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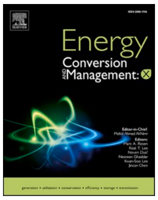

Can green hydrogen drive economic transformation in Saudi Arabia? – An input–output analysis of different Power-to-X configurations

Viktor Paul Müller[a,b,*], Malte Besler[a,c], Detlef van Vuuren[b,d], Wolfgang Eichhammer[a,b,e]

[a] Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Straße 48, 76139 Karlsruhe, Germany
[b] Copernicus Institute of Sustainable Development, Utrecht University, Utrecht 3584 CB, the Netherlands
[c] Technische Universität Bergakademie Freiberg, Schlossplatz 1, 09599 Freiberg, Germany
[d] PBL Netherlands Environmental Assessment Agency, Bezuidenhoutseweg 30, AV, The Hague NL-2594, the Netherlands
[e] Institute for European Energy and Climate Policies IEECP, Amsterdam 1043 GR, the Netherlands

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ABSTRACT

Global demand for fossil fuels is projected to decline by up to 75 percent by 2050, requiring new economic strategies for fossil exporters to promote diversification. This study employs an inter-country input-output model to assess sector interdependence in Saudi Arabia and explore the macroeconomic impacts of investing in Power-to-X (PtX) plants. We analyze four configurations: pure solar and hybrid solar-wind systems, producing either green hydrogen or ammonia. Our comparative analysis shows that hybrid plants appear to have stronger domestic effects than pure solar configurations, while producing green ammonia instead of hydrogen generates stronger relative employment. These trends remain consistent across different sensitivities and domestic supply shares. However, the differences between configurations and sensitivities decrease with increasing domestic supply. Currently Saudi Arabia has limited developed manufacturing sectors and the economy is heavily dependent on exports of crude oil and related products-a situation often referred to as the "resource curse". For all PtX configurations, the construction sector therefore emerges as the largest contributor to domestic employment and value added. At current import shares, foreign effects, particularly in China and the United States, account for about half of the total impact, especially in sectors such as electronics and machinery. Without embedding the hydrogen supply chain into their industrial landscape by starting to produce parts of clean technologies locally, exporters risk substantial value creation occurring predominantly abroad. Overall, our research highlights the need for targeted policy measures to capitalize on the „renewables pull effect" when installing PtX plants for green energy exports.

Introduction

The global energy landscape is undergoing a substantial transformation, driven by the urgent need to mitigate climate change and transition towards sustainable energy sources. According to the International Energy Agency [1] achieving net-zero emissions by 2050 will require global demand for fossil oil and gas to be cut by around 75 percent compared to today's levels, necessitating new economic strategies for fossil fuel-exporting countries [2]. The interaction between fossil resource wealth and economic development is a topic of great scientific interest, especially in the context of the possible negative impact on economic diversification according to the "resource curse" hypothesis [3–6]. One of the most cited phenomena in this regard is the "Dutch disease", named after the economic challenges the Netherlands faced after the discovery of large natural gas fields in the 1960 s. The inflow of foreign currency from natural resource exports leads to an appreciation of the real exchange rate, making other domestic sectors less competitive on the world market. The resulting shift to technology imports potentially crowds out the manufacturing sector and undermines efforts to diversify the economy [6]. The situation is somewhat

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Abbreviations: CAPEX, Capital expenditure; GDP, Gross domestic product; H2, Hydrogen; ICIO, Inter-country input-output; IO, Input-output; IRENA, International Renewable Energy Agency; ISIC, International Standard Industrial Classification; MRIO, Multi-regional input-output; NH3, Ammonia; OECD, Organisation for Economic Co-operation and Development; PtX, Power-to-X; PV, Photovoltaics; RE, Renewable energies; TRL, Technology Readiness Level; USD, US Dollar; USA, United States of America.

* Corresponding author.

E-mail address: viktor.paul.mueller@isi.fraunhofer.de (V.P. Müller).

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similar in Saudi Arabia, which is highly dependent on fossil fuel exports, exposing its economy to the instability of global commodity price fluctuations and demand shocks abroad [7]. Despite efforts to diversify the Saudi Arabian economy over the last fifty years, progress has been slow, with the share of extractive industries in the economy remaining largely static. Volatile oil prices and international geopolitical risks have disrupted diversification efforts, with oil rents fostering rent-seeking activities instead of growth [6,8,9].

However, given the likely future decline in fossil fuel exports as a result of global decarbonization, efforts to diversify the economy are becoming increasingly urgent. The production of green hydrogen (H2) based on renewable energies (RE) appears as an important strategy in this shift. According to van de Graaf et al. [10], green hydrogen could fundamentally reshape global energy trade, create new energy exporters and alter geopolitical relations. Given their abundant RE resources and their expertise in transporting fossil fuels, Gulf countries such as Saudi Arabia are therefore keen to take a leading role in the uptake of hydrogen and downstream trade to avoid losing key export markets. [11]. Several studies [12–14] highlight the technical feasibility and economic potential of green hydrogen production in Saudi Arabia using different combinations of solar and wind. A scenario-based analysis of global trade flows up to 2050 by Zhang et al. [15] also indicates that imports of hydrogen and ammonia from the Middle East and North Africa region are particularly economical and can cover a large part of the future European demand. However, there are still technological, economic, and societal barriers that exporting countries must overcome in order to fully realize the benefits and become a major player in the global green hydrogen market. According to Hassan et al. [16,17], to achieve this, Saudi Arabia will need to increase investment in RE technologies, develop a comprehensive hydrogen strategy, and foster international cooperation. Additionally, building a robust hydrogen infrastructure, supporting research and development, and developing local demand for green hydrogen are crucial steps.

The global transition to RE is not only expected to change energy trade relations, but also likely to influence industrial production locations and global value chains. Samadi et al. [18] introduce the concept of the so-called “renewables pull effect”. They argue that stringent climate policies will drive industrial production to shift from fossil fuels to renewables and suggest that regions with abundant RE resources will attract energy-intensive industries due to lower marginal costs. This restructuring of global industrial value chains might not only promote the economic viability of RE projects, but spur also regional economic growth and environmental sustainability. In a case study for Germany, Verpoort et al. [19] estimate the potential energy-cost savings from relocating industries such as steel, urea, and ethylene production to regions with cheaper renewable electricity. They find substantial savings, when outsourcing energy-intensive upstream parts of industrial processes as transport cost for intermediate products such as ammonia or methanol are lower than shipping hydrogen. Egerer et al. [20] come to similar results when assessing various defossilization strategies for Germany including hydrogen imports and partial industrial relocation. In other words, the renewables pull effect addresses the question of whether, in the long term, certain energy-intensive industries such as ammonia or steel production will locate where cheap renewable energy is available, instead of transporting green hydrogen at comparatively high cost to countries such as Germany, which currently have such industries but insufficient RE potential. For countries such as Saudi Arabia, this could hence open up opportunities that go beyond pure energy exports.

One example of an attempt to strategically leverage the renewables pull effect to overcome the resource curse and drive industrial diversification is the NEOM green hydrogen complex in northwestern Saudi Arabia. The flagship project of Saudi Arabia’s hydrogen strategy aims to produce green hydrogen and ammonia (NH3) on a large scale for the global market and is in line with the vision to diversify the Saudi economy and achieve net zero greenhouse gas emissions by 2060 [21]. In addition to export revenues, the project is also envisioned to create new jobs, attract local and international experts, and promote regional economic growth and diversification. With a production capacity of up to 1.2 million tons of green ammonia per year, it is currently the world’s largest renewable Power-to-X (PtX) plant with a final investment decision. The project is scheduled to start production by the end of 2026 and will be powered entirely by renewable solar and wind energy [22,23]. This analysis therefore uses the NEOM green hydrogen complex – an essential part in the Saudi hydrogen strategy – as a case study to quantitatively investigate the macroeconomic effects associated with the installation of such green hydrogen and PtX (e.g. green ammonia) plants using input–output (IO) modeling.

This paper is organized as follows. Section 2 provides an overview of related literature on IO modeling with a focus on clean energy technologies. Section 3 describes the data and methods used in this paper. Section 4 presents the results for analyzing the status quo of the Saudi Arabian economy and potential macroeconomic impacts of installing different PtX plant configurations. Finally, section 5 discusses the main findings and derives policy implications.

Related literature

The approach of using IO models to quantify the macroeconomic impact of investments in clean energy technologies is well established in the scientific community. Table 1 presents an overview of different related studies based on a literature review, indicating the technology focus, the analyzed country or region, the methodological approach and a selection of the indicators covered. A more detailed evaluation of the literature is provided in the supplementary material. In terms of approach, a distinction is made between national IO models, which focus on specific countries, and multiregional IO models (MRIO), which also capture interactions between different countries or regions. The table also indicates how the analyzed clean energy technologies are treated. Typically, these technologies are not explicitly included as sectors in IO tables and must therefore either be added as new sectors, disaggregated from existing sectors or captured via a demand-driven approach using so-called “synthetic industries”.

Most studies use national IO tables and focus on renewable electricity, while there are only a few studies to date that focus on hydrogen. For electrolysis, there are only three studies for different European countries [24–26], while the others focus either on biohydrogen production in the United States of America (USA) and China [27] or on the use of hydrogen in the transportation sector in South Korea [28,29]. For renewable electricity, the overview includes national IO analyses for various European countries [30–33], USA [34], Morocco [35–37], Tunisia [38] and Kenya [39] as well as two studies [40,41] that use MRIO models to analyses the broader impacts of global decarbonization, including both renewable and fossil power plants.

In terms of the indicators covered, most studies analyze employment effects and either output, value added or gross domestic product (GDP), but only one study includes figures on compensation of employees. Likewise, only a small number of studies examine the linkages between different economic sectors, and none of them cover all five indicators. This paper therefore addresses different research gaps by applying a global MRIO model with the “synthetic industry” approach to a case study of different PtX plant configurations in Saudi Arabia, including investments in PV, wind turbines, electrolysis and ammonia synthesis. The analysis assesses sectoral linkages as well as the impact on output, value added, employment and compensation of employees.

Data & methods

The data and methods section is divided into three parts. The first part describes the methodological approach of MRIO models. The second part provides the techno-economic background for the different PtX plant configurations considered and explains the assumptions for the

Table 1
Overview of related research on the macroeconomic impact of clean energy technologies using input–output (IO) analysis.

Author (Year)	Technology Focus	Region	Approach	Covered indicators					Source
				OUT	VA / GDP	EMP	LABR	Link	
Chun et al. (2014)	H2 sector with focus on transport	South Korea	National IO model + synthetic industry approach	x	–	–	–	x	[28]
Guionie et al. (2023)	Electrolysis replacing grey H2	France	National IO model + synthetic industry approach & new sector	x	–	x	–	x	[25]
Gupta et al. (2023)	Electrolysis & refueling stations	Switzer-land	National IO model + new sector	x	x	x	–	x	[24]
Kim et al. (2024)	Fuel cells	South Korea	National IO model + new sectors	x	x	x	x	–	[29]
Lee et al. (2011)	Bio-H2 production	USA & China	National IO models + new sector	x					[27]
Wietschel & Seydel (2007)	Electrolysis & fuel cell vehicles	Six European countries	National IO models + synthetic industry approach	–	–	x	–	–	[26]
Černý et al. (2024)	Renewable & fossil electricity	Global, focus on Europe	MRIO model + sectoral disaggregation	–	–	x	–	–	[41]
Ciorba et al. (2004)	PV	Morocco	National IO model + new sector	x	x	x	–	–	[35]
de Arce et al. (2012)	PV, CSP, wind	Morocco	National IO model + synthetic industry approach	–	x	x	–	–	[36]
Dell'Anna (2021)	Five different RE plants	Italy	National IO model + synthetic industry approach	–	–	x	–	–	[30]
Fatiha et al. (2022)	PV, CSP, wind	Morocco	National IO model + synthetic industry approach	–	x	x	–	–	[37]
Garett-Peltier (2017)	Energy efficiency, RE & fossil fuel mining	USA	National IO model + synthetic industry approach	–	–	x	–	–	[34]
Kamidelivand et al. (2018)	Renewable & fossil electricity	Ireland	National IO model + sectoral disaggregation	–	x	x	–	–	[31]
Keček et al. (2019)	Five different RE plants	Croatia	National IO model + synthetic industry approach	–	x	x	–	–	[32]
Lehr et al. (2016)	RE & energy efficiency	Tunisia	National IO model + synthetic industry approach	–	–	x	–	–	[38]
Siala et al. (2019)	Renewable & fossil electricity	Global, focus on Germany	MRIO model + sectoral disaggregation	–	x	x	–	–	[40]
Tourkolias et al. (2011)	Five different RE plants	Greece	National IO model + synthetic industry approach	–	–	x	–	–	[33]
Woollacott et al. (2023)	Five different RE plants	Kenia	National IO model + synthetic industry approach	–	–	x	x	–	[39]
This study	PV, wind, electrolysis & ammonia synthesis	Global, focus on Saudi Arabia	MRIO model + synthetic industry approach	x	x	x	x	x	

OUT: output, VA: value added, GDP: gross domestic product, EMPN: employment, LABR: compensation of employees, Link: sectoral linkages.

technology and country specific capital expenditure (CAPEX) values. The third part outlines the methodology for quantifying the macroeconomic impact of investments in different plant configurations using "synthetic industries" and presents different breakdowns of technology CAPEX across the IO sectors.

