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Industrial planning with input-output models: empirical evidence from low-carbon hydrogen in France

Raphael Guionie^{1,2}, Rodica Loisel¹, Lionel Lemiale¹, Mathias Guerineau¹

Abstract

Energy industry represents roughly 2% of the GDP in energy importing countries ([France, 2019](#)). Yet any energy shock can lead to massive disruptions in the economy, since some energy vectors have features of General Purpose Technology and Source (Noce, 2015). We use input-output models to assess impacts on the French economy from substitution of imported natural gas with domestic low-carbon hydrogen. A new sector producing hydrogen is introduced to supply petroleum refining and ammonia sectors, based on domestic inputs exclusively. Two input-output models are built, a demand-driven model for the emergence of the H₂ sector (investment phase), and a mixed model for H₂ production (operating phase). Results show that the energy shock (350 kt of low-carbon H₂ per year) generates significant growth (1 bln€ of GDP) and jobs (12,000), but needs ambitious planning for industrial development. Firstly, the investment phase triggers industries such as machinery and equipment, electrical equipment, construction and metal products manufacturing, suggesting that massive needs for labor requires more attractiveness to make the hydrogen infrastructure effective. Secondly, the hydrogen production being electricity intensive, the model shows very sensitive to this input and to the availability of power plants. At even higher shocks to remove all grey hydrogen in industry (415 kt H₂) and steel production (700 kt H₂), impressive domestic resources are required along with massive energy planning similar to the French nuclear program over 80s.

Keywords: input-output, linkages, BLI, FLI, gas imports, domestic hydrogen

¹ Nantes Université, LEMNA, F-44000 Nantes, France.

² Corresponding author: raphael.guionie@gmail.com.

1. Introduction

Achieving global carbon neutrality will require removing fossil fuels and developing low-carbon energy sources, on the supply-side, and improving process efficiency and decreasing energy consumption through sobriety, on the demand-side (IPCC, 2022). Studies dedicated to energy at macro-economic level, point out the complex relationships that exist among sectors, as any sector implicitly produces or consumes energy (Blackburn & Moreno-Cruz, 2021). This paper deals with the energy security within the decarbonation strategy and builds two input-output models to highlight inter-industrial relationships (Leontief, 1936), that further supports industrial planning to substitute grey hydrogen with domestic low-carbon hydrogen.

Hydrogen has recently gained interest worldwide, as a key fuel of the energy transition in support to massive decarbonation of transport, industry, heat and power sectors (Ball & Weeda, 2015; Brandon & Kurban, 2017; Maggio et al. 2019). By 2050, the low-carbon H₂ demand is estimated at some 500 million tons (IEA, 2021 [1]). In Europe, the share of H₂ in the energy mix is projected to increase at 14% by 2050, from the current 2% (EC, 2020). At a country level, a set of national roadmaps include hydrogen in support to decarbonation (Germany, United Kingdom, Russia, Australia, Korea, United States, etc). Similarly, the French government has enacted a low-carbon hydrogen Plan within a more global strategy of carbon neutrality by 2050 (Ministry of Ecological Transition, 2020; NHS, 2020).

This paper develops a methodology to study the deployment of hydrogen in France, based on projections of the national transmission system operator, of 35 TWh H₂ in 2050 (RTE [2], 2021). Large uncertainties still remain whereas the H₂ production potential is enough to meet the domestic demand and about the origin of the H₂ infrastructure, hence this research depicts the factors needed to the emergence of a large-scale hydrogen ecosystem. The goal is to replace the current grey hydrogen produced with fossil-fuels, with green and yellow hydrogen produced with renewable energies and with nuclear-dominated electricity from the grid.

The paper describes the inter-industrial linkages by means of conventional indicators of input-output model, such as the output multipliers and backward and forward linkage indexes, which further contribute to assess industrial needs of hydrogen ecosystems. We simulate a complete substitution between grey and low-carbon hydrogen consumed by two industries, “Coke and refined petroleum products” (for oil refining) and “Chemicals and chemical products” (for ammonia production)³. We design a domestic low-carbon hydrogen sector in two stages. The first one simulates the integration of a new hydrogen sector via a classical input-output modeling (demand driven). The second one assesses the impact of the new hydrogen sector operation using a mixed input-output model (exogenous production). Global indicators (GDP, H₂ volumes and costs) ultimately give an overview the hydrogen sector development.

The remaining structure of the paper is organized as follows. Section 2 provides a literature review of input-output theory and models applied to hydrogen development. Section 3 describes the mathematical formulation of the problem and calibrates the economic system crossed with energy flows and values. Section 4 discusses simulation results on model performances of the case study. Section 5 concludes with some policy recommendations for industrial planning and opens work perspective.

2. Literature review

Input-output (IO) models are linear models suited to characterize interactions among all sectors in an economy (Miller & Blair, 2009). The IO model has been developed first by Leontief (1936, 1941) and is still widely used to analyze the impact of economic policies and shocks of demand and price variations, etc.

³ We refer to the net consumption of hydrogen, i.e. excluding co-production.

IO method has been rapidly extended to the environmental field.

In the water sector, Velázquez (2006) examines the water management and highlights the sectors mostly consuming the resource in Andalusia. Llop (2013) proposes an IO method to assess the water allocation in response to changes in the final demand under the constraint of technical water needs in Catalonia. In Northeast China, an integrated framework with input-output analysis evaluates the water use and risks from virtual flows (Zhang et al., 2020).

In the agriculture sector, pioneers such as Heady & Schnittker (1957) apply a basic model to describe and predict interrelations between agriculture and the others sectors of the economy. Similar analysis are later performed by Johnson & Kulshreshtha (1982) for the Canadian region Saskatchewan, and more recently, by Heringa et al. (2013) for a Dutch region with a multifunctional agriculture concept. Loizou et al. (2019) use also IO analysis to examine the interconnections of agriculture with the other sectors and show the importance of agriculture in promoting an integrated development in regional rural economy.

In the field of greenhouse gas emissions, Alcántara & Padilla (2009) develop an IO model to study the CO₂ emissions of service sector in Spain. Lixon et al. (2008) assess the economic impacts for Canada by decreasing industrial output to reduce greenhouse gas emissions to a level consistent with the Kyoto protocol. At a global level, Hertwich & Wood (2018) conduct an input-output analysis to investigate the indirect carbon dioxide emissions for the economy. Liu et al. (2018) provide an environment extended IO simulation to study the industrial greenhouse gas mitigation policies. In order to find the most effective reduction pathway, they estimate the impacts of different mitigation policies on several industries in the socio-economic system. In China, Wei et al. (2022) examine the households' footprint with a multi-regional input-output model over the period 1995-2019.

In the energy field, Hans et al. (2004) perform an IO analysis to investigate the role of the power sector in Korea. Liang et al. (2010) build an energy input-output model to study the energy metabolism in China. In Italy, Cellura et al. (2013) assess national sustainable production and consumption strategies through IO analysis. Llope (2020) has a different approach by evaluating the role energy import price in an IO price model.

