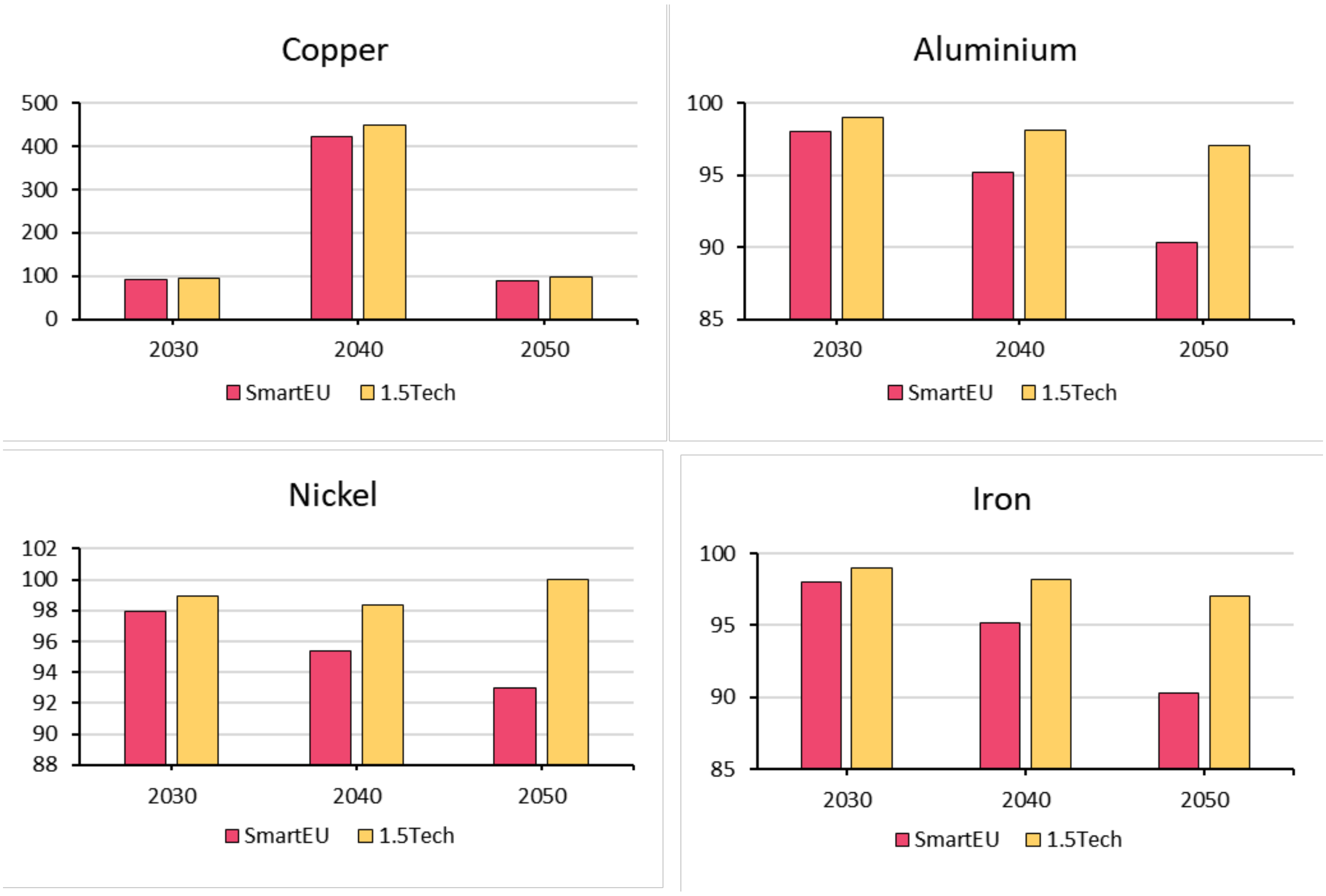

Figure 6: *Material prices in Smart Energy Europe and 1.5 TECH relative to Baseline (Index 100).*

Copper prices significantly increase mid-simulation as the energy transition is unfolded. However, copper prices would potentially drop as the installation of new technologies decreases. That will probably be unavoidable even in the *Smart Energy Europe* scenario. Nevertheless, the effect is less pronounced in the *Smart Energy Europe* scenario. This improved performance can be seen more notably when looking at Aluminium, and similar tendencies are observed for other critical materials such as Nickel and Iron.