Macroeconomic approach

The section on the macroeconomic approach focuses on three aspects:

- Interdependencies between economic sectors
- Forward and backward linkages
- Flow of goods and share of origin

Interdependencies between economic sectors

IO analysis is an economic method for studying structural relationships within an economy and the impacts of changes in one industrial sector on others. It allows for the examination of direct and indirect impacts of an economic impulse and is particularly useful for understanding the ripple effects of economic activities and policy changes across various sectors. Economies are represented in matrix form, ranging in scale from national to regional and multi-regional conceptions that illustrate the geo-spatial fragmentation of production and consumption [42]. This study uses the Inter-Country Input-Output (ICIO) table from the Organisation for Economic Co-operation and Development (OECD) for the base year 2019 to exclude the effects of COVID-19. ICIO provides data on 45 unique industries based on International Standard Industrial Classification (ISIC) Revision 4 for 76 countries and the aggregated rest of the world from 1995 to 2020 [43]. Fig. 1 shows the structure of ICIO tables, which can be extended with OECD employment statistics [44] providing consistent data for estimating the impact on the number of jobs and compensation of employees. The tables cover a wide range of countries, are easily accessible and are regularly updated. This ensures transparency, traceability, and reproducibility of results, as well as the transferability of the method to other countries, including emerging and developing economies.

The following section presents the key principles of IO modeling based on the comprehensive overview by Miller and Blair [42]. The total output X of the different economic sectors in each country is the sum of intermediate use Z and final demand Y for the products of given sectors. The taxes less subsidies TLS section accounts for the net amount of taxes paid by producers and end consumers to the government, minus any subsidies received. The value added VA section represents the additional value created in the production process, including wages, profits, and depreciation. These components ensure maintaining the balance where the total input (sum of intermediate inputs, value added, and taxes less subsidies) matches the total output (sum of intermediate outputs and final demand). In other words, the sum of all rows is always equal to the sum of all columns in an IO table.

$$X = \sum\nolimits_j Z + Y = \sum\nolimits_i Z + TLS + VA \tag{1}$$

The Leontief demand-side model [45] allows to assess the impact of changes in final demand on the overall output of different sectors and

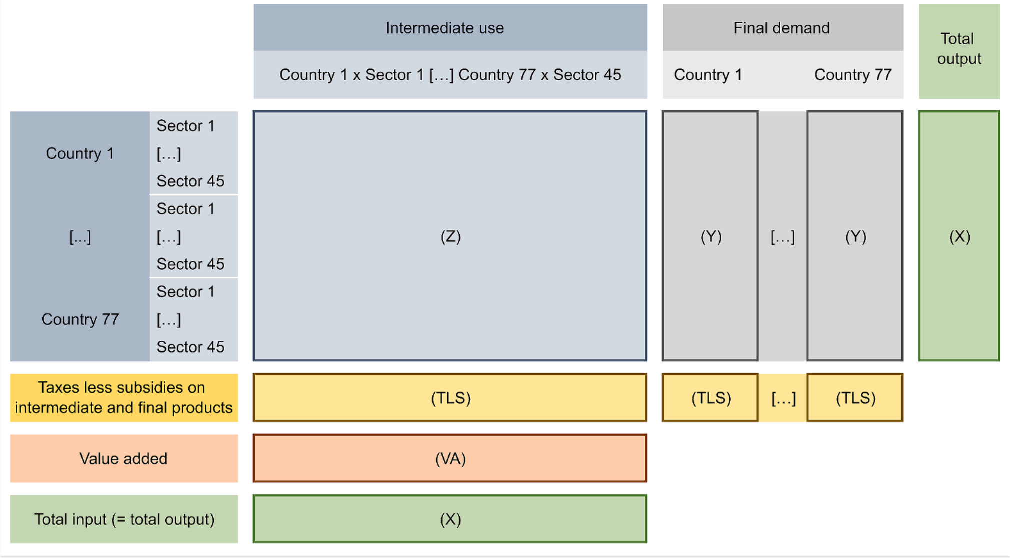


Fig. 1. Overview of the structure of ICIO tables (own depiction based on [43]).

provides insights in the interdependencies between different sectors of an economy. At the core of this model are two key matrices: the matrix of technical coefficients A and the Leontief inverse matrix L. The matrix of technical coefficients or direct input coefficients captures the direct input requirements of each sector per unit of output. Each element a_{ij} in A represents the input from sector i needed to produce one unit of output in sector j. This matrix provides a detailed view of the direct production relationships within the economy.

$$A = Z \bullet diag(X^{-1}) \tag{2}$$

However, in a complex economic system, sectors are interdependent not just directly but also indirectly. For example, an increase in final demand for cars will not only increase the demand for steel (a direct input) but also for coal (an input to steel production) and various other upstream industries. The technical coefficient matrix does not cover these second- and third-order cascade effects. For this purpose, the inverse Leontief matrix L is required, which can be determined by combining Eqs. (1) and (2) and rearranging the linear equation system using the Identity matrix I.

$$L = (I - A)^{-1} \tag{3}$$

With the Leontief inverse, also known as total requirements matrix, one can calculate the direct and indirect effects of a change in final demand on the output of each economic sector in each country by multiplying L with the vector of changes in final demand.

$$\Delta X = L \bullet \Delta Y \tag{4}$$

The change in output can be translated directly into the other macroeconomic effects by using multipliers for relative value added, jobs and compensation of employees per unit of output. The ICIO model used (see Fig. 1) maps the flows and thus the effects not only in the focus country but also in the 76 other countries and regions. This makes it possible to analyze the spillover effects of a change in demand in the focus country in other countries, e.g. through imports of intermediate goods.

Forward and backward linkages

Forward and backward linkages are critical concepts for understanding the interdependencies within an economy. Forward linkages measure the extent to which a sector supplies inputs to downstream sectors, whereas backward linkages assess the extent to which a sector relies on inputs from upstream sectors. These linkages can be analyzed using the Leontief demand-side model, and the supply-side model, developed by Ghosh [46].

To calculate the backward linkages l_B for a specific sector, one sums the elements of the columns of the Leontief inverse matrix L. This sum indicates how changes in final demand affect the entire production system. For normalization, the calculated sums are divided by the average linkage value across all sectors.

$$l_B = \frac{\sum_i L}{mean\left(\sum_i L\right)} \tag{5}$$

In contrast to the Leontief demand-side model, the supply-side model by Ghosh focuses on the distribution of outputs across various sectors and how changes in supply can propagate through the economy. This model utilizes the Ghosh inverse matrix G, to assess forward linkages l_F, illustrating how supply changes in one sector influence other sectors. To calculate the forward linkages for a specific sector, one sums the elements of the rows of G. As for the backward linkages, the values are normalized by dividing by the average linkage value:

$$l_F = \frac{\sum_j G}{mean\left(\sum_j G\right)} \tag{6}$$

With

$$G = (I - B)^{-1} \tag{7}$$

The matrix of allocation coefficients or direct output coefficients B indicates which economic sectors of each country use the output of a given sector as an intermediate input.

$$B = diag(X^{-1}) \bullet Z \tag{8}$$

In the context of ICIO tables, the calculated linkages provide insights into the interdependencies across different countries and sectors. This analysis helps to understand how economic activities in a given industry in one country influence and are influenced by activities in other countries' sectors. Total normalized forward linkages measure the extent to which an economic sector in a specific region supplies inputs to other sectors across all regions. This indicates the sector's role as a supplier within the global production network. High total normalized forward linkages suggest that a given sector is crucial for providing inputs to many other sectors internationally, highlighting its importance in the global supply chain. Total normalized backward linkages, on the other hand, assess the extent to which an economic sector in a specific region depends on inputs from other sectors in all regions. This indicates the industry's reliance on the global supply chain to meet its production needs. High total normalized backward linkages imply that a given sector is highly dependent on inputs from various sectors worldwide, making it sensitive to changes in the global supply.

Normalization results in values of one indicating the average. Higher or lower values therefore mean that certain sectors score above or below average. To visualize these relationships, one can plot normalized forward linkages against normalized backward linkages, resulting in a four-quadrant framework (see Fig. 2).

I. **Dependent on upstream supply and downstream demand:** Economic sectors in the first quadrant have both high forward and backward linkages. They are interdependent on the supply from upstream sectors and the demand from downstream sectors, making them highly integrated within the economic network. Typical sectors include manufacturing of intermediate goods, such as iron and steel.
II. **Dependent on downstream demand:** Economic sectors in the second quadrant exhibit high backward linkages but low forward linkages. They depend primarily on the demand from downstream sectors, making them sensitive to changes in the final demand for their products. Mining sectors such as oil extraction fall into this category.
III. **Independent from upstream supply and downstream demand:** Economic sectors in the third quadrant have low forward and backward linkages. They operate relatively independently of other sectors, indicating that changes in their production or demand have minimal ripple effects on the broader economy. Public services, such as education, are a good example of this.
IV. **Dependent on upstream supply:** Economic sectors in the fourth quadrant have high forward linkages but low backward linkages. They are heavily reliant on the supply of inputs from upstream sectors, indicating that disruptions in their input supply can significantly impact their output. Wholesale and retail trade are typical sectors for this.

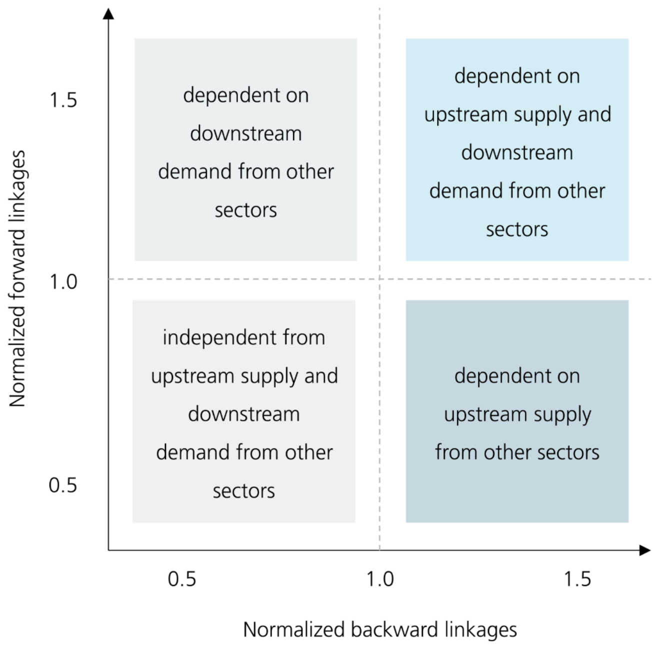


Fig. 2. Overview and explanation of the different quadrants, defined by the combination of normalized backward and forward linkages of a country's economic sectors.

Flow of goods and share of origin

ICIO tables can also be used to analyze the different flows of goods within and between countries and the resulting shares of origin. For a given country c, the flow of goods $f_{c_i,c}$ per ecomomic sector E and country of origin c_i consists of three components:

1. Domestic Supply: Output from sectors in country c to supply (intermediate and final) demand in c
2. Exports: Output from sectors in country c to supply (intermediate and final) demand in other countries
3. Imports: Output from sectors in other countries to supply (intermediate and final) demand in c

Fig. 3 shows a graphical representation of the different components of the flow of goods for a simplified ICIO table with two economic sectors and three countries.

In general, this can be formulated as a case-differentiated formula as follows. Where c indicates the country for which the flows are analyzed, $\overline{c}$ refers to all other countries, and c_i indicates the country of origin of the goods.

$$f_{c_i,c} = \begin{cases} \sum_j (Z_{c,c} + Y_{c,c}) + \sum_j (Z_{c,\overline{c}} + Y_{c,\overline{c}}), if c_i = c \\ \sum_j Z_{c_i,c} + Y_{c_i,c}), if c_i \neq c \end{cases} \tag{9}$$

For the simple example with three countries and two economic sectors, the sums of the row entries result in a vector with six entries for the flows per country and sector of origin for each of the three countries. The complete ICIO table thus results in 76 vectors with 3496 entries for each country. This paper focuses on the flow of goods vector for Saudi Arabia.

Adding up all flow of goods values per sector across all countries of origin c_i gives the total flow of goods $f_{tot,c}$ per economic sector for the selected country c. For the ICIO table, this means that for each of the 45 sectors, all import and export flows from and to the various other countries as well as the domestic supply flows in the country c itself are summed up.