There are only a few studies of input-output models applied to hydrogen. The majority of studies dedicated to hydrogen use computable general equilibrium models to assess the viability of hydrogen investment or to forecast hydrogen development within a net zero national objective. See Lee (2014) for Japan, Lee (2012) and Lee et al. (2009) for Taiwan, Jokisch & Mennel (2009) for European Union, Bae & Cho (2010) for Korea, Silva et al (2014) for Portugal and more recently Espegren et al. (2021) for Norway.

Most of the studies built on hydrogen input-output models focus on the transport sectors. Wietschel & Seydel (2007) identify shifts in employment due to hydrogen development in Europe with focus on fuel cell vehicles. Chun et al. (2014) make an input-output analysis for hydrogen deployment in Korea. Yet only a few studies are dedicated to hydrogen and to electrolysis infrastructure. See for instance Lee et al. (2011) and Lee & Chiu (2012) showing that investment in biohydrogen should have priority over investment in hydrogen infrastructure.

3. Methodology

We build a two-stage input-output model (IOM). The first model is a demand-driven IOM aiming for capturing the economic consequences of the emergence of domestic low-carbon hydrogen sector, i.e. based on water electrolysis with low-carbon electricity (from renewables and nuclear). The second model is a mixed IOM which assesses the economic impacts of the H₂ sector once the infrastructure is fully operational. The method follows a gradual procedure described at **Fig. 1**.

Data and assumptions. French Symmetric Input-Output Table (IOT) with 64 products/sectors is extracted from Eurostat⁴ for the year 2018. The database is next harmonized, yet the original subdivision holds (64 products/sectors). Economic data is crossed with energy data on gas imports, expressed in both volume and price, as issued from the French energy balance in 2018 (Ministry of Ecological Transition, 2021). A database on employment is also depicted, based on the census of population of the French National Institute of Statistics and Economic Studies in 2018 (INSEE).

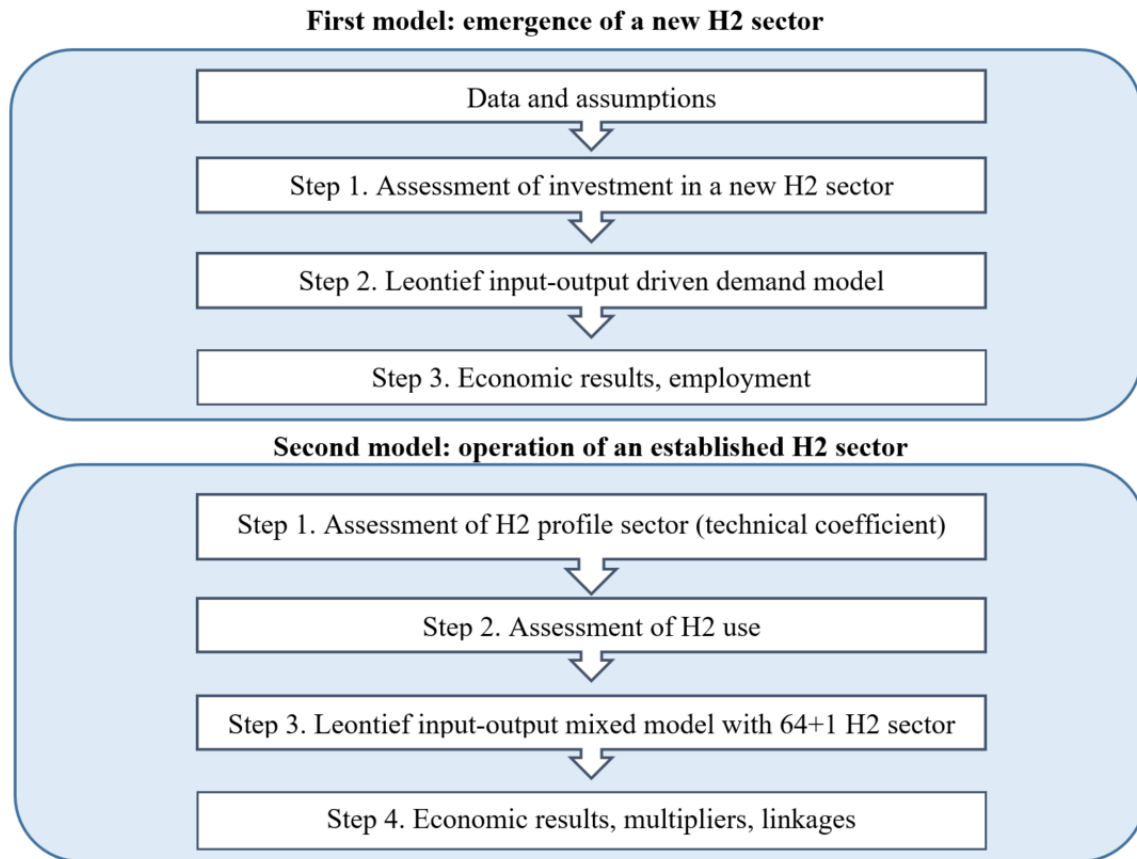


Fig. 1. Methodology flow chart

We focus on two major sectors traditionally using grey hydrogen: oil refining and ammonia production. In the Eurostat Input-Output Table, these activities are grouped as “Coke and refined petroleum products” (CRP) and “Chemicals and chemical products” (CC) respectively (Eurostat, 2008). Based on estimations of RTE ([2], 2022), in 2019 these sectors consume 350 kt of H₂ (refining 130 kt H₂; ammonia 220 kt H₂). In our model, the two sectors will consume domestic low-carbon (obtained through electrolysis with alkaline technology), instead of grey hydrogen from imported natural gas (obtained through steam reforming process). These sectors are selected based on national low-carbon hydrogen targets set by the French National Low-Carbon Strategy (Ministry of Ecological Transition, 2020).

I-O demand-driven model (H₂ investment phase)

Before H₂ production, there is the infrastructure construction stage, implying that H₂ sector receives investment for facility building. In the IO model, these investments are part of the final demand, therefore they are modeled as additional final demand. As part of the methodology specific to demand-driven IOM, we describe the demand at the level of sectors that specifically require new inputs (Step 1), the new product and sector technical coefficients from the demand shock (Step 2) and the indicators that describe impacts of the shock (Step 3).

⁴ http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=naio_10_cp1700&lang=fr

Step 1. Assessment of investment in a new H2 sector

The new low-carbon hydrogen is used by two sectors, yet all sectors contribute to H2 infrastructure building (see Fig. 2 for the breakdown of the sector contribution). Investments in H2 infrastructure essentially rely on electrolysers (including stacks), power for building and systems for hydrogen processing and cooling and water circulation. Note that storage, if any, belongs to those industries consuming hydrogen, thus not included in the H2 sector; and that the existing H2 compression facilities used for grey hydrogen are also employed for the new low-carbon hydrogen (IRENA, 2020; Lee, 2014; Wietschel & Seydel, 2007).