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4 Conclusions and Policy Implications

Based on existing literature and insights from policymakers and other stakeholders, indicators and parameters for evaluating renewable energy systems were established and categorised according to the topics of energy security, resilience, and flexibility. Energy system scenarios, including a 100% renewable energy scenario were modelled for Europe with the energy system modelling tool EnergyPLAN and the integrated assessment models MARIO and WILIAM, providing insights into the functioning of concrete, tangible renewable energy scenarios for the future.

Overall conclusions

- *An independent renewable European energy system is possible:* It is feasible to design 100% renewable energy system scenarios for the EU without fuel imports, underlining the possibility of having a functioning independent energy system.
- *Key indicators can (and should) be established to evaluate security, resilience, and flexibility:* Through multi-model approaches evaluating security, resilience, and flexibility of different energy scenarios is feasible. There is a need for further development of adequate indicators for renewable energy systems.

Security

- *New energy security dynamics:* Diversity of primary energy supply decreases as gas, oil and coal are phased out but is offset by increased geographical dispersion and improved self-sufficiency rate.
- *Lower external supply chain dependency from renewable energy technologies:* Dependency values (backward linkages) associated with electricity production from renewable sources closely resemble fossil fuels. However, photovoltaics and wind power rely predominantly on European supply chains, while fossil fuel-based technologies to a greater extent rely on non-European industries.
- *Lower material demand and prices in a renewable energy system:* Modelling of material prices and demand in future energy scenarios demonstrated that increased sector integration, strategic use of e-fuels, and biogas generation as demonstrated in the *Smart Energy Europe* scenarios results in lower material prices and consumption for copper, aluminium, nickel, and iron. This indicates that the transition to renewable alternatives can positively influence production costs, energy prices and material demand, contributing to a more sustainable and resilient energy matrix.

Resilience

- *Secure sufficient dispatchable generation capacity:* From a system resilience perspective, dispatchable generation capacity must be maintained to cover the residual demand.
- *Energy storage for resilience and flexibility:* Energy storage capacity (electricity, gas/hydrogen, and thermal) reduces vulnerability and increases the flexibility of the system.

Flexibility

- *Prioritise flexibility enabling measures and technologies:* It is essential that future renewable energy systems are designed in a way that enables the exploitation of large variable renewable electricity generation capacities through flexible electricity demands – key technologies for this are electrolysis and electric vehicles with smart charging.
- *Flexibility is essential on both the supply and demand side:* Without significant flexibility on both the supply and demand, 100% renewable energy systems are not feasible without overly relying on external markets and imports.

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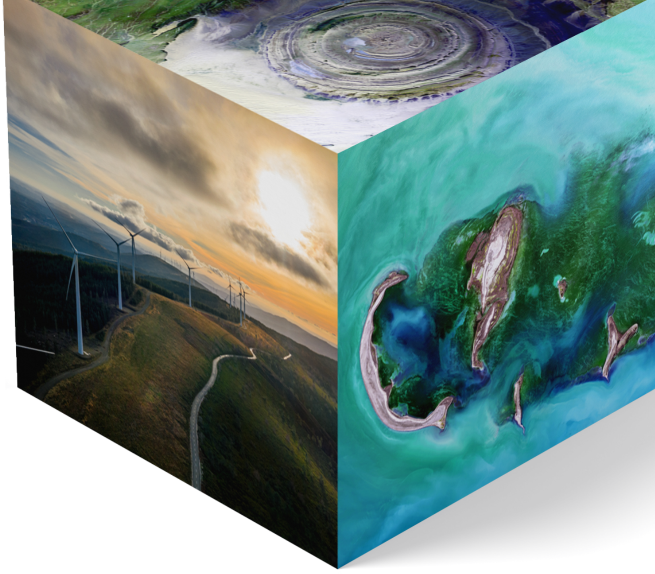

Policy Brief

Enhancing Renewable Energy System Metrics: Security, Flexibility and Sustainability

In a nutshell

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 aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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