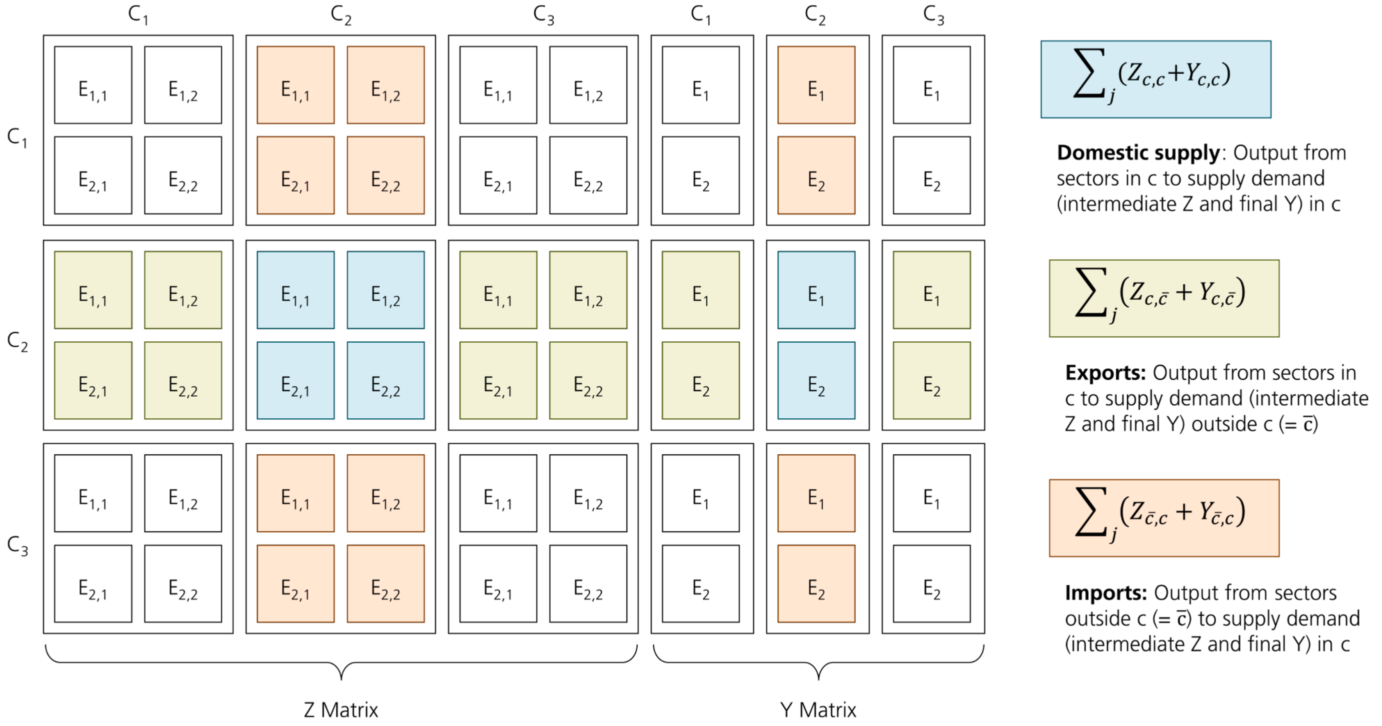
$$f_{tot,c} = \sum_{c_i} f_{c_i,c} \tag{10}$$

Dividing the flow of goods per country of origin $f_{c_i,c}$ by the total flow of goods $f_{tot,c}$ gives the share of countries of origin $s_{c_i,c}$ for each economic sector. The total of all countries of origin is therefore always equal to one for each of the 45 economic sectors.

$$s_{c_i,c} = \frac{f_{c_i,c}}{f_{tot,c}} \tag{11}$$

Techno-economic background

The case study in Saudi Arabia compares four different green PtX plant configurations that differ in terms of power source and end product. The options for power generation include a combination of solar photovoltaics (PV) and wind turbines or a pure solar plant. The PtX end products considered are hydrogen and ammonia. These configurations are selected as solar PV and wind the most widespread renewable power sources and hydrogen and ammonia are the dominant products of all PtX projects announced worldwide, both in terms of number and production capacity [47]. The number of operational projects for green ammonia is lower than for green hydrogen, resulting in a slightly lower technology readiness level (TRL) of 5–8 [48] compared to TRL 7–9 for low temperature electrolysis [49]. However, all components can be considered well established, especially compared to other possible PtX routes such as e-kerosene, which is also reflected in the larger number of announced green ammonia projects. In addition, a *meta*-analysis of life cycle assessments for different PtX pathways [50] shows that green hydrogen and ammonia have a comparatively higher greenhouse gas reduction potential compared to their current reference pathways than



$$\sum_j (Z_{c,c}+Y_{c,c})$$

Domestic supply: Output from sectors in c to supply demand (intermediate Z and final Y) in c

$$\sum_j (Z_{c,\bar{c}}+Y_{c,\bar{c}})$$

Exports: Output from sectors in c to supply demand (intermediate Z and final Y) outside c (= $\bar{c}$)

$$\sum_j (Z_{\bar{c},c}+Y_{\bar{c},c})$$

Imports: Output from sectors outside c (= $\bar{c}$) to supply demand (intermediate Z and final Y) in c

Fig. 3. Simplified example of an ICIO table with three countries (C) and two economic sectors (E) with a color-coded explanation of the different flows of goods in a given country: domestic supply (blue), exports (green) and imports (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

carbon-based PtX products such as methanol. This is also in line with the plans behind the NEOM green hydrogen complex, which is a key element of Saudi Arabia's hydrogen strategy and is set to produce green ammonia for export from 2026 based on a combination of wind and solar energy.

Data from the Global PtX Atlas [51] is used for dimensioning the various configurations. The WebGIS application provides a freely accessible overview of the cost-optimized plant design for various PtX products at around 600 locations worldwide. Further details on the methodology of the PtX Atlas can be found in Pfennig et al. [52]. All plant configurations examined in this study are located in the Tabuk region in north-western Saudi Arabia, where the NEOM green hydrogen complex is planned. Table 2 gives an overview of the required installed capacity per technology in relative values per GWh of PtX product.

The capacity figures are converted into monetary terms by multiplying them by technology-specific CAPEX values (see Table 3). The values for solar PV and wind turbines come from the International Renewable Energy Agency (IRENA) [53]. For solar PV, this is country-specific data for Saudi Arabia based on the total installed cost of recent projects. For wind turbines, it is the global weighted average of all projects worldwide in 2022. Figures for electrolysis and ammonia synthesis are taken from Moritz et al. [54] and converted to 2022 USD using the World Bank's Consumer Price Index [55].

Table 2
Installed capacities of different technologies for different end products and plant configurations in Tabuk, Saudi Arabia [51].

Technology	Unit	Solar H2	Solar NH3	Hybrid H2	Hybrid NH3
Solar PV	$kW_{el,out}$/ $GWh_{PtX,out}$	833	978	341	424
Wind Turbines	$kW_{el,out}$/ $GWh_{PtX,out}$	–	–	244	282
Electrolysis	$kW_{el,in}$/ $GWh_{PtX,out}$	479	577	247	297
Ammonia Synthesis	$kW_{H2,in}$/ $GWh_{PtX,out}$	–	146	–	190

Table 3
Capital expenditure values of different technologies.

Technology	Unit	CAPEX	Source	Comments
Solar PV	2022 USD/ $kW_{el,out}$	653	[53]	country specific value for Saudi Arabia
Wind Turbines	2022 USD/ $kW_{el,out}$	1274	[53]	global weighted average value
Electrolysis	2022 USD/ $kW_{el,in}$	1096	[54]	converted from 2019 USD/$kW_{H2,out}$
Ammonia Synthesis	2022 USD/ $kW_{H2,in}$	1296	[54]	converted from 2019 USD/kW_{NH3out}

Fig. 5 presents the total investment by technology for the four plant configurations, expressed in relative terms per TWh of PtX production. Two limitations should be considered. First, the PtX Atlas optimization was performed for the year 2050, using projected future CAPEX values that differ from current values in Table 3. Second, the PtX Atlas includes additional cost components such as intermediate electricity or hydrogen storage and nitrogen supply for ammonia synthesis, but does not provide capacity values for these components, excluding them from the system boundary for the subsequent IO analysis (see Fig. 4). Both may lead to some uncertainties regarding the cost-optimal system configuration and total investment, but the general figures and key findings remain valid, as the cost shares of storage and air separation are rather small compared to the other components.

The different dimensioning of electrolysis and synthesis in the solar and hybrid configurations is noteworthy. In the pure solar configurations, it is more economical to design the electrolysis larger and to operate it flexibly and with fewer full load hours following to the solar generation profile. In the hybrid configurations, on the other hand, the electrolysis capacity is lower and is operated with higher full-load hours due to the complementary wind and solar time series. The opposite applies to ammonia synthesis. Here, the PV configuration has higher full load hours than the hybrid variant. In this case, the optimization

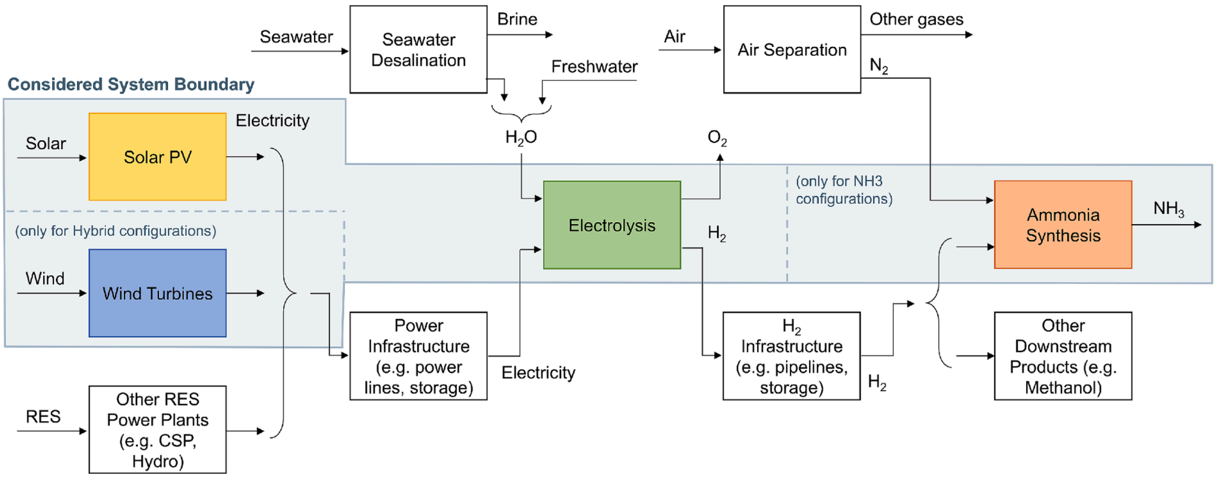


Fig. 4. Schematic overview of the different parts of the PtX value chain and the considered system boundary for the four analyzed plant configurations.

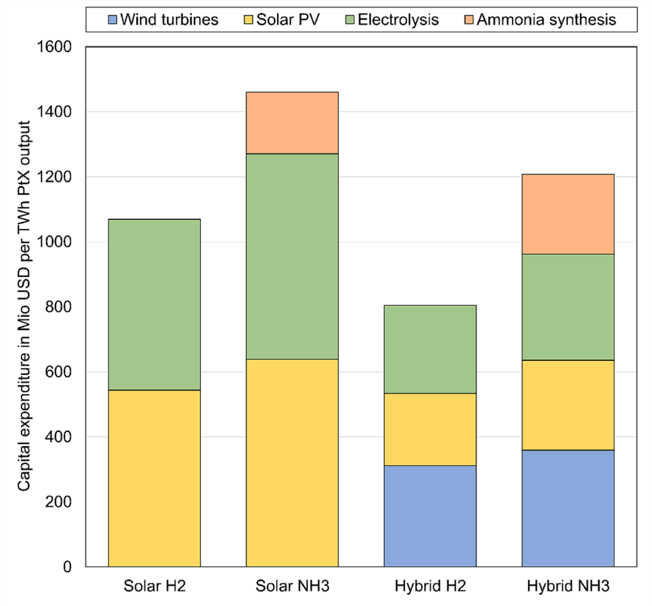


Fig. 5. Capital expenditure by technology in Mio USD per TWh PtX output for different end products and plant configurations in Tabuk, Saudi Arabia.

indicates that the installation of a larger hydrogen storage system is more economical, as it enables more constant operation and lower installed capacity. In the hybrid configuration, however, a larger system is preferred, which is operated more flexibly with less hydrogen storage.

Synthetic industries approach and sectoral breakdown of technologies

The method of “synthetic industries” [34], also referred to as “The Final-Demand Approach” by Miller and Blair [42], is applied to estimate the macroeconomic impacts associated with the installation of the different PtX plant configurations, including wind turbines, PV systems, electrolysis, and ammonia synthesis plants. This approach allows consideration of sectors that are not explicitly defined in IO tables by treating investments in these sectors as demand shocks. Although sectors such as “wind turbines” and “solar PV” are not included in the IO tables, the services and materials that make up these industries are implicitly captured in the national accounts of the IO tables by sectors such as machinery, electronics, and construction. The demand vectors of the synthetic industries thus represent a package of goods and services that comprise the individual technologies.