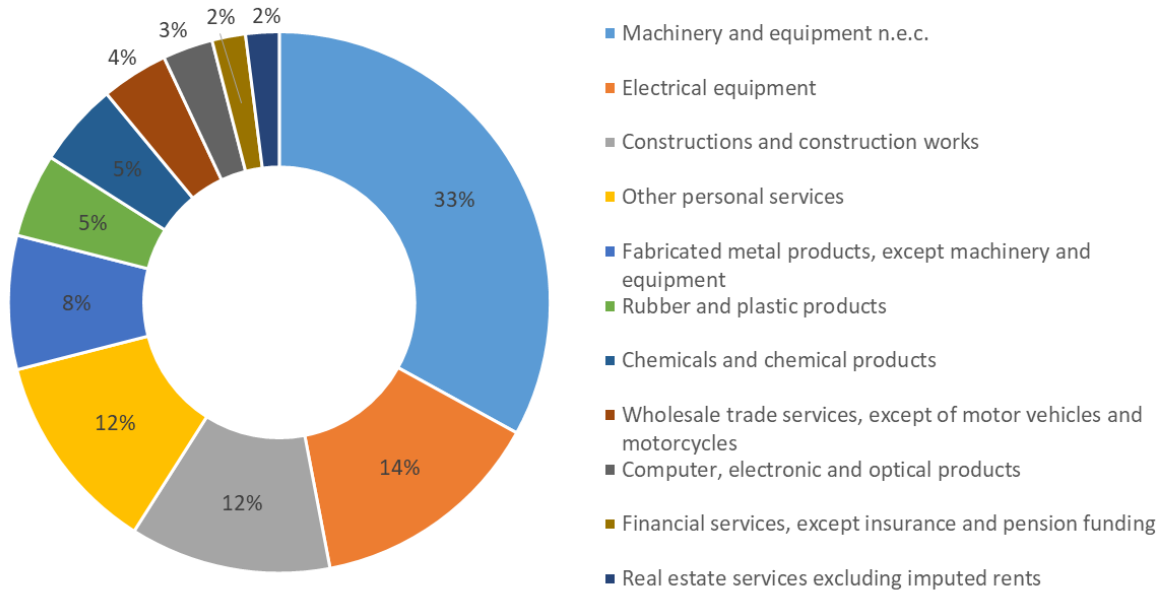


Fig. 2. Sectoral view of investment in H2 sector

Reading: “Electrical equipment” being 14% of the total new investment means that for 1€ invested in the H2 infrastructure, the final demand (or investment) in the “Electrical equipment” sector represents 0.14 €.

Step 2. Leontief input-output driven-demand model

We define Z the matrix of intermediate consumption, f the final demand vector and x the production vector, as follows:

$$x = Zx + f \quad (1)$$

with $z_{i,j}$ the intermediate consumptions of product i by sector j in matrix Z , f_i the final demand of product i and x_i the output of sector i .

We calculate the matrix of technical coefficients A . This matrix is composed of $a_{i,j}$ showing the proportion of input i consumed by sector j ($z_{i,j}$) needed to produce one product of sector j (x_j) with the following equation:

$$a_{i,j} = \frac{z_{i,j}}{x_j} \quad (2)$$

Equation (1) can be rewritten as follows:

$$x = Ax + f \quad (3)$$

$$(I - A)x = f \quad (4)$$

$$x = (I - A)^{-1}f \quad (5)^5$$

$$x = Lf \quad (6)$$

With I a unit matrix of dimension i .

$(I - A)^{-1}$ matrix is the Leontief matrix, denoted L . It is composed of $l_{i,j}$, which measures the effect of a one euro change in final demand of product i for domestic production in sector j .

From equation (6), any effect on global output from variation of final demand is computed as follows:

$$\Delta x = L\Delta f \quad (7)$$

Step 3. Assessment indicators

We estimate results with traditional indicators, i.e. the gross domestic product (GDP), national output and employment, in both absolute and relative terms. The GPD is calculated using the sum of value added, plus taxes, minus subsidies, and employment is depicted using the INSEE database and relevant multipliers. The impact is measured in terms of new jobs generated by the new low-carbon demand by sector (matrix LCL).

We build the diagonalized matrix (LC) of dimension i , as follows:

$$LC = \hat{E}\hat{X}^{-1} \quad (8)$$

With \hat{E} the diagonalized matrix of jobs of dimension (n, n) and \hat{X}^{-1} the diagonalized matrix of dimension (n, n) and composed by $\frac{1}{x_j}$.

employment (e) composed of e_i the number of jobs in sector i , and output (x) composed of x_i the output of sector i .

Next the matrix of employment LCL is composed of elements $lcl_{i,j}$:

$$LCL = LC.L \quad (9)$$

Each element $lcl_{i,j}$ measures the effect on employment of any euro variation in the final demand of product i in sector j . Hence, we can assess how many jobs will be created by a final demand shock. Note that number of jobs include both full and partial-time types of employment.

I-O mixed model (H2 operating phase)

Hydrogen is obtained with alkaline electrolyzers by using electricity from the national grid, and by assumption, no additional power generation capacity (wind turbine, solar farms or nuclear power) is considered for this new power demand for H2. Methodologically, we assess the technical coefficients of low-carbon H2 sector (Step 1), the new coefficients in industries consuming H2 (Step 2) that will mix to form a new IO table and model (Step 3) and will be analyzed by means of multipliers and linkage indices (Step 4).

Step 1. Assessment of H2 profile sector (technical coefficients)

A new sector/product named “low-carbon hydrogen” (H2) is added to the I-O table to substitute the grey hydrogen in two sectors (CRP and CC). All intermediate consumptions of the H2 sector being domestically produced, they need to be identified into the I-O table. Firstly, their specific share is obtained by braking down operational expenditure (OPEX) into the main categories of inputs to H2 production, such as electricity, labor, maintenance and other costs (see Table 1).

Type of input	Cost	Source
Electricity	60 €/MWh	IEA (2019) ; Lee et al. (2021) ;
Maintenance	2% of CAPEX	

⁵ Because A is the Leontief matrix, we can consider it as a productive matrix. Hence for any $x \geq 0$, equation (5) has a nonnegative solution. Matrix $(I - A)$ is then invertible.

Labor	0.03% of CAPEX	Nordio et al. (2021)
Other	1.5% of CAPEX	

Table 1. OPEX costs breakdown in the H2 sector

Each OPEX cost type is associated to the relevant sector in the input-output table such as to obtain the intermediate consumption and technical coefficients (see Table 2).

Type of inputs	Supplying sector in input-output table	Technical coefficient
Electricity	Electricity, gas, steam and air conditioning	0.9466
Maintenance	Machinery and equipment n.e.c.	0.0281
Others	Electrical equipment	0.0211
Labor	Value added	0.0042

Table 2. H2 sector's input origin

Step 2. H2 use and changes in technical coefficients in consuming industries

The two sectors (CRP and CC) replace grey hydrogen with low-carbon hydrogen, which represents 350 kt H2 per year (130 kt of H2 in the CRP sector and 220 kt in CC). We estimate that this substitution might occur as soon as the H2 sector becomes operational, i.e. around the year 2030. The new intermediate consumption will generate new technical coefficients in the two sectors, in replacement to steam reforming activities using natural gas. New low-carbon H2 production is next compensated by removing the equivalent import natural gas (the row "Use of imported product"), while accounting for similar efficiency rate of 70% of steam reforming process and alkaline electrolyser (Nikolaidis & Poullikkas, 2017; Staffell et al., 2018; Ishaq et al., 2022). This ensures the equilibrium of the new IO table (IOT2).

