Strategies of decarbonation.
Applied industrial symbiosis to low carbon hydrogen

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Abstract

Energy industry represents roughly 2% in the GDP in energy importing countries (France, 2019), yet any energy shock can lead to massive disruptions in the economy, as already demonstrated with the GPES concept (general purpose energy source, Noce, 2015). We develop an input-output model to describe the French economy focused on energy sectors, and show that a shock on imports, replaced entirely by domestic production, changes not only the output multiplier but also severely modifies the inter-industrial relationships. For an equivalent volume displaced instead of value, the Leontief technical coefficients are modified in sectors affected by the shock, due to non-linear indirect changes. We apply the model to the case study of low carbon hydrogen and show that a small shock on gas imports (-25 TWh) needs ambitious planning of industrial development (0.8 Mt of low carbon H2, or 80% of the French current H2 demand). This leads to massive structural changes: GPD increases by 3.8 Bln €, the H2 sector records an output-to-output multiplier of 1.88 and it ranks first with Backward Linkage Index. An even higher gas to hydrogen shock (>90 TWh) would need impressive domestic resources and require massive energy planning similar to nuclear State program over 80s.

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

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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 a 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 issue within the decarbonisation strategy and builds an input-output model to highlight inter-industrial relationships (Leontief, 1936), to further support industrial planning for reducing gas import and developing 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). 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). In France as well, the 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 [1], 2021). Large uncertainties still remain whereas the H2 production potential is enough to meet the domestic demand and about the location of the H2 infrastructure, hence this research depicts those factors needed for the emergence of a large-scale hydrogen ecosystem. The prior goal is to replace the current brawn or grey hydrogen produced with fossil-fuels, with green and yellow hydrogen produced with renewables and nuclear, i.e. 1 Mt of H2 consumed in France; and secondly, we will add new usages in transport and industry.

The paper describes the inter-industrial linkages by means of conventional indicators of input-output model, such as the output multipliers, backward linkage index, and forward linkage index, which further contribute to assess industrial needs of hydrogen ecosystems. We simulate a shock on gas import removing that is mainly used to produce grey hydrogen fueling three sectors, and we design a domestic low carbon hydrogen sector as the only alternative. 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 describes the mathematical formulation of problem and calibrates the economic system crossed with energy flows and values. Section 3 discusses simulation results on model performances of the case study. Section 4 concludes with some policy recommendations for industrial planning and opens work perspective.

2. Methodology

The model follows a gradual procedure as described at Fig. 1. We first describe the shock on gas imports, substituted by a new sector of hydrogen production; then we formalize the inter-industrial relationships among actors through input-output analysis. Once hydrogen sector is integrated, the conventional Leontief input-output approach applies first, together with the inverse matrix to get Leontief coefficients and inter-industrial relationships. We then apply output to output multiplier method (Miller & Blair, 2009) to model an exogenous output of the hydrogen sector and to further estimate hydrogen development impacts in terms of GDP, intermediate consumptions, multipliers, backward linkage and forward linkage.

Step 1. IOT 19 sectors (2018 data)

Step 2. Gas shock
⇘ 25 TWh import (≈ 605M€) → ⇗ H2 domestic output (605 M€)

Step 3. IOT2 20 sectors (19 + 1 H2)

Step 4. I-O open Leontief model

Step 5. IOT3 20 sectors - with inter-industrial Relationships

Step 6. Output to Output model
H2 output = 4 587M€ = 0.8 MtH2 = 25 TWh

Step 7. IOT4

Step 8. Ranking: Backward Linkage, Foward Linkage. Multipliers.

Fig. 1. Methodology flow chart

Step 1. A symmetric Input Output Table (IOT) is built based on data documented from Eurostat[3] for the year 2018, further adapted to a 19-product/sector table[4]. Economic data is crossed with energy data on gas imports, in both volume and price, issued from the French energy balance in 2019 (Ministry of Ecological Transition, 2021).