As shown in Table 1, this method is widely used in scientific literature to estimate the macroeconomic impact of clean energy technologies. A key advantage of this method is its simplicity and lower data requirements compared to the disaggregation of existing sectors or the introduction of new sectors into IO, which are usually based on a larger number of assumptions. The sectoral breakdowns for wind and PV from previous scientific publications are already several years old and not country-specific. Therefore, this study provides new sectoral breakdowns for solar PV, wind turbines, electrolyzers and ammonia synthesis based on recent technology reports from different international institutions such as IRENA [53], the National Renewable Energy Laboratory [56] and the Fraunhofer society [57], reflecting a better representation of the current state of technology and investment distribution. Table 4 provides a comprehensive overview of all allocations, both the new breakdowns proposed by this study and the existing literature values. New allocations are identified by the number 1 after the starting letter, literature values by the numbers 2 to 4, depending on the technology. This study initially uses the new sectoral breakdowns W1, S1, E1 and N1 for the analyses, as the authors believe that these best reflect the current data. The historical breakdowns (W2-W4, S2-S4, E2) differ considerably in some cases, both among each other and in comparison to the new variants.

In order to take this into account and test the results for robustness, additional sensitivity analyses and statistical tests are therefore carried out with all possible combinations of the breakdowns listed in Table 4. For the two hybrid variants, there are 32 combinations each, and for the solar hydrogen or ammonia configurations, there are eight options for pairing the different technology breakdowns. In addition, two variants are used for the sensitivities with regard to local content. On the one hand, the current level of domestic supply is used, which results from the calculated share of origin. The other is a hypothetical maximum, which assumes that all components are fully domestically sourced. In total, this gives 160 variants of different combinations, which are used to statistically test the significance of the differences between the PtX configurations (hybrid vs. solar and hydrogen vs. ammonia) in terms of resulting output, value added, employment and compensation of employees.

Results

The results section is organized as follows. The first part provides insights into the general structure and interconnectedness of the Saudi economy based on the ICIO table. The second part describes the impact of the four PtX plant configurations on output, value added, employment and compensation of employees. Finally, sensitivity analyses with

Table 4
Breakdown of capital expenditure for various PtX technologies by the economic sectors listed in the input–output table; compilation of different sources.

Economic sectors	Wind				Solar PV				Electrolysis		NH3
	(W1)	(W2)	(W3)	(W4)	(S1)	(S2)	(S3)	(S4)	(E1)	(E2)	(N1)
C20: Chemical and chemical products	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	5.0	0.0
C22: Rubber and plastics	0.0	12.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0
products											
C23: Other non-metallic	21.4	0.0	0.0	0.0	0.0	0.0	0.0	12.0	0.0	0.0	0.0
mineral products											
C25: Fabricated metal	13.9	12.0	12.0	34.0	10.0	14.0	17.5	41.0	4.8	8.0	5.6
products											
C26: Computer, electronic and optical equipment	0.0	0.0	3.0	0.0	34.7	0.0	17.5	0.0	22.7	3.0	0.0
C27: Electrical equipment	35.0	6.0	3.0	34.0	4.6	14.0	17.5	33.0	29.5	14.0	0.0
C28: Machinery and equipment, nec	0.0	37.0	37.0	0.0	0.0	49.0	0.0	0.0	16.9	33.0	39.4
F: Construction	19.7	26.0	26.0	25.5	26.0	20.0	30.0	9.5	14.1	12.0	45.0
G: Wholesale and retail trade; repair of motor vehicles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0
H49: Land transport and transport via pipelines	0.0	1.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
I: Accommodation and food	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
service activities											
K: Financial and insurance	1.6	0.5	0.0	0.0	0.4	0.5	0.0	0.0	0.0	2.0	0.0
activities											
L: Real estate activities	0.0	5.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	2.0	0.0
M: Professional, scientific and technical activities	8.4	0.0	7.0	4.0	24.3	0.0	17.5	2.0	9.0	12.0	10.0
S: Other service activities	0.0	0.0	0.0	2.5	0.0	0.0	0.0	2.5	0.0	0.0	0.0
Sum of weights	100	100	100	100	100	100	100	100	100	100	100

(W1) own allocation based on [56]; (W2/S2) values from [30] based on [33]; (W3/S3) values from [34] based on [58]; (W4/S4) values from [34] based on [59]; (S1) own allocation based on [53]; (E1) own allocation based on [57]; (E2) values from [25] based on [26]; (N1) own allocation based on [60–62].

different “synthetic industry” allocations and domestic supply shares are conducted and validated with statistical tests.

Status quo of the Saudi Arabian economy

Fig. 6 gives an overview of the total flow of goods within Saudi Arabia and its share of different countries of origin. Besides domestic supply it also specifies the share of China, USA, Germany, Japan, South Korea and India, while the share of all other countries is shown combined.

Currently the economic sectors with the highest total flow of goods in Saudi Arabia are oil related. By far the dominant sector is “Mining and quarrying, energy producing products” (B05_06) with flows worth more than 225 bn USD stemming from crude oil extraction and export. The

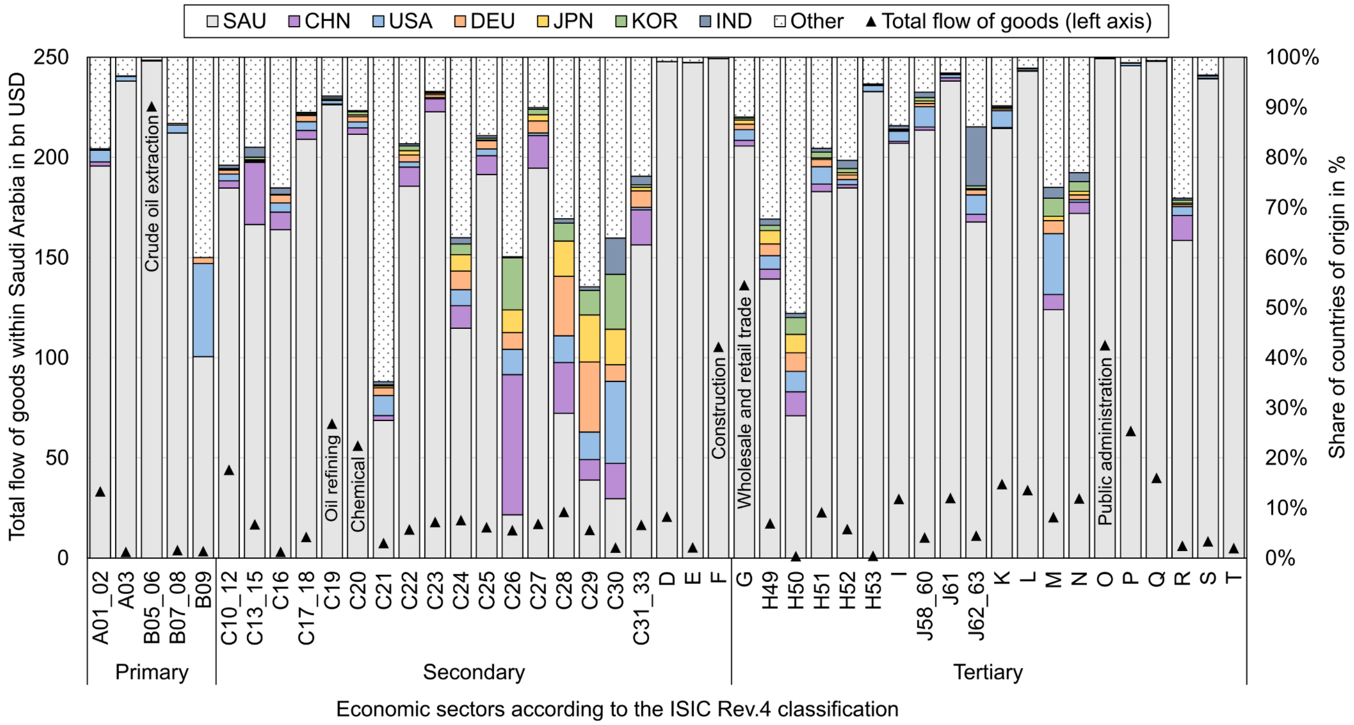


Fig. 6. Overview of the total flow of goods within Saudi Arabia by economic sector (black triangles, left axis) and its share of different countries of origin (stacked bars, right axis).

two largest manufacturing sectors are oil refining (C19) and chemical industries (C20) with flows worth 67 and 56 bn USD respectively. In addition construction (F), wholesale and retail trade (G) and public administration and defence (O) have high monetary values of between 106 and 136 bn USD. All of these sectors have domestic supply shares of at least 82 %. In comparison, many manufacturing sectors especially these with high relevance for clean technologies such as “Computer, electronic and optical equipment” (C26) and “Machinery and equipment” (C28) have high import shares. For instance, for C26 China is the main supplier with 28 % of the total flow of goods in this sector. For C28 Germany has supply shares of 12 %. The United States, Japan and South Korea also are important suppliers of different relevant goods and services.

A closer look at the downstream flows of the three main oil-related sectors in Saudi Arabia by country and sectoral classification (see Fig. 7) sheds light on the utilization of their output. Around 80 % of Saudi Arabian crude oil output (B05_06) is exported and is primarily used to supply the refinery sector (C19) and utilities for electricity and gas (D) in the importing countries. China is the most important target market for Saudi crude oil, followed by Japan, the USA, Korea and India. Domestically, crude oil serves as an important feedstock and fuel for refineries, chemical and petrochemical industries (C20) and other manufacturing sectors. Direct final demand for crude oil is very low at only 4 % of total production. The situation is different for refining, where final demand is the most important application, accounting for 27 % of total output. However, the output of refined oil products is around four times smaller than that of crude oil. In addition to final demand, relevant parts of refinery production are used as an intermediate product within the refining process, as an input for the chemical industry and as a fuel in the transport sector (H). There are recognizable differences between domestic use and export, with both accounting for roughly equal shares of production. While internationally Saudi Arabian refined products are mainly used for final demand and in the transportation sectors, the range of applications in Saudi Arabia is broader and includes other sectors, in particular the chemical industry, utilities, construction and services. The target countries for refinery exports from Saudi Arabia are relatively diverse, with India being the most important destination, accounting for 8 % of total output. The Saudi Arabian chemical industry, which has a similar total output as the refinery sector, exports more than two thirds of its production. China is the largest market, accounting for 26 % of total output. The chemicals produced in Saudi Arabia are primarily used as intermediate products in the chemical industry itself (23 %), but also in other manufacturing sectors, primarily in the rubber and plastics industry (C22), as well as in agriculture (A01_02) and construction (F).

Fig. 8 provides insight into the economic interdependence of the various sectors using forward and backward linkages. The linkage values are normalized across countries and sectors, and the bubbles are scaled according to sectoral value added. The left subchart shows all sectors of the Saudi Arabian economy, while the right subchart includes only the manufacturing and mining sectors, but for all countries of the ICIO table. As for total flow of goods in Fig. 6, crude oil extraction (B05_06) is also by far the dominant sector in terms of value added, accounting for 27.3 % of total value added in Saudi Arabia. The following sectors are public administration and defense (O), wholesale and retail trade (G), education (P) and construction (F) with 10.3 %, 8.0 %, 7.1 % and 5.7 % respectively. In contrast, all manufacturing sectors combined account for only 13.6 % of national value added, with the largest shares coming from refining (C19) and chemicals (C20), which together account for 5.9 %. In addition, most manufacturing sectors in Saudi Arabia have low normalized forward and backward linkage values below one, meaning that there are few economic linkages with other sectors, either nationally or internationally. Rubber and plastic products (C22), basic metals (C24) and fabricated metal products (C25) are the only Saudi Arabian manufacturing sectors with normalized backward linkages above one, indicating stronger interaction with upstream sectors. However, their values are still below the global industry average for the manufacturing sector and the value added shares are comparatively low. Energy mining, mining support activities (B09), refining and the chemical industry, on the other hand, have relatively high normalized forward linkages of more than one, but their backward linkages are well below the global average. For energy mining, Saudi Arabia even has the lowest value of all mining sectors worldwide. These sectors are therefore heavily dependent on demand from downstream sectors, particularly from abroad, but have few links to upstream sectors. As a result, the demand for their output has hardly any second- or third-order effects on other sectors of the economy, highlighting the strong dependence on export revenues.