Step 3. Leontief input-output mixed model with 64+1 H2 sector

The new input-output table (IOT2) has 65 sectors made of 64 initial sectors and the new H2 sector. The substitution of grey hydrogen in the CC and CRP sectors gives the need of hydrogen which represents an exogenous demand for the hydrogen sector, thus setting exogenously the output level of H2. Note that in a standard open demand model (Leontief model), the direct and indirect output effects of an economy are determined by exogenous final demand. Yet at exogenous production, we use mixed input-output model with the output-to-output multipliers, based on Miller & Blair (2009). Output-to-output (OTO) multipliers give the same results as mixed input-output model when only one production is exogenous, but they are easier to use. They are obtained from Leontief multipliers, hence previous equations (1) and (2) are rewritten to get a technical coefficient matrix, denoted A' . We define v and m the value added vector and imported input vector respectively, in order to get the associated technical coefficient vector a'^v and a'^m respectively composed of a'^v_j and a'^m_j computed as follow:

$$a'^v_j = \frac{v_j}{x_j} \quad (10)$$

$$a'^m_j = \frac{m_j}{x_j} \quad (11)$$

where a'^v_j is the proportion of value added in the production of sector j and a'^m_j is the proportion of imported input j in production of sector j .

Technical coefficients of H2 sector ($a'_{i,h2}$) build on the OPEX breakdown coefficients described at step 1. For further identification, two elements of A' ($a'_{h2,CRP}$ and $a'_{h2,CC}$) are set according to the new low-carbon hydrogen inputs (depending of H2 output), and two elements of a'^m (a'^m_{CRP} and a'^m_{CC}) are calculated to keep equilibrium in the IOT as mentioned at step 2 (domestic hydrogen is added, fossil gas in subtracted).

The new Leontief matrix is obtained with initial equations (3), (4), (5) and (6), and denoted L' . The matrix L' allow us to compute OTO multipliers and build the related matrix O made of $o_{i,j}$ elements as follows:

$$o_{i,j} = \frac{v_{i,j}}{v_{j,j}} \quad (12)$$

Each $o_{i,j}$ element is a production multiplier resulting from production variation. They indicate the change in the output i to one euro change in the output of industry j . The matrix O allows to compute the production needed in all sectors of the economy for a given output of H2.

We define p a column vector made of elements p_j , where all elements are zero except for $j = H2$ that is equal to the given level of production of H2. Hence p_j is always equal to 0 except for p_{H2} which is equal to the production shock. The new production vector x' is generated by this production shock as follows:

$$x' = O \cdot p \quad (13)$$

Based on x' and equations (3), (10) and (11) we can find new values of the intermediate consumption, value added and imports to further evaluate the impacts of the production shock.

Step 4. Results analysis and multipliers

By means of the Leontief and OTO approach, we calculate multipliers and linkage indices to depict the way the sectors are connected.

Output to output multipliers are direct and indirect cumulated impacts of a production change in the exogenous branch on the overall economy. The algebraic expression of the output to output multiplier for sector j is:

$$oto_j = \sum_{i=1}^n o_{i,j} \quad (14)$$

Backward linkages measures the increase of activity in a specific sector on all the others sectors. It means that an increase in the output of a specific sector will increase the input demands of other sectors. We use a normalized version of this linkage to compare H2 sector with others sectors of the economy. The normalized backward linkage (BLI) for sector j is calculated as follows:

$$bli_j = \frac{bli_j}{\left(\frac{1}{n}\right) \sum_{i=1}^n bli_j} \quad (15)$$

$$bli_j = \sum_{i=1}^n oto_{ij} \quad (16)$$

Sectors with above-average BLI have indexes greater than 1 and sectors with weaker than average BLI have indices below 1.

FLI measures how likely it is that another sector will use a specific sector's output as an input (Hirschman, 1958). As FLI from Leontief IOM have been criticized (Jones, 1976, Cai & Leung, 2004), Gosh model (1968) is often preferred to Leontief's for calculating downstream links because it analyzes the impact of industries on the economy through supply-side. Hence we calculate the Gosh invert matrix G :

$$G = (I - B)^{-1} \quad (17)$$

With B matrix of output coefficient. This matrix is composed by $b_{i,j}$ the share of the production of j that is delivered to enter the production process of product i :

$$b_{i,j} = \frac{z_{i,j}}{x_i} \quad (18)$$

We use a normalized version of this linkage to compare H2 sector with others sectors of the economy.

The normalized forward linkage (FLI) for sector j is calculated as follows:

$$fli_j = \frac{fli_j}{\left(\frac{1}{n}\right) \sum_{i=1}^n fli_j} \quad (19)$$

$$\text{With } fli_j = \sum_{i=1}^n g_{ij} \quad (20)$$

Sectors with above-average FLI have indexes greater than 1 and sectors with weaker than average FLI have indices below 1.

4. Results

4.1. H2 investment phase (I-O demand-driven model)

Substitution of grey hydrogen in CRP and CC sectors requires 350 kt of low-carbon hydrogen per year and about 2.1 GW of electrolyzers operating at efficiency rate of 70% and load factor of 93% (RTE [3], 2020). At cost assumptions of 700 k€/MW [500-900] (Saba et al. 2018; IEA, 2021 [2]; IRENA, 2020 [2]), we further calibrate shocks of fixed H2 demand and investment needs.

Main results are summarized at **Table 3**. As direct aggregated effects, investing 1.47 Bln€ in H2 production generates 2.5 Bln€ of revenues and 12,045 of jobs, and has an added value of 1 Bln€. Yet as the investment phase is longer than one statistical year, the results are obtained over the entire investment period, which besides the duration of construction, should cover human capital training and new ecosystem establishment for the hydrogen industry to emerge, i.e. from three years to at least five years.

Final demand shock (M€)	GDP (M€)	Output (M€)	Employment (number of jobs)
1 470 [1 050 - 1 890]	1 047 [748 - 1 346]	2 452 [1 753 - 3 151]	12 045 [8 608 - 15 481]

Table 3. Aggregated results with upper and lower bounds in brackets function of the electrolyser costs (700 k€/MW [500-900]).

Fig. 3 shows the impact of the shock on sectors contributing to the investment in electrolyzers, subject to investment assumptions made at Fig.2, with lower and upper bounds function of the cost of electrolyzers (700 k€/MW [500-900]).