Macroeconomic impacts of installing PtX plants in Saudi Arabia

After analyzing the status quo of the Saudi Arabian economy the

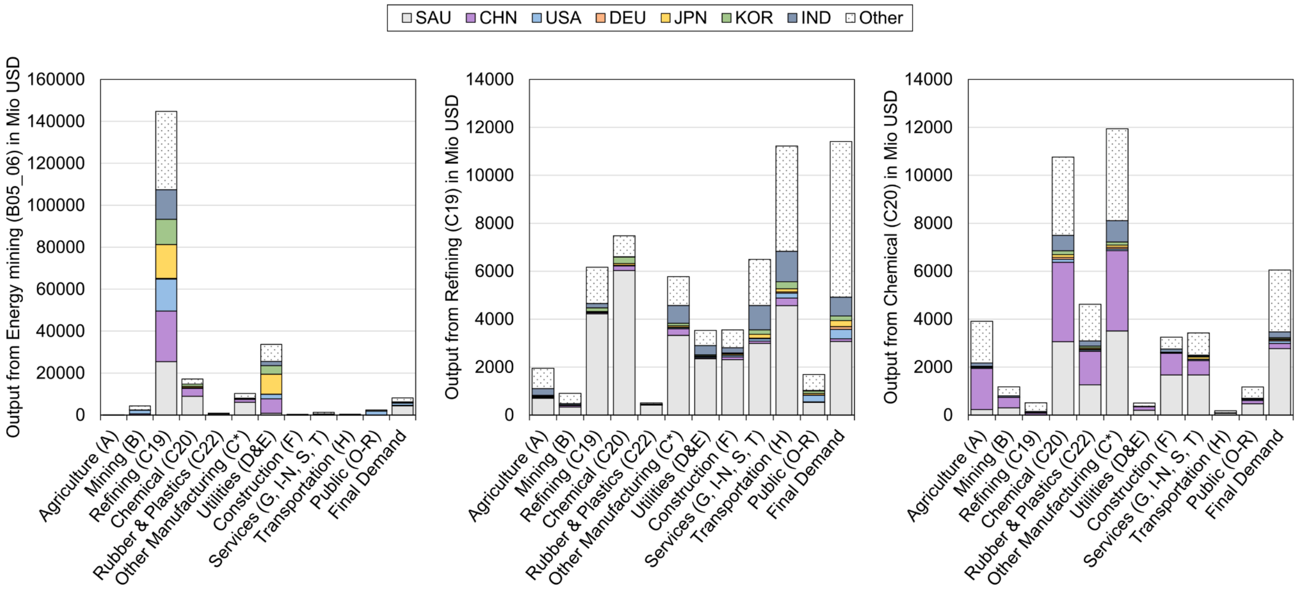


Fig. 7. Overview of the output of Saudi Arabia’s oil-related sectors (B05_06 – Energy mining, C19 – Refining & C20 – Chemical) and their respective further use as intermediate or end product by country and sectoral classification.

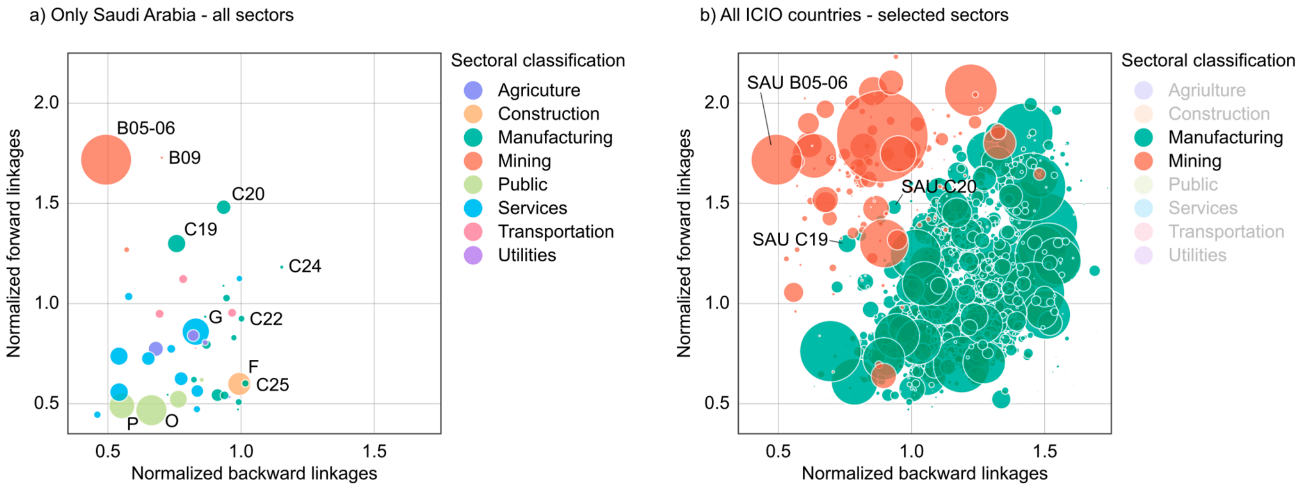
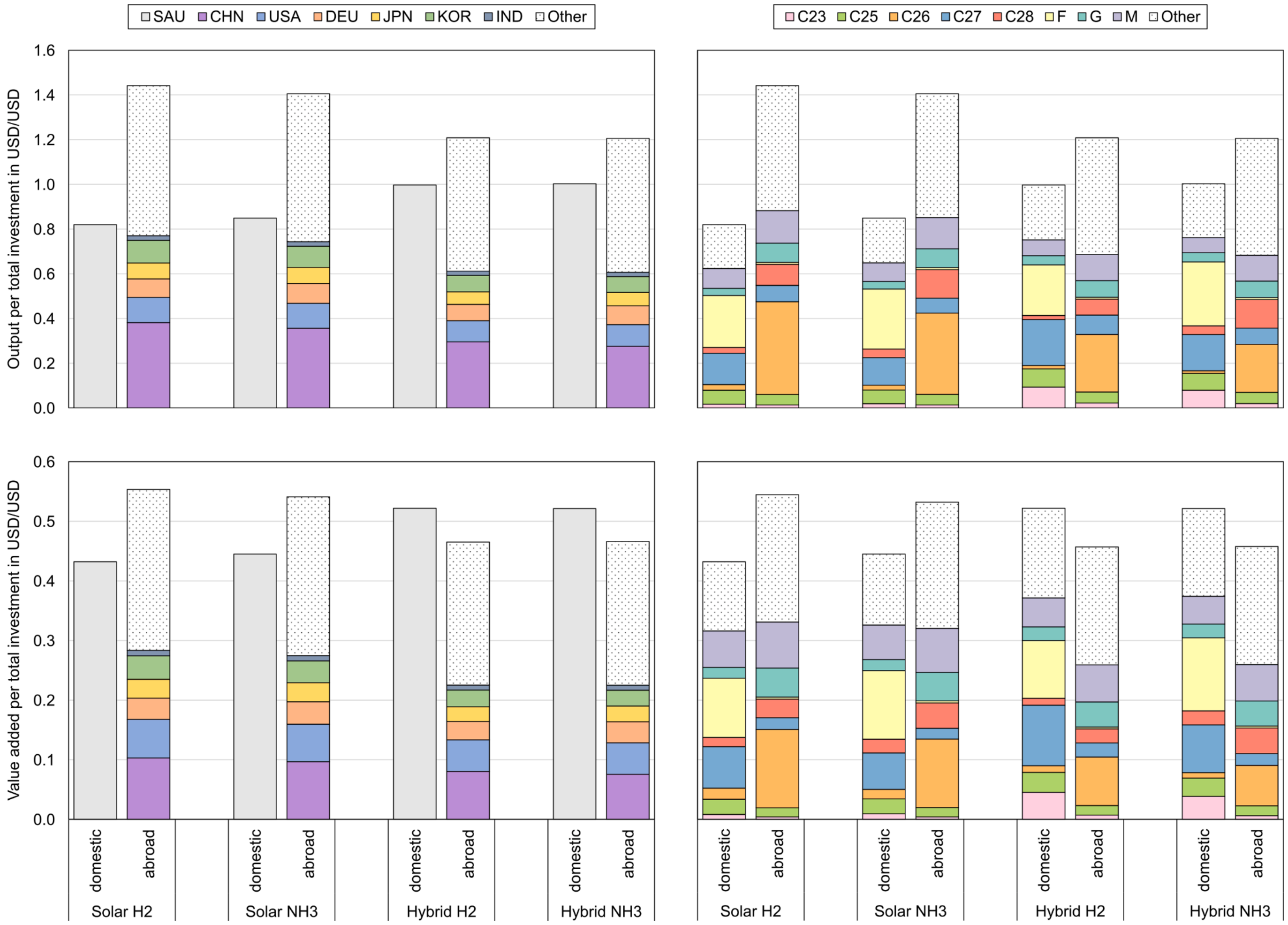


Fig. 8. Bubble chart of economic sectors, scaled by value added, shown according to their normalized forward and backward linkages and color-coded by their sectoral classification: a) Only Saudi Arabia – all sectors, b) All ICIO countries – selected sectors.



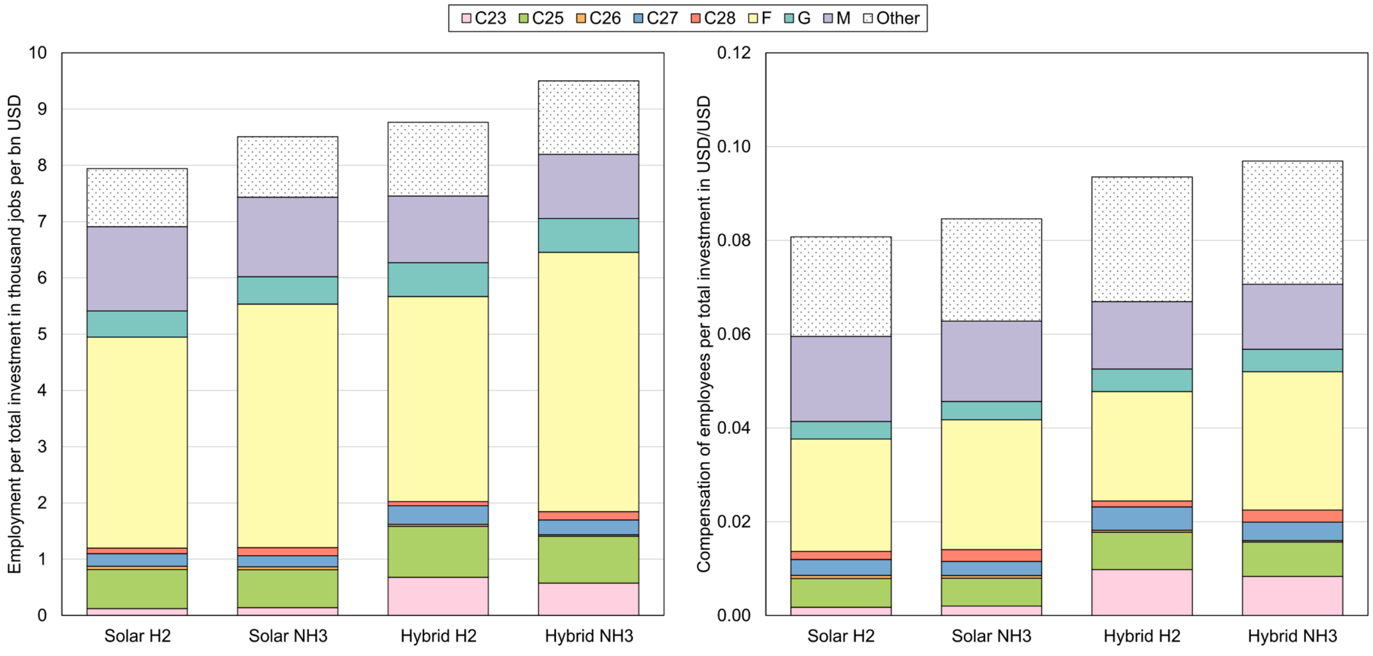
Classification note: C23: Other non-metallic mineral products; C25: Fabricated metal products; C26: Computer, electronic and optical equipment; C27: Electrical equipment; C28: Machinery and equipment, nec; F: Construction; G: Wholesale and retail trade, repair of motor vehicles; M: Professional, scientific and technical activities

Fig. 9. Overview of the relative output (top) and value added (bottom) in USD per USD total investment by country (left) and sector (right) for the four PtX plant configurations.

following section presents the results of the various PtX scenarios in terms of macroeconomic effects. Fig. 9 depicts the relative output and value added per total investment in the different plant configurations as stacked bar charts by country and sector. The four sub-charts show specific results for seven selected countries and sectors, while the remainder is summarized under "Other".

For all system configurations, the foreign effects caused by the estimated investments are stronger than the effects in Saudi Arabia in terms of output. The figures for Saudi Arabia range between 0.82 and 1.00 USD output per USD invested and a total of 1.21–1.44 USD/USD in other countries. The values for value added are generally lower, and the differences between domestic and foreign effects are smaller overall at 0.42–0.52 and 0.47–0.55 USD value added per USD invested respectively. In the case of hybrid plant configurations, more value added is generated in Saudi Arabia than abroad. The demand for "Electrical equipment" (blue, C27) and "Other non-metallic mineral products" (pink, C23), which are essential for wind turbines, could, for example, be met to a greater extent by domestic suppliers, which would increase domestic output and value added. Conversely, the "Computer, electronic and optical equipment" sector (orange, C26), which is crucial for PV systems, is primarily dependent on imports from China and Korea, leading to an increase in foreign output and value added. Geographically, the foreign effects are strongest in China for all configurations, followed by the USA. Germany, Japan and South Korea also show notable effects, while the potential impact in India appears to be minimal. In all four variants, construction (yellow, F) has the highest share of domestic production and value added. In addition, "Professional, scientific and technical activities" (lavender, M) account for a considerable share of output and, in particular, value added both in Saudi Arabia and abroad. There is also some impact on "Wholesale and retail trade" (aquamarine, G), which is remarkable insofar as no direct demand for this is specified in the "synthetic industries "scenarios. The effects in Wholesale and retail trade are thus indirect, reflecting the sector's integral upstream support function in the value chain of PtX components. The differences between the hydrogen and ammonia scenarios are rather small in terms of total output and value added. However, there are some changes in the breakdown by country and sector. In the ammonia scenarios, the share of "machinery and equipment" (red, C28) is higher, while the share of "computer, electronic and optical equipment" (orange, C26) is lower. In terms of foreign effects, this leads to higher output and value added in Germany due to its strong machinery sector with high supply shares to Saudi Arabia and lower impacts in China and South Korea. As the ammonia scenarios are also associated with higher shares of construction, the overall domestic effects are slightly higher than in the hydrogen scenarios.

Fig. 10 shows the domestic employment effects in Saudi Arabia in terms of jobs and compensation of employees, which includes wages as well as additional payments such as social security contributions, private pensions and health insurance. As for output and value added, the results are presented as stacked bar charts for seven main sectors and the aggregate remainder. The highest relative job creation comes from the "Hybrid NH3" scenario with 9.50 jobs per million USD of investment, while the lowest job creation results from the "Solar H2" scenario with 7.94 jobs/million USD. The impact on compensation of employees ranges between 0.081 ("Solar H2") and 0.097 USD/USD investment ("Hybrid NH3"). Overall, the relative domestic employment effects in Saudi Arabia are stronger for hybrid plants than for solar configurations and for ammonia plants compared to hydrogen plants. With more than 40 % in all scenarios, most jobs can be attributed to the construction sector, which is even more relevant for ammonia plants than for pure hydrogen production, as ammonia reactors require a higher proportion of additional infrastructure to be built in order to be commissioned. The stronger employment effects for the hybrid configurations arise from potential jobs in the domestic manufacturing of non-metallic mineral products (C23) and fabricated metal products (C25). These sectors have already a relatively high domestic supply share, which may be used to produce higher shares of parts of wind turbines such tower and blades domestically. In addition, there are relevant job potentials for all configurations in tertiary sectors such as "Professional, scientific and technical activities" (M) and "Wholesale and retail trade" (G). In terms of



Classification note: C23: Other non-metallic mineral products; C25: Fabricated metal products; C26: Computer, electronic and optical equipment; C27: Electrical equipment; C28: Machinery and equipment, nec; F: Construction; G: Wholesale and retail trade, repair of motor vehicles; M: Professional, scientific and technical activities

Fig. 10. Overview of the relative domestic employment effects (left) and compensation of employees (right) generated by the total investments in the four PtX scenarios, by sector in Saudi Arabia.

compensation of employees, the dominance of construction is less pronounced, as many of the jobs in construction tend to be lower-skilled and thus lower-paid. Conversely, "Professional, scientific and technical activities" (M) such as for the planning of PtX plants imply higher paid jobs and have thus a higher share in terms of compensation of employees.

All results presented so far are based on the calculated shares of origin (see Fig. 6) and the new proposed sectoral splits for the "synthetic industries" solar PV (S1), wind turbines (W1), electrolysis (E1) and ammonia synthesis (N1). These classifications are based on recent technology-specific literature (see Table 4).However, for PV, wind turbines and electrolysis there are also alternative sectoral breakdowns from other publications that used the synthetic industry approach to examine potential macroeconomic impacts of clean energy development in the United States [34], Italy [30] and France [25]. Fig. 11 shows the resulting shares of origin by country for the different technologies and sectoral splits. Overall, there is a tendency for PV and electrolysis to have higher import shares than wind turbines. However, the specific allocations of the individual technologies differ considerably in some cases and therefore also the calculated shares of origin of the various technologies. In the case of wind turbines, the greatest differences result from the allocation of generator sets either to "Electrical equipment" (C27) as in W1 and W4 or to "Machinery and equipment" (C28) as in W2 and W3. As C28 has higher import shares than C27, the share of domestic supply in the latter is lower overall, while Germany's share in particular is increasing. In the case of solar PV, allocation S1 has the highest import share, particularly from China. This is due to the relatively high share of "Computers, electronic and optical equipment" (C26) at 34.7 %, where the PV modules are allocated based on OECD conversion tables [63]. Dell'Anna [30] indicates for S2 very high shares of "Machinery and equipment" at 49 % of total PV CAPEX, without providing further information on this assumption, which leads to relatively high supply shares from Germany in this configuration. Garrett-Peltier [34], on the other hand, gives high shares of "Fabricated metal products" (C25) and "Electrical equipment" (C27) and lower shares of "Professional, scientific and technical activities" (M) for S4, which explains the lowest overall import share. The sector breakdown S3, also by Garret-Peltier, shows the highest share of construction (F) at 30 %, which in combination with respective shares for C25 and C27 also leads to a higher domestic supply share than in S1 or S2. For electrolysis, the differences between E1 and E2 (Guionie et al. [25]) are smaller overall than for the different breakdowns of wind turbines or PV. The main variation lies in the different shares between C26, C27 and C28, which leads to a slightly higher total share of domestic supply for E2 than for E1.

In order to test the robustness of the macroeconomic effects, all combinations of the various sectoral splits for wind power plants (W1-W4), solar PV (S1-S4) and electrolysis (E1-E2) are examined for the four PtX configurations. This is done in two variants, both with the current domestic supply shares and with the theoretical maximum of a completely domestic supply for all sectors. Fig. 12 shows the results of the total of 160 variants in terms of relative output, value added, compensation of employees and jobs created in Saudi Arabia as boxplots. The trends between configurations remain the same for the different sensitivities. There is an overall stronger impact for the hybrid configuration compared to solar-only plants. A Mann-Whitney *U* test confirms that this difference is significant ($p < 0.05$) for all impacts assuming current domestic supply shares, and significant for output and employment assuming full domestic supply. Comparing the impacts for ammonia and hydrogen as final products, there is a slightly stronger overall economic impact for ammonia plants than for hydrogen plants. However, this is only significant for employment assuming current domestic supply ($p < 0.05$) and for employment and compensation of employees assuming full domestic supply. The higher employment effects can be explained by the relatively high proportion of construction work required for the installation of ammonia reactors. In terms of output and value added, there are no significant differences between the hydrogen and ammonia configurations, neither with current domestic supply nor with full domestic supply. Table 5 provides the p-values of all statistical tests. In general, the differences between the configurations and the sensitivities decrease with higher assumed domestic supply shares. The changes observed for different levels of domestic supply are strongest for value added, while the changes in employment are less pronounced. This suggests that in more labor-intensive sectors (e.g. construction) a high share of domestic demand is already supplied domestically, while in less labor-intensive sectors (e.g. professional, scientific and technical activities) a higher share of value added is currently generated abroad.

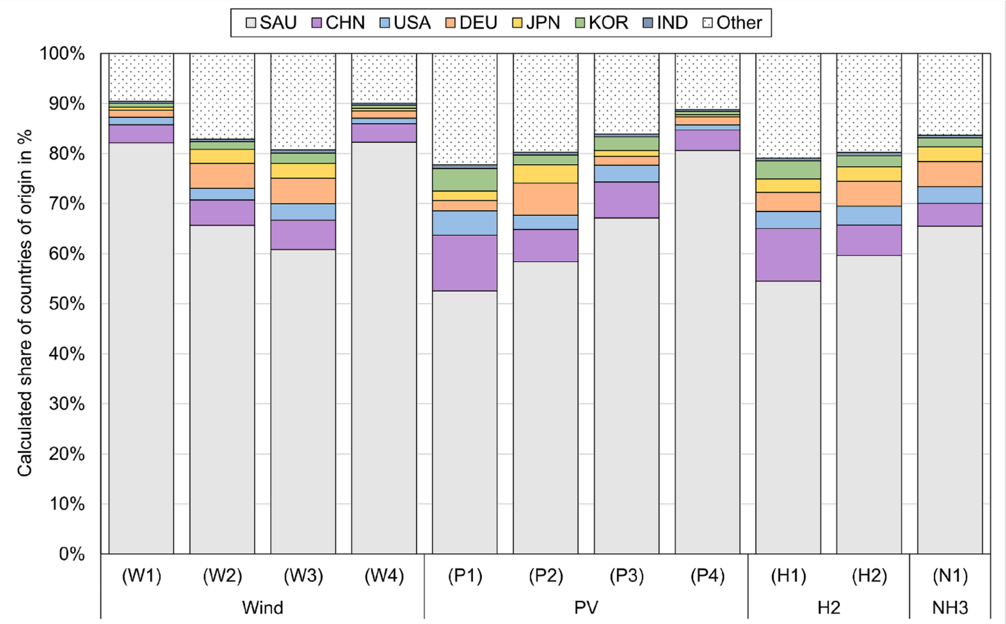


Fig. 11. Calculated shares of different countries of origin for various PtX technologies and sources.

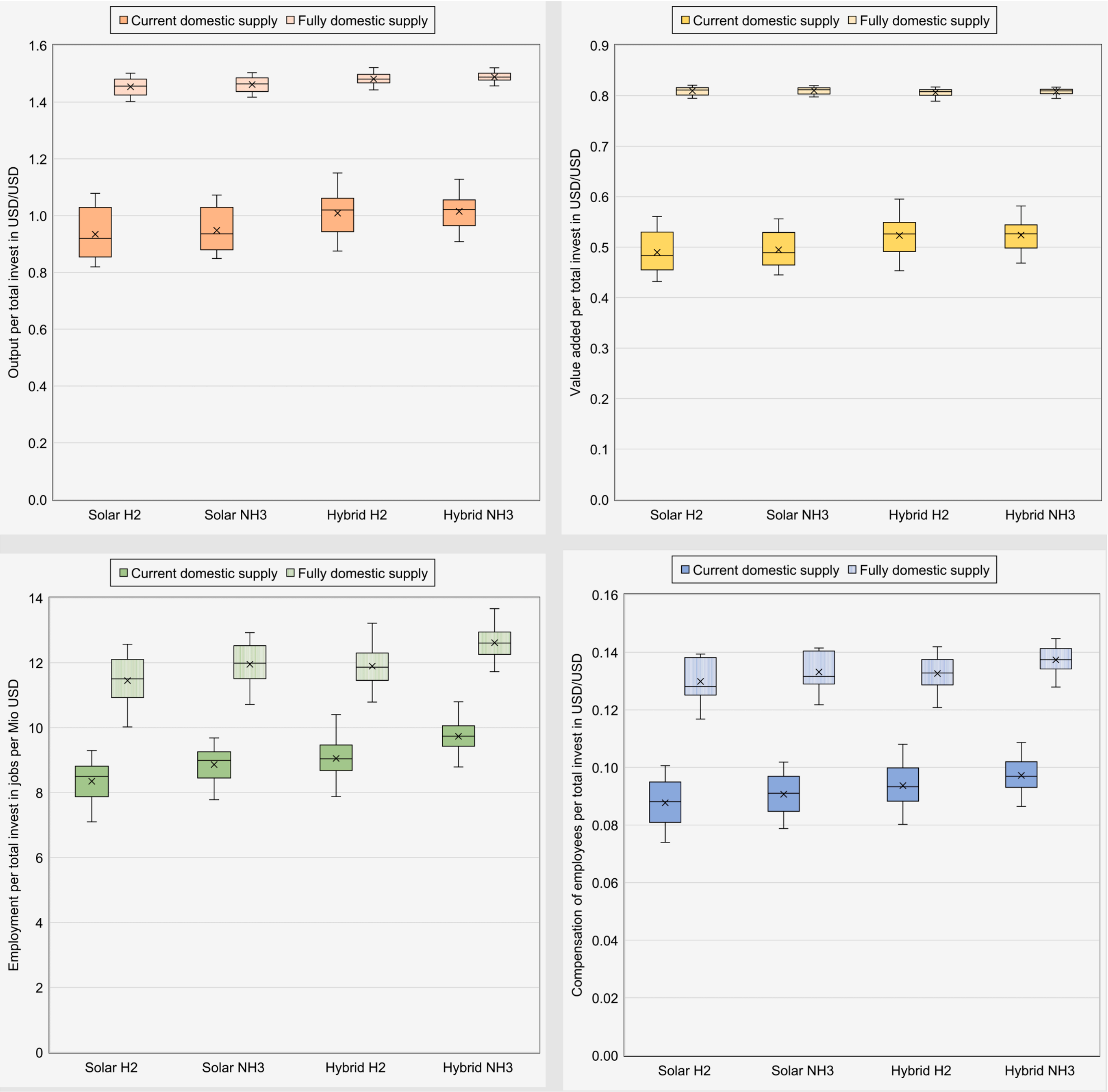


Fig. 12. Boxplots showing the ranges of total effects (direct + indirect) in terms of output, value added, employment and compensation of employees resulting from the 144 combinations of sectoral splits for the synthetic industries, both with the current domestic supply shares and a fully domestic supply.

Table 5
Summary of p-values for Mann-Whitney U-tests on the significance of the choice of renewable energy sources and end products on different domestic effects for various CAPEX allocations and shares of domestic supply.