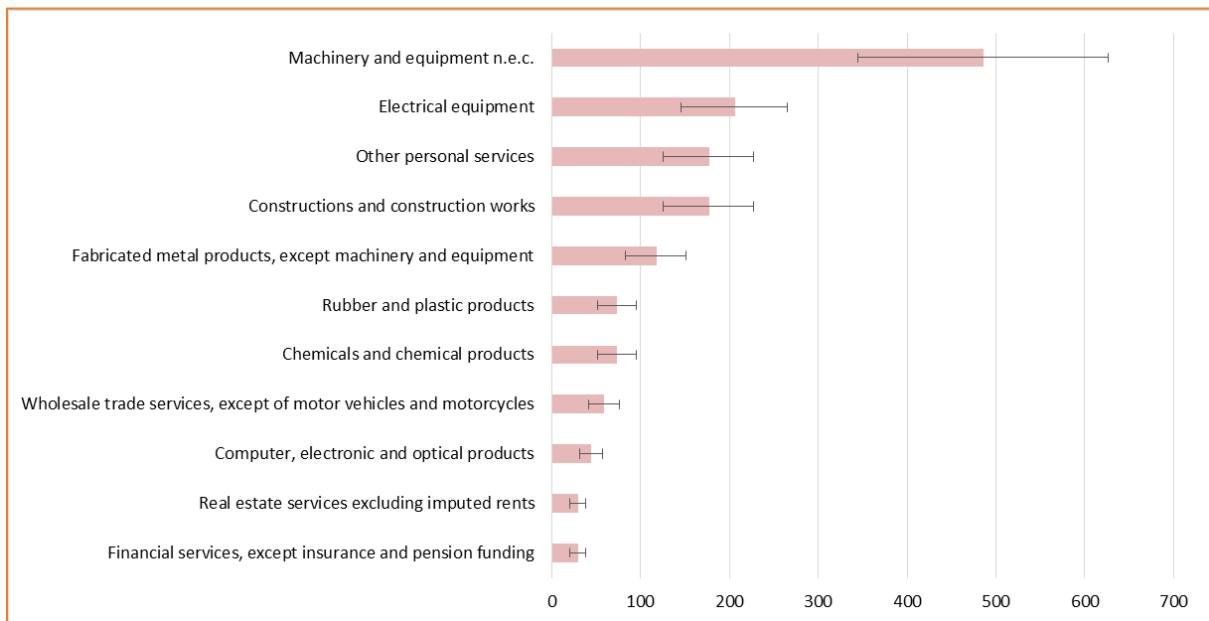


Figure 3. Final demand shock distribution by sector (M€)

The 20 sectors that mostly contributed to the GDP during the investment period are shown at **Fig. 4**, while those with the highest output are shown at **Fig. 5**. Results embed all initial, direct and indirect effects. More precisely, sectors affected by the shock increase their output (initial effect), and in this way they stimulate their suppliers' production (direct effect) and their suppliers as well etc. (indirect effect). Indirect effects are the main difference in ranking among **Fig. 3**, **Fig. 4** and **Fig. 5**. Note that results at **Fig. 3** show that the shock of demand is equivalent to the initial effect. **Fig. 4** and **Fig. 5** capture

the spillovers effects of this shock. As expected, main contributors to the GDP and to the aggregated output are industry-related sectors (machinery and equipment, construction, electrical equipment, fabricated metal product etc.).

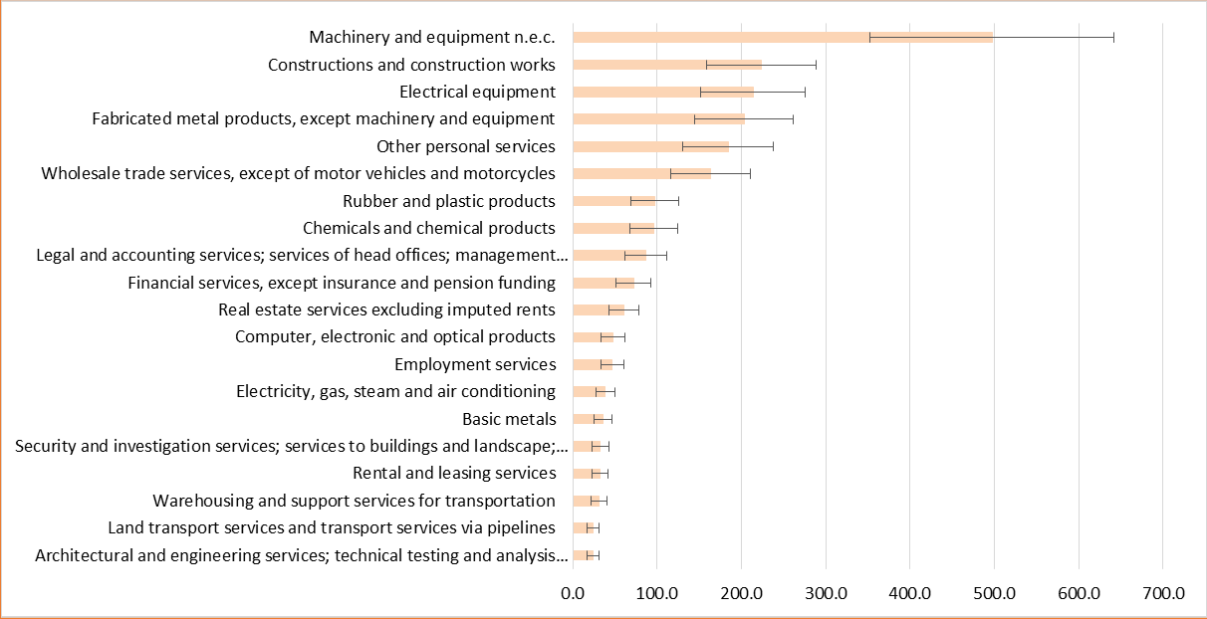


Figure 4. Output generated by sector (M€)