Effect	Current supply shares		Fully domestic supply	
	RE source	**End product**	**RE source**	**End product**
Output	0.00462^{**}	0.64762^{ns}	0.00088^{***}	0.16149^{ns}
Value added	0.00577^{**}	0.85871^{ns}	0.16476^{ns}	0.32398^{ns}
Employment	0.00040^{***}	0.00005^{***}	0.01344^{*}	0.00001^{***}
Compensation of employees	0.00921^{**}	0.05135^{ns}	0.09815^{ns}	0.00113^{**}

Discussion & conclusions

With oil exports expected to decline as a result of global decarbonization, Saudi Arabia faces the challenge of overcoming the so-called “resource curse” and finding ways to diversify its economy. At the same time, the global energy transition offers opportunities to leverage the country’s excellent RE potential and attract energy-intensive industries or parts of their value chains, in line with the concept of the “renewables pull effect”. Due to the supposedly transferable know-how of parts of the fossil fuel industry, the production of green hydrogen and downstream PtX products is often discussed in this context. A good example of this is the NEOM green hydrogen complex, which aims to produce and export green ammonia based on wind and solar energy from 2026 onwards. In addition to export revenues, the flagship project of Saudi Arabia's hydrogen strategy is expected to have additional positive impacts such as job creation and local value added. This paper therefore analyzes to what extent green hydrogen and PtX projects can help to drive economic transformation in Saudi Arabia. Besides the "hybrid ammonia" configuration of the NEOM project, it explores three additional options with hydrogen as the end product instead of ammonia, and solar-only power generation instead of a hybrid PV-wind system. Green hydrogen and ammonia are both promising building blocks for the decarbonization of the Saudi Arabian economy, given their lower environmental impact compared to carbon-based PtX production [50]. The multi-regional ICIO model, considers not only the impacts in Saudi Arabia but also indirect impacts abroad resulting from international linkages in the value chain of green technology components. Five main findings are presented and discussed below.

New synthetic industry splits for input–output analyses of PtX value chains

Applying synthetic industries to assess the macroeconomic impact of investments in technologies not explicitly included in IO tables is a widely used approach in the scientific community. To this end, the investments are proportionally distributed as demand across the sectors represented in the tables. For clean energy technologies, there are examples from different countries regarding the installation of renewable power plants. However, these sectoral allocations often originate from older publications failing to account for recent cost reductions and changes in the shares of various components in total installed costs. Currently, only one study provides a sectoral breakdown for hydrogen electrolysis, and there is none for ammonia synthesis. We therefore use recent technology-specific reports to develop new and up-to-date sectoral breakdowns for the four main technologies of the PtX value chain analyzed in this paper: onshore wind turbines, solar PV, water electrolysis and ammonia synthesis. These breakdowns offer a solid foundation for future IO analyses and can be adapted to other countries and evolving CAPEX developments as needed.

Most domestic jobs created by PtX projects are in construction

The presented analysis shows that there are considerable differences between the sectors in which the jobs are created. This has in turn a major impact on the skills required, the salary and the long-term nature of the jobs. In this case study, the construction sector accounts with between 42 % and 51 % for the largest share of jobs in Saudi Arabia for all system configurations analyzed. As the analysis focuses only on the installation phase, it does not quantify the number of jobs during the operational phase of PtX projects. Nevertheless, it appears likely that a large proportion of jobs in the construction sector are only required during the first project phase and therefore only in the short to medium term. This assumption is supported by other publications [64,65], which show that RE projects require the highest proportion of workers in the manufacturing and installation phase, while the long-term employment effects are smaller. A comparison of the figures for the number of jobs and compensation of employees furthermore shows that most of these jobs are comparatively poorly paid. This can generally be seen as a negative factor with regard to the employment of local workers, as a higher minimum wage applies to nationals than to foreigners [66]. This is also reflected in the analysis of the current situation by Al-Sinan and Bubshait [67]. They describe that although the construction sector accounts for 26.4 % of total employment in the Saudi Arabian private sector and 15.4 % of Saudi nationals were unemployed in 2020, only 12.5 % of workers in construction are locals. Theoretically, therefore, there seems to be great potential for local job creation. However, most unemployed Saudis are college graduates and therefore too qualified for low-skilled construction jobs and have mostly studied subjects that are not suitable for high-skilled construction jobs. Even the unemployed Saudis who are potentially suited to work in construction are currently discouraged by the poor job security and unattractive salaries compared to other sectors such as the drilling industry.

Hybrid configurations have a stronger domestic macroeconomic impact than solar ones

The different technology and supply shares of the four plant configurations affect the domestic macroeconomic impact. In particular, the synthetic industry splits W1 and S1 show that the estimated total domestic supply share for wind turbines (82.1 %) is notably higher than for PV (52.6 %). It is important to emphasize that these figures are based on the total installed project costs, including planning and installation, not just technology CAPEX. Furthermore, the nature of IO tables and in particular the method of synthetic industries entails a relatively high degree of uncertainty due to sectoral aggregation. All investments for a specific technology component are assigned to one of the 45 industry sectors represented in the IO table. For instance, solar modules fall under "Computer, electronic and optical equipment" (C26), while the generator set and blades of a wind turbine are allocated to "Electrical equipment" (C27) and "Other non-metallic minerals" (C23), respectively. In Saudi Arabia, the current domestic supply share is 9 % for C26, 78 % for C27, and 89 % for C23. However, these sectors cover a wide range of products, and allocation is not always straightforward. Consequently, general sectoral shares of origin may not directly translate into specific supply shares for particular technology components. For the given case study this might lead to an overestimation of the domestic supply share, particularly for wind turbine components. As shown in Fig. 11, the resulting shares of countries of origin vary for the different sectoral breakdowns of wind turbines (W1-W4) and solar PV (S1-S4). Despite this, statistical tests indicate that the trend toward stronger domestic effects for hybrid configurations compared to solar-only configurations is significant for output, value added, employment and compensation of employees, assuming the current sectoral supply shares in Saudi Arabia. This finding is crucial for developers of PtX projects and aligns with the planned configuration of the NEOM project in Saudi Arabia. The synthetic industries approach in combination with the current sectoral supply shares is a good first estimate and helps to show which technologies are likely to have a larger domestic impact. Nevertheless, more detailed and country-specific analyses need to be carried out in order to better understand the exact effects.

Foreign effects of investments in Saudi Arabian PtX plants are strongest for China

The advantage of ICIO tables over national tables is their ability to analyze effects in other countries by considering international trade flows. Currently, Saudi Arabia relies heavily on crude oil and related downstream products from refineries and the chemical industry. On the other hand, there are only a few manufacturing sectors with relevant domestic value added. Consequently, many intermediate and end products are imported. Following the resource curse hypothesis, the development of human capital and industrial know-how can be constrained in resource-rich countries compared to others [6]. This is particularly pertinent for the green hydrogen value chain, as many technology components are complex to produce. Müller and Eichhammer [68] empirically show that countries with a higher share of natural resource rents in their GDP are less prepared to producing these components due to a lack of industrial capacities. The analysis in this paper confirms these findings for Saudi Arabia. Between 55 % to 64 % of output and 47 % to 56 % of value added from investments in installing PtX plants in Saudi Arabia occur abroad. For all plant configurations, China generates the strongest effects, accounting for 13 % to 17 % of total output. The fact that the calculated Chinese supply shares for the various technology splits shown in Fig. 10 are only between 4 % and 11 % shows that particularly high shares of second- and third-order effects occur in China. The USA, South Korea, Germany, and Japan also experience foreign macroeconomic effects, though the exact order varies by system configuration. For example, the hybrid ammonia configuration shows the strongest effects in Germany due to the high share of machinery and equipment. These figures should be interpreted with caution, as they are based on the general allocation of technology components to aggregated sectors and their calculated total supply shares. Currently, more than 80 % of all PV modules come from China [69], meaning its share is likely underestimated in this study. For the electrolyzers of the NEOM project, there is already a signed supply contract with Thyssenkrupp Nucera [70], suggesting Germany's share might be higher than assumed by the synthetic industries approach. Given the experience of other green technologies, China's share of global trade in electrolyzers might also increase further in the future [71]. Despite these limitations, the method and results are valuable for gaining a better understanding of the global impact of PtX projects, reflecting indirect effects in the value chains.

Increasing local supply would affect value added more than employment

The calculated figures show that an increase in the local supply of components and services required for PtX plants tends to impact value added more than employment. This discrepancy arises from the different labor intensities across sectors. For example, construction, a highly labor-intensive sector, already meets the demand almost entirely domestically (although currently mainly by foreign workers), leaving limited potential for additional jobs through increased local supply. Conversely, ICIO data show that manufacturing sectors like “Computer, electronic and optical equipment” and “Machinery and equipment” currently contribute only a small share of local supply, at 9 % and 29 %, respectively. As these sectors have a relatively high value added per employee, there is theoretically greater untapped potential to increase value added by increasing local supply without proportionally increasing employment. Although the resulting number of jobs would be smaller compared to the construction sector, these jobs would also target other groups in terms of salaries and skills required. This is of particular interest with regard to the difficulties discussed above concerning Saudi workers in the construction sector. These findings therefore suggest that targeted policy measures to increase local manufacturing of relevant technology components and the establishment of technology development and manufacturing in Saudi Arabia offer relevant potential for industrial diversification, increasing domestic value added and the creation of selected and therefore higher-skilled jobs.

Akhtar et al. [72] show that increased local production of technology components would bring further benefits from a social perspective in addition to increased value added. They conduct a social life cycle analysis for various potential hydrogen exporting countries, including Saudi Arabia, and find that risks related to social indicators such as child labor and health expenditures are drastically reduced if key equipment is produced domestically rather than imported. A more detailed analysis and the development of a targeted strategy is therefore recommended. To this end, Lashitew et al. [7] identify three key areas for Saudi Arabia to focus its development efforts on in order to achieve greater economic diversification. First, the country should improve its human capital by raising the level of tertiary education. Second, the country lags behind other countries in R&D spending and patent applications, indicating limited progress in knowledge-intensive industries. And thirdly, support for entrepreneurship and private sector growth still has room for improvement, which is reflected in comparatively low firm creation rates. These aspects are also part of Vision 2030, a long-term development plan launched by Saudi Arabia that aims to reduce the country's dependence on oil by diversifying its economy. In addition to tourism and the digital economy, it places particular emphasis on RE and hydrogen technologies as one of the promising sectors [73]. In its National Renewable Energy Program, the Ministry of Energy has set the goal of increasing the share of local content by localizing the production of 75 % of the components in Saudi Arabia's RE projects by 2030. To this end, the Renewable Energy Localisation Company, wholly owned by the Public Investment Fund, has been established to create partnerships between global manufacturers of renewable technologies and the Saudi private sector. In July 2024, two joint venture agreements were signed between the Renewable Energy Localisation Company, the private Saudi company Vision Industries and two Chinese manufacturers of wind turbines (Envision Energy) and PV modules (Jinko Solar). The agreements aim to produce 4 GW of wind turbines and 10 GW of solar modules in Saudi Arabia [74]. Furthermore, Saudi Arabia waives customs duties on certain clean technologies, such as PV modules, to encourage investment in RE projects. The current policy therefore relies on a mix of measures to enhance international cooperation, in order to simultaneously promote the expansion of RE technologies and industrial diversification.

The issue of industrial transformation and overcoming dependence on fossil fuel exports is not unique to Saudi Arabia. Many other countries, such as Algeria, Kazakhstan and Nigeria, are facing similar challenges and need to find strategies to deal with them. It is very likely that profits from the export of hydrogen or other green fuels will not be sufficient to fully compensate for declining revenues from fossil fuel exports, as both the global demand for green fuels and their profit margins will be lower than for oil today. Integration into the local economy, both upstream and downstream, is therefore crucial to benefit from the development of a hydrogen economy in the long term. Some of the results of the analysis for Saudi Arabia, such as the role of local manufacturing, can also be transferred to other countries to a certain extent. However, the specific situation is of course different for each case. Country-specific analyses can provide more in-depth insights. The approach developed in this paper builds entirely on publicly available data and could therefore be applied to other countries and PtX projects in the future. To facilitate this, a comprehensive set of input data and results for this case study is made freely available on zenodo [75] as supplementary material.

Naturally, the methodology is also associated with certain limitations. Some of these, such as the relatively strong aggregation of the sectors contained in IO tables and the question of the appropriate breakdown of the “synthetic industries”, have already been mentioned above. Future work could address this and collect additional data through surveys and interviews to supplement the aggregated information from the IO table. In addition to sectoral granularity, mapping economic activity in Saudi Arabia's domestic regions in a regional IO table would allow for a more focused analysis of regional production capacities and resource allocation. While a regional IO table is currently not available for Saudi Arabia, this data would be a valuable addition to future research. Besides the economic impact assessment, which is the main objective of this study, expanding the IO model with environmental extensions would allow the comparison of trade-offs and synergies of different PtX configurations between a broader range of environmental and socio-economic impact categories. This can lead to additional insights, for example in relation to decarbonization and water consumption. A more differentiated breakdown of the cost components of the various technologies according to plant size and geographical region would also be interesting.

In general, IO models have the advantages of ease of use and transparency, provide good insights into the interlinkages between different sectors and, in the case of the ICIO tables used, are freely available for a large number of countries in a consistent manner. However, due to their linear and static nature, they also impose certain simplifications that may lead to distortions depending on the scope of the analysis. For long-term analysis, especially when large changes in economic structure are expected, alternative approaches such as dynamic IO modeling or general equilibrium models could be a good complement. Yet these models require substantially more data, are more complex to interpret and more computationally intensive. It is therefore important to carefully consider which models are most appropriate for a given type of analysis.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DeepL and FhGenie in order to improve the language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Viktor Paul Müller: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **Malte Besler:** Writing – original draft, Methodology, Data curation, Conceptualization, Visualization, Writing – review & editing. **Detlef van Vuuren:** Writing – review & editing, Supervision, Conceptualization. **Wolfgang Eichhammer:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2024.100798.

Data availability

Supplementary data for this article is openly available on Zenodo https://doi.org/10.5281/zenodo.13385870

References

[1] International Energy Agency, *World Energy Outlook 2023*, Paris **2023**.
[2] Jensen L. Global decarbonization in fossil fuel export-dependent economies-fiscal and economic transition costs. Available at SSRN 4509213 2023.
[3] Papyrakis E. J Dev Stud 2017;53(2):175–85. https://doi.org/10.1080/00220388.2016.1160070.
[4] Badeeb RA, Lean HH, Clark J. Resour Policy 2017;51:123–34. https://doi.org/10.1016/j.resourpol.2016.10.015.
[5] Mien E, Goujon M. Comp Econ Stud 2022;64(3):351–83. https://doi.org/10.1057/s41294-021-00177-w.
[6] Alssadek M, Benhin J. Resour Policy 2023;84:103741. https://doi.org/10.1016/j.resourpol.2023.103741.
[7] Lashitew AA, Ross ML, Werker E. World Bank Res Obs 2021;36(2):164–96. https://doi.org/10.1093/wbro/lkaa001.
[8] Matallah S. Resour Policy 2020;66:101602. https://doi.org/10.1016/j.resourpol.2020.101602.
[9] Sweidan OD, Elbargathi K. International Economics 2023;175:13–24. https://doi.org/10.1016/j.inteco.2023.05.003.
[10] van de Graaf T, Overland I, Scholten D, Westphal K. Energy Res Soc Sci 2020;70:101667. https://doi.org/10.1016/j.erss.2020.101667.
[11] A. Michaelowa, S. Butzengeiger, in press. doi: 10.5167/UZH-175363.
[12] Al-Sharafi A, Sahin AZ, Ayar T, Yilbas BS. Renew Sustain Energy Rev 2017;69:33–49. https://doi.org/10.1016/j.rser.2016.11.157.
[13] Garud SS, Tsang F, Karimi IA, Farooq S. Energ Conver Manage 2023;286:117059. https://doi.org/10.1016/j.enconman.2023.117059.
[14] AlZohbi G, AlShuhail L, Almoaikel A. Energy Rep 2023;9:262–7. https://doi.org/10.1016/j.egyr.2023.09.010.
[15] Zhang Q, Wang L, Chen W, Zhang C. Appl Energy 2024;376:124233. https://doi.org/10.1016/j.apenergy.2024.124233.
[16] Hassan Q, Sameen AZ, Salman HM, Jaszczur M, Al-Hitmi M, Alghoul M. Results Eng 2023;18:101165. https://doi.org/10.1016/j.rineng.2023.101165.
[17] Hassan Q, Algburi S, Sameen AZ, Jaszczur M, Salman HM, Mahmoud HA, et al. Int J Hydrogen Energy 2024;55:124–40. https://doi.org/10.1016/j.ijhydene.2023.11.117.
[18] Samadi S, Fischer A, Lechtenböhmer S. Energy Res Soc Sci 2023;104:103257. https://doi.org/10.1016/j.erss.2023.103257.
[19] Verpoort PC, Gast L, Hofmann A, Ueckerdt F. Nat Energy 2024;9(4):491–503. https://doi.org/10.1038/s41560-024-01492-z.
[20] Egerer J, Farhang-Damghani N, Grimm V, Runge P. Appl Energy 2024;358:122485. https://doi.org/10.1016/j.apenergy.2023.122485.
[21] Climate Action Tracker, Saudi Arabia Targets **2023**, https://climateactiontracker.org/countries/saudi-arabia/targets/, accessed 31 July 2024.
[22] NEOM, NEOM ACCELERATES PROGRESS TOWARDS GREEN HYDROGEN FUTURE **2023**, https://www.neom.com/en-us/newsroom/neom-accelerates-green-hydrogen-future, accessed 3 July 2024.
[23] ACWA Power, NEOM Green Hydrogen Project **2024**, https://acwapower.com/en/projects/neom-green-hydrogen-project, accessed 31 July 2024.
[24] Gupta R, Guibentif TM, Friedl M, Parra D, Patel MK. Energy Policy 2023;183:113768. https://doi.org/10.1016/j.enpol.2023.113768.
[25] Raphael Guionie, Rodica Loisel, Lionel Lemiale, Mathias Guerineau, *Industrial planning with input-output models: empirical evidence from low-carbon hydrogen in France* **2023**.
[26] Wietschel M, Seydel P. Int J Hydrogen Energy 2007;32(15):3201–11. https://doi.org/10.1016/j.ijhydene.2007.02.041.
[27] Lee D-H, Lee D-J, Chiu L-H. Int J Hydrogen Energy 2011;36(21):14238–44. https://doi.org/10.1016/j.ijhydene.2011.05.084.
[28] Chun D, Woo C, Seo H, Chung Y, Hong S, Kim J. Int J Hydrogen Energy 2014;39(15):7627–33. https://doi.org/10.1016/j.ijhydene.2014.03.058.
[29] Kim B-J, Hyun M-K, Yoo S-H. Int J Hydrogen Energy 2024;68:955–69. https://doi.org/10.1016/j.ijhydene.2024.04.267.
[30] Dell’Anna F. Energy Policy 2021;149:112031. https://doi.org/10.1016/j.enpol.2020.112031.
[31] Kamidelivand M, Cahill C, Llop M, Rogan F, O’Gallachoir B. Sustain Energy Technol Assess 2018;30:1–10. https://doi.org/10.1016/j.seta.2018.08.003.
[32] Keček D, Mikulić D, Lovrinčević Ž. Energy Policy 2019;126:402–10. https://doi.org/10.1016/j.enpol.2018.11.028.
[33] Tourkolias C, Mirasgedis S. Renew Sustain Energy Rev 2011;15(6):2876–86. https://doi.org/10.1016/j.rser.2011.02.027.
[34] Garrett-Peltier H. Econ Model 2017;61:439–47. https://doi.org/10.1016/j.econmod.2016.11.012.
[35] Ciorba U, Pauli F, Menna P. Energy Policy 2004;32(8):949–60. https://doi.org/10.1016/S0301-4215(03)00018-1.
[36] de Arce R, Mahía R, Medina E, Escribano G. Energy Policy 2012;46:335–45. https://doi.org/10.1016/j.enpol.2012.03.068.
[37] Fatiha B, Anouar G, Zineb Z, Karim M. Empirical evaluation of the socio-economic impacts of renewable energies in Morocco by 2035: an input-output model. Econ Policy Energy Environ 2022;2(2022):193–217. https://doi.org/10.3280/EFE2022-002009.
[38] Lehr U, Mönnig A, Missaoui R, Marrouki S, Salem GB. Energy Procedia 2016;93:223–8. https://doi.org/10.1016/j.egypro.2016.07.174.
[39] Woollacott J, Henry CL, de Hernández AB, DiVenanzo L, Oliveira H, Cai Y, et al. Energy Econ 2023;125:106810. https://doi.org/10.1016/j.eneco.2023.106810.
[40] Siala K, de La Rúa C, Lechón Y, Hamacher T. Energ Strat Rev 2019;26:100391. https://doi.org/10.1016/j.esr.2019.100391.
[41] Černý M, Bruckner M, Weinzettel J, Wiebe K, Kimmich C, Kerschner C, et al. Ecol Econ 2024;216:108014. https://doi.org/10.1016/j.ecolecon.2023.108014.
[42] Miller RE, Blair PD. Input-output analysis: Foundations and extensions. Cambridge: Cambridge University Press; 2022.
[43] OECD, OECD Inter-Country Input-Output Database **2023**, http://oe.cd/icio, accessed 2 February 2024.
[44] OECD, Trade in Value Added (TiVA) Database **2023**, https://www.oecd.org/industry/ind/measuring-trade-in-value-added.htm, accessed 2 February 2024.
[45] Leontief WW. Rev Econ Stat 1936;18(3):105. https://doi.org/10.2307/1927837.
[46] Ghosh A. Economica 1958;25(97):58. https://doi.org/10.2307/2550694.
[47] Müller VP, Riemer M, Eckstein J. Are Carbon-Based E-Fuels a Viable Path to Decarbonization?-A Critical Comparison of Global Supply and Demand. In: 2024 20th International Conference on the European Energy Market (EEM). IEEE; 2024. p. 1–7. https://doi.org/10.1109/EEM60825.2024.10608862.
[48] Mohamed AM, Economou IG, Bicer Y. Curr Opin Green Sustain Chem 2024;49:100947. https://doi.org/10.1016/j.cogsc.2024.100947.
[49] Hassan NS, Jalil AA, Rajendran S, Khusnun NF, Bahari MB, Johari A, et al. Int J Hydrogen Energy 2024;52:420–41. https://doi.org/10.1016/j.ijhydene.2023.09.068.
[50] Sillman J, Havukainen J, Alfasfos R, Elyasi N, Lilja M, Ruuskanen V, et al. Appl Energy 2024;359:122772. https://doi.org/10.1016/j.apenergy.2024.122772.
[51] Fraunhofer IEE, Global PtX Atlas | Fraunhofer IEE **2023**, https://maps.iee.fraunhofer.de/ptx-atlas/, accessed 26 January 2024.
[52] Pfennig M, Böttger D, Häckner B, Geiger D, Zink C, Bisevic A, et al. Appl Energy 2023;347:121289. https://doi.org/10.1016/j.apenergy.2023.121289.
[53] International Renewable Energy Agency Renewable Power Generation Costs in 2022 2023.
[54] Moritz M, Schönfisch M, Schulte S. Int J Hydrogen Energy 2023;48(25):9139–54. https://doi.org/10.1016/j.ijhydene.2022.12.046.

[55] The World Bank, World Development Indicators **2024**, https://databank.worldbank.org/source/world-development-indicators/preview/on, accessed 15 April 2024.
[56] Tyler Stehly PD. 2021 Cost Wind Energ Rev 2022.
[57] Holst M, Aschbrenner S, Smolinka T, Voglstätter C, Grimm G. Cost forecast for low-temperature electrolysis-technology driven bottom-up prognosis for PEM and alkaline water electrolysis systems. Fraunhofer Institute for Solar Energy Systems ISE: Freiburg, Germany 2021.
[58] Garrett-Peltier H. Creating a clean-energy economy: How investments in renewable energy and energy efficiency can create jobs in a sustainable economy. Saarbrücken: LAP Lambert Academic Publishing; 2011.
[59] Black Veatch Cost and Performance Data for Power Generation Technologies 2012.
[60] Rouwenhorst KHR, Lefferts L. Catalysts 2020;10(9):999. https://doi.org/10.3390/catal10090999.
[61] Arnaiz del Pozo C, Cloete S. Energ Conver Manage 2022;255:115312. https://doi.org/10.1016/j.enconman.2022.115312.
[62] Danish Energy Agency, Energienet, *Technology Data - Renewable fuels,* 0011th ed. **2023**.
[63] OECD, HS to ISIC to End-use conversion key, https://www.oecd.org/sti/ind/ConversionKeyBTDIxE4PUB.xlsx.
[64] Lambert RJ, Silva PP. Renew Sustain Energy Rev 2012;16(7):4667–74. https://doi.org/10.1016/j.rser.2012.03.072.
[65] Meyer I, Sommer MW. Int J Sustain Dev 2016;19(3):217–45.
[66] Hasanov FJ, Mikayilov JI, Javid M, Al-Rasasi M, Joutz F, Alabdullah MB. Appl Econ 2021;53(45):5267–80. https://doi.org/10.1080/00036846.2021.1922590.
[67] Al-Sinan MA, Bubshait AA. Univ J Manag 2021;9(5):129–39. https://doi.org/10.13189/ujm.2021.090501.
[68] Müller VP, Eichhammer W. Renew Sustain Energy Rev 2023;182:113304. https://doi.org/10.1016/j.rser.2023.113304.
[69] International Energy Agency, *Special Report on Solar PV Global Supply Chains* **2022**.
[70] thyssenkrupp AG, *One of the largest green hydrogen projects in the world: thyssenkrupp signs contract to install over 2GW electrolysis plant for Air Products in NEOM* **2021**.
[71] Müller VP, Zheng L. Can Success be Planned? - China’s Path to Technology Leadership in Green Electricity and Hydrogen and its Implications for Europe and the United States. In: 2024 20th International Conference on the European Energy Market (EEM). IEEE; 2024. p. 1–8. https://doi.org/10.1109/EEM60825.2024.10608492.
[72] Akhtar MS, Khan H, Liu JJ, Na J. J Clean Prod 2023;395:136438. https://doi.org/10.1016/j.jclepro.2023.136438.
[73] Kingdom of Saudi Arabia, *Vision 2030* **2016**.
[74] Public Investment Fund, *PIF strengthens renewable energy localization in Saudi Arabia with three new joint ventures* **2024**.
[75] Müller VP, Besler M. Can green hydrogen drive economic transformation in Saudi Arabia? - An input-output analysis of different Power-to-X configurations. Supplementary Data (v1.0.0) [Data set]. Zenodo 2024. https://doi.org/10.5281/zenodo.13385870.