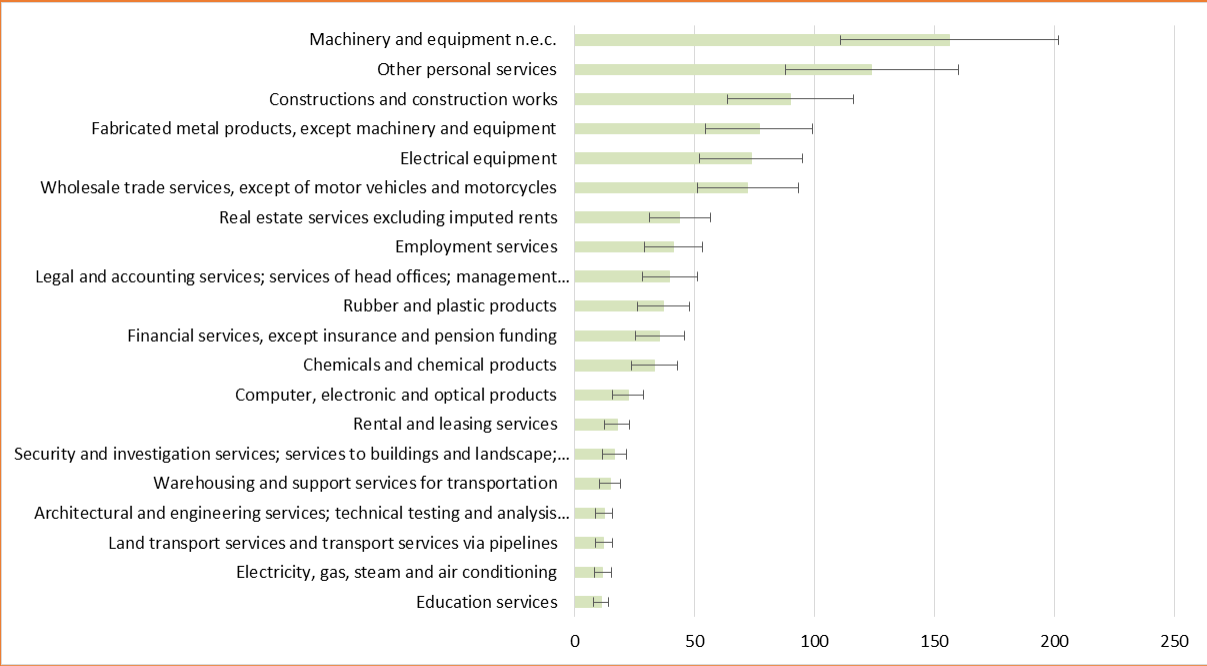


Figure 5. GDP generated by sector (M€)

Fig. 6 presents the number of jobs created, both part time and full time, over the investment phase, and embeds also all initial, direct and indirect effects. As expected, jobs creation is the highest in sectors related to the industry, i.e. the five sectors with largest effects are industries such as machinery and equipment, fabricated metal products, electrical equipment and construction, followed by services (other personal services). This finding suggests that in order to successfully establish a domestic H2 sector, a national policy may be needed to attract workers, as generally these jobs have a poor public image, difficult working conditions and relatively low wages.

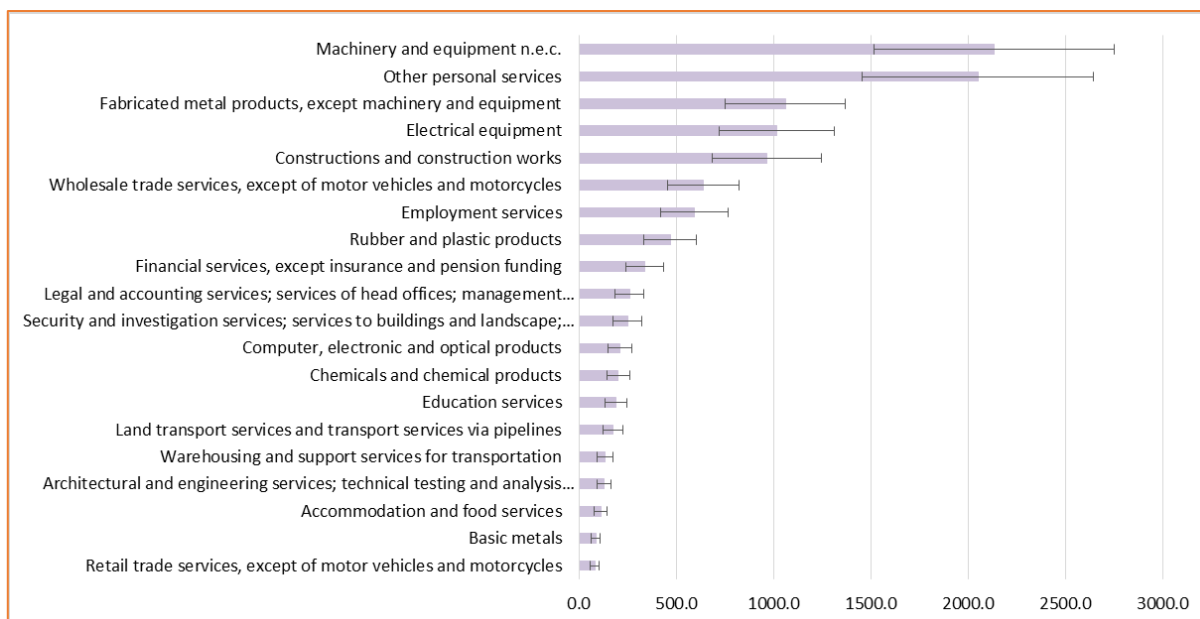


Figure 6. Job creation by sector

4.2. H2 operating stage (I-O mixed model)

The shock applied to the initial demand-driven model of 1,470 M€ as CAPEX investment has built the H2 infrastructure that becomes operational at this stage. The current shock consists of a yearly exogenous production of 350 kt H2 (or 16.5 TWh) that needs to be expressed in value following the IO design in monetary value. This value sums up the costs of all inputs entering the H2 production as OPEX. **Table 4** breaks down the cost of H2 production by input type, and these costs trigger next the supplying sectors (column *Shock by input*). In contrast with previous results displayed over several years, the outcomes obtained within this operational stage are yearly results which are expected, while admitting, all things equal in between, that no other change occurs in the economy.

Type of input	Cost per unit (assumptions)	Cost (M€) / Shock by input
Electricity	60€/MWh	990
Labor	0.3% of CAPEX·yr	4
Maintenance	2% of CAPEX·yr	29
Other costs	1.5% of CAPEX·yr	22
Total costs	-	1046

Table 4. OPEX breakdown by input type

Production shock at **Table 4** mixed with the second model, allows estimating aggregated impact indicators presented at **Table 5**, along with multipliers at **Tables 6, 7, 8 and 9**. **Table 5** indicates a GDP of 721 M€ and a total output (H2 plus inputs) of 3,2 Bln€, mostly from the electricity sector since hydrogen produced by electrolysis is electricity intensive. The shock reduces gas imports (16.5 TWh or 3% of total gas imports) and the energy bill (1.1 Bln € evaluated at 68 €/MWh). Beyond numbers, the outcome generated by the H2 sector embeds positive externalities such as the advantage of creating a domestic business environment with local and not relocatable assets where all maintenance jobs are domestic; and also reduces dependence on gas from other countries and improves the balance of trade.

Sector	Production shock (M€)	GDP (M€)	Output (M€)	Decrease in gas import (M€, TWh)
H2 sector	1046	5	1140	1 130 16.5
National economy	-	721	3165	

Table 5. Sector impacts and aggregated results

To understand the new overall picture of the economy, **Table 6** shows the output-to-output multipliers for 20 sectors, ranked in descending order. An output-to-output multiplier shows the variation of the total output produced by all industries in response to one euro increase in a given sector. Each sector shows in this way the contribution to the economy to one euro increase in its own output. In this new economy, the H2 sector ranks first, with an output multiplier of 3.026, which means that an increase in the H2 production with 1 € generates 3.026 € of output value in the whole economy, split between 1 € as H2 output (initial effect) and 2.026 € as direct and indirect effects. The other sectors keep their initial OTO multipliers, except for CRP and CC sectors that modify their coefficients. The first rank that H2 holds is partly due to its specific activity focused on one good, hence not mixed with other energy vectors. This concentrates the impact on the economy by spreading the shock of one euro variation on a limited number of sectors supplying its inputs. Moreover, the specificity of H2 is that all intermediate inputs should be supplied domestically, which triggers therefore local sectors and inflates the domestic bubble of all sectors multipliers as well.

Sector	Output multiplier	Rank
H2	3.026	1
Water transport services	2.182	2
Insurance, reinsurance and pension funding services, except compulsory social security	2.044	3
Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials	1.774	4
Food, beverages and tobacco products	1.773	5
Basic metals	1.742	6
Other non-metallic mineral products	1.729	7
Mining and quarrying	1.725	8
Paper and paper products	1.706	9
Accommodation and food services	1.697	10
Machinery and equipment n.e.c.	1.691	11
Motion picture, video and television programme production services, sound recording and music publishing; programming and broadcasting services	1.690	12
Fish and other fishing products; aquaculture products; support services to fishing	1.688	13
Motor vehicles, trailers and semi-trailers	1.681	14
Wholesale trade services, except of motor vehicles and motorcycles	1.668	15
Natural water; water treatment and supply services	1.665	16
Services auxiliary to financial services and insurance services	1.655	17
Advertising and market research services	1.629	18
Other professional, scientific and technical services and veterinary services	1.625	19
Printing and recording services	1.623	20

Table 6: Output-to-output multipliers

Table 7 summarizes the sectoral impacts linked to an increase in H2 output for the top 20 sectors, and shows the variation of each sector output due to the variation of one euro of H2 output value. For instance, if H2 sector raises output with 1€, direct and indirect effects make the “Machinery and equipment n.e.c.” sector to increase its production with 0.031€. As expected, the “Electricity, gas, steam and air conditioning” sector returns the highest outcome among all sectors supplying the hydrogen production, partly due to the input intensity and partly to the condition that all H2 inputs are domestically supplied. For the others sectors, the impacts from H2 shock are largely derived from indirect effect and, in general, they remain modest (lower than 0.05).

Interestingly, the sector “Electricity, gas, steam and air conditioning” sector has a low output multiplier, i.e. 1.2 (ranking 62 out of 65), therefore H2 sector strongly stimulates a sector with a low output potential and ultimately has low overall sectoral effects. On the other hand, the electricity sector remains the key supplier to hydrogen produced by electrolysis, and any production drop in this sector could strongly impact the H2 sector itself and, by domino effect, all the sectors that depend on (direct and indirect industries relying on hydrogen-consuming sectors, etc.).

Sector	Total effect	Rank
Electricity, gas, steam and air conditioning	1.621	1
Legal and accounting services; services of head offices; management consultancy services	0.043	2
Wholesale trade services, except of motor vehicles and motorcycles	0.031	3
Machinery and equipment n.e.c.	0.031	4
Electrical equipment	0.023	5
Security and investigation services; services to buildings and landscape; office administrative, office support and other business support services	0.021	6
Chemicals and chemical products	0.021	7
Constructions and construction works	0.021	8
Financial services, except insurance and pension funding	0.016	9
Land transport services and transport services via pipelines	0.015	10
Rental and leasing services	0.015	11
Warehousing and support services for transportation	0.012	12
Fabricated metal products, except machinery and equipment	0.012	13
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery services; remediation services and other waste management services	0.012	14
Education services	0.012	15
Real estate services excluding imputed rents	0.010	16
Computer programming, consultancy and related services; Information services	0.010	17
Employment services	0.009	18
Architectural and engineering services; technical testing and analysis services	0.009	19
Services auxiliary to financial services and insurance services	0.007	20

Table 7: Direct and indirect effect of H2 sector’s output

Beyond the total effect, the shock spread among industries could be understood with backward and forward linkages. **Table 8** returns the Backward Linkage Index (BLI) for the top 20 sectors, ranked in descending order. The BLI measures the potential for an industry to pull the other industries upward through its own intermediate consumption. In other words, an increase in a sector output with high BLI

will lead to a significant increase in the output of the upstream industries. Here, the hydrogen sector ranks again first, which is quite expected as BLI is calculated by means of the output multiplier where H2 sector has shown the highest ranking. This result is thus triggered by the initial condition that H2 is produced with French electricity and that maintenance is operated in France. The level of BLI for H2 sector could be even higher in a scenario where electricity would require additional electricity generation capacity, yet not modelled here.

Sector	BLI	Rank
H2	1.956	1
Water transport services	1.411	2
Insurance, reinsurance and pension funding services, except compulsory social security	1.321	3
Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials	1.147	4
Food, beverages and tobacco products	1.146	5
Basic metals	1.126	6
Other non-metallic mineral products	1.118	7
Mining and quarrying	1.115	8
Paper and paper products	1.103	9
Accommodation and food services	1.097	10
Machinery and equipment n.e.c.	1.093	11
Motion picture, video and television programme production services, sound recording and music publishing; programming and broadcasting services	1.093	12
Fish and other fishing products; aquaculture products; support services to fishing	1.091	13
Motor vehicles, trailers and semi-trailers	1.087	14
Wholesale trade services, except of motor vehicles and motorcycles	1.079	15
Natural water; water treatment and supply services	1.077	16
Services auxiliary to financial services and insurance services	1.070	17
Advertising and market research services	1.053	18
Other professional, scientific and technical services and veterinary services	1.051	19
Printing and recording services	1.049	20

Table 8 : Backward Linkage Index

Table 9 shows forward linkage indices (FLI) for top 20 sectors, which surprisingly does not contain the H2 (ranked 23th), meaning that the demand for H2 is relatively low in the economy. This result is driven by the assumption that hydrogen is used in two sectors only (CRP and CC), as intermediate consumption and not as final demand. However, this average FLI does not mean that H2 sector's output is not a dependant input for downstream industries, since a drop in H2 production could lead to a drop in CRP and CC output that stand at the beginning of the chain of intermediate products crucial for the economy.

Sector	FLI	Rank
Services auxiliary to financial services and insurance services	1.654	1
Printing and recording services	1.621	2
Employment services	1.534	3
Electricity, gas, steam and air conditioning	1.466	4
Legal and accounting services; services of head offices; management consultancy services	1.460	5

Financial services, except insurance and pension funding	1.433	6
Warehousing and support services for transportation	1.420	7
Mining and quarrying	1.407	8
Other professional, scientific and technical services and veterinary services	1.391	9
Security and investigation services; services to buildings and landscape; office administrative, office support and other business support services	1.336	10
Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials	1.325	11
Postal and courier services	1.309	12
Travel agency, tour operator and other reservation services and related services	1.302	13
Rental and leasing services	1.287	14
Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery services; remediation services and other waste management services	1.283	15
Other non-metallic mineral products	1.271	16
Products of forestry, logging and related services	1.234	17
Fabricated metal products, except machinery and equipment	1.224	18
Advertising and market research services	1.222	19
Products of agriculture, hunting and related services	1.201	20
...
H2	1.161	23

Table 9: Direct and indirect effects of H2 sector's output

Mixing all BLI and FLI indicators at **Fig. 7** shows that the H2 sector holds a specific position with very high BLI, and has, interestingly, downstream index concentrated around low levels specific to the supply of only one good (here H2) used in only two sectors (refining and ammonia).

But multipliers and linkages do not correctly take into account the inter-sectoral dependence issue. In a case of a drop in H2 production, most of the economic effects will come from the decrease in the electricity sector (upstream effects) and from CRP and CC sector (downstream effects), limiting thus the effect to direct monetary consequences. Nevertheless, in practice, a drop in H2 means also a decrease in two crucial inputs for the economy: fertilizers (that need ammonia) and gasoline (produced by refining oil). With less fertilizers, crops are less productive, and with less gasoline, the transport sector affects the entire economy. These physical effects are not taken into account by the indicators.

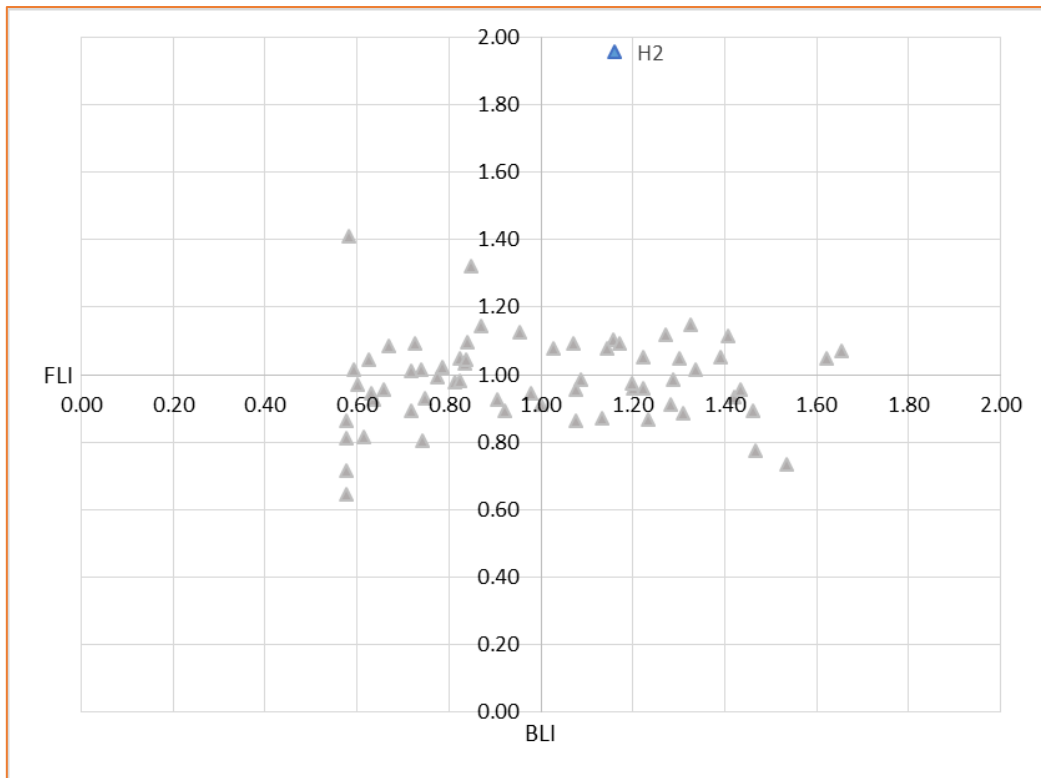


Fig. 7. Backward Linkage Index and Forward Linkage Index for the 65 sectors

5. Conclusions

This paper provided a methodological framework to address the issue of the energy security in France. In line with the national strategy to deploy low-carbon energy vectors, we design an energy policy that removes the grey hydrogen obtained with natural gas and substitutes imports with domestic low-carbon hydrogen. We use input-output model to estimate first the human and material resources needed to build a domestic low-carbon hydrogen sector, and secondly to obtain hydrogen to supply two industries (ammonia production and oil refining). Results show that the H2 construction phase generates significant economic activity (1 bn€ of GDP over 3-5 years of building) and creates jobs (more than 12,000) and that during operation, the H2 sector largely relies on electricity as intermediate input, and generates around 5 M€ of GDP per year.

The use of input-output model allows estimating upstream and downstream industry connections by means of forward and backward linkage indexes. Numerically, producing H2 leads to very high BLI but low FLI, in the sense that H2 strongly stimulates the electricity sector but it is input for two sectors only, with albeit two critical outputs for all the other sectors (gasoline) and for primary goods supply (fertilisers for agriculture). Indirectly, hydrogen proves sensitive for the economic activity, as any drop in the H2 output could significantly impact all the other sectors. Yet despite the sensitivity of the economy to a domestic H2 production, the vulnerability of the economy in front of gas imports initially used to obtain grey hydrogen is reduced, hence the resilience of the system improves.

Two main domestic vulnerabilities are created with our model, one upstream related to the availability of human capital during the construction phase and for H2 infrastructure maintenance, and one downstream related to the dependence of H2 on the electricity supply. Both issues require a high level of industrial planning and anticipation, firstly to make attractive industry for people again and to remove the negative image from the imbalance efforts to wage, in particular in sectors like machine building,

electrical industry, chemicals, and construction. Downstream, the second issue is addressed by the capacity of the electricity sector to address this new demand for H₂ production with electrolysis. This cross-sector dependence has already been highlighted by the French system operator (RTE, 2021), which prevents the demand for H₂ with new nuclear reactors and large capacities of renewable energy plants (scenario N03 Hydrogen high). Absent this massive electricity planning, a slowdown in the development of new power plants could threaten our prospective scenario to sustainably produce domestic low-carbon hydrogen.

Methodologically, input-output models contain intrinsic limitations due to linear calculation, a static representation of impacts of the transition, and exogenous innovation. Yet the model gives useful insights into the role that energy holds in the economy, and the cost-benefit structure from producing domestic sources (electricity) and vectors (hydrogen) that reduce the country energy dependence. As any industrial development, the State intervention is crucial at this stage (Van der Spek et al. 2022) and the French government has already designed massive support initiatives (7 Bln€) and ambitious milestones (10% clean hydrogen for 2023 and 20-40% for 2028; NHS, 2020).

This research opens further work perspective in the field of industrial planning. The infrastructure necessary to build a national industry will be made up of local clusters for H₂ production and transport and distribution for other usages, such as heavy transport. At industry level, various firms can switch to low-carbon hydrogen such as steel production (700 kt H₂/year) and small industrial activities (hexamethylenediamine, hydrogen peroxide, glass, surface treatment of metals, 65 kt of H₂). Future research could focus on the extension of the model to these industries to finely describe the production process (storage and distribution), along with the integration of new modes of production (hydrogen from biomass).

At more decentralized level, further research is necessary to understand the most appropriate drivers that can combine sector synergies. Hydrogen deployment, based on concepts of innovation system (Pirainen et al, 2017) and hydrogen clusters (Madsen and Andersen, 2010) will complete the macro-economic vision of the hydrogen sector defined here, such as to integrate the technological and spatial dynamics of the hydrogen supply and demand, function of the level of the existing infrastructure, the regional industrial evolution, and the level of specialization of territories.

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