For the first model building (IOT 19), we define $IC_{i,j}$ as the matrix of intermediate consumptions of product *i* by sector *j*, va_j is the line vector of value added of sector *j* and imp_j

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

[4] We first aggregated data into a 17-product/sector table to obtain an equivalent of NAF 17 French national institute for statistical and economic studies (INSEE), but in order to get more accurate results we have divided sector DE (Mining, quarrying, energy, water, waste management and remediation) into three sub-sectors (DE - Mining and quarrying; DZ - Electricity, gas, steam and air conditioning supply; EZ - Water supply; sewerage, waste management and remediation activities).

is the line vector of the use of imported products (imported intermediate consumptions) of the sector j. x_j, the output of sector j, can be expressed as follow:

$x_j = IC_{i,j} + va_j + imp_j$ (1)

Step 2. For gas shock simulation, a new sector/product named "low carbon hydrogen" (H2) is created such as to entirely substitute the imports of gas on a domestic basis, e.g. H2 production and all its intermediate consumptions. The gas shock applies assuming that the removed gas flows are entirely substituted by low carbon hydrogen. Note that the shock is estimated in physical quantities (TWh) and impacts are returned in monetary value (M€). In this model, only three sectors are impacted by the gas shock and will instead consume low carbon hydrogen domestically produced. These sectors are selected based on targets by industry set by the French National Low Carbon Strategy (Ministry of Ecological Transition, 2020):

- C5 sector: "Manufacture of other industrial products". It uses gas to produce grey hydrogen for chemicals and mostly ammonia.
- C2 sector: "Manufacture of coke and refining". It uses gas to produce grey hydrogen for crude oil refining.
- DZ sector: "Electricity, gas, steam and air conditioning supply". It uses gas for electricity production or for direct gas injection (heat).

Each of the three sectors is differently affected by the gas shock (denoted β), function of the usage of low carbon hydrogen, with the following distribution of the national H2 targets:

- C5 sector = β · 0.6
- C2 sector = β · 0.3
- DZ sector = β · 0.1

For instance, a gas shock β of 10 M€, implies that C5 sector is impacted by 6 M€ in value, C2 sector by 3 M€ and DZ sector by 1 M€.

Gas is accounted as an import intermediate product in the domestic IOT for each of the three sectors, hence a decrease in gas consumption in sector j means a decrease by imp_j. To keep output equilibrium x_j in sectors C5, C2 and DZ, we create a new intermediate consumption which replaces β in the same proportion.

Next we determine the way the low carbon hydrogen is produced, and to that, we create a new raw in the IOT, corresponding to the H2 *product demand*, and a new column representing the H2 *supply*.

Step 3. Domestic H2 sector building

Creation of H2 product (raw). H2 defined in raw represents the quantity of low carbon hydrogen that is used as intermediate consumption by others sectors. As presented above, the gas shock is assumed to be distributed among the three sectors, C5, C2 and DZ, and replaced by H2 as intermediate consumption at the same ratio 1 gas: 1 H2, meaning that β will equalize low carbon hydrogen production ($\beta = x_{h2}$). We define $IC_{h2,j}$ as the intermediate consumption of H2 product used by the sector j.

$IC_{h2,C5} = 0.6 \cdot x_{h2}$
$IC_{h2,C2} = 0.3 \cdot x_{h2}$
$IC_{h2,DZ} = 0.1 \cdot x_{h2}$

Creation of H2 supply (column). The H2 column represents intermediate consumptions that the H2 sector needs in product i to generate the output x_{h2}. As national hydrogen targets give priority to hydrogen produced with the water electrolysis, based on renewables and nuclear power, we estimate hydrogen technical coefficients $a_{i,h2}$ by merging technical coefficients of three sectors: “DZ - Electricity, gas, steam and air conditioning supply”($a_{i,DZ}$), “FZ – construction” ($a_{i,FZ}$) and “C3 - Manufacture of electrical equipment and machines”($a_{i,C3}$). To each of three technical coefficients is attributed a coefficient (θ_j) which determines the weight of intermediate consumption in the hydrogen sector:

$\theta_{DZ} = 0.5$; $\theta_{FZ} = 0.3$; $\theta_{C3} = 0.2$

We can now calculate $a_{i,h2}$, which is the column vector of technical coefficients of the hydrogen sector demand for product *i* as follow:

$a_{i,h2} = a_{i,DZ} \cdot \theta_{DZ} + a_{i,FZ} \cdot \theta_{FZ} + a_{i,C3} \cdot \theta_{C3}$

Finally, we obtain $IC_{i,h2}$, the column vector of intermediate consumption of low carbon hydrogen sector for the product *i*, with the following equation:

$IC_{i,h2} = (a_{i,h2}) \cdot x_{h2}$

As there is no import in the hydrogen sector, the added value, va_{h2}, is obtained as residual value as follows:

$va_{h2} = x_{h2} - \sum IC_{i,h2}$

We get a new IOT named IOT_2 with 20 sectors/products (19 sector/product + 1 low carbon H2 sector/product).

Step 4. We simulate next the way the new intermediate consumptions of H2 sector/product affect the others sectors, by using a classical open Leontief model. We first calculate the matrix of technical coefficients $A_{i,j}$ of IOT_2, obtained with the equation:

$A_{i,j} = \frac{IC_{i,j}}{x_j}$ (2)

We compute the raw vector of added valued coefficient (Ava_j) and import product coefficient ($Aimp_j$) as follows:

$Ava_j = \frac{va_j}{x_j}$ (3) and $Aimp_j = \frac{imp_j}{x_j}$ (4)

Then, we get Leontief reverse matrix $\propto_{i,j}$ by solving the following equation:

$\propto_{i,j} = (I - A_{i,j})^{-1}$,

with I as a unity matrix.

By means of Leontief approach, equation (1) can be expressed:

$x_j = \sum IC_{j,i} + fd_i$ (5)

with fd_i final demand of product i.

We can now rewrite equation (5):

$x_j = \propto_{i,j} \cdot fd_i$ (6)

Step 5. This new production allow calculating the new $IC_{i,j}$ with equation (2), new va_j with equation (3) and new imp_j with equation (4), and we finally get IOT_3, with 20 sectors/products and inter-industrial relationships with the hydrogen sector.

Step 6. Inter-industrial relationships are now modeled in IOT3 by means of an Output-to-Output Leontief model.

So far, β = x_{h2} was expressed in *monetary value* (M€) and not in physical units, because the low carbon H2 is way more expansive than gas. For example, a gas shock of 25.5 TWh represents 604.94 M€ (2018 prices) whereas 25.5 TWh of low carbon hydrogen costs 4,587 M€ evaluated at 6 €/kg H2. Industries needing the same amount of TWh to keep the energy balance, we design a new input-output model with β = x_{h2} expressed in *physical flows.*

In the initial IOT3, we set x^*_{h2} at the monetary value (M€) of the same amount of gas to be removed in physical quantity (at cost assumption of 6 €/kg H2). To that, we use an output-to-output Leontief model, instead of mixed input-output model when only one production is exogenous (Miller & Blair, 2009), which is the case here (x^*_{h2} is exogenous).

We rewrite the Leontief reverse matrix $\propto_{i,j}$ and calculate output-to-output matrix $\propto^*_{i,j}$ as follows:

$$\propto^*_{i,j} = \frac{\propto_{i,j}}{\propto_{j,j}}$$

We next calculate $IC^{\forall}_{i,h2}$, the intermediate consumption of product *i* needed in the hydrogen sector to reach the hydrogen target:

$$IC^{\forall}_{i,h2} = \propto^*_{i,j} \cdot \delta_i$$

δ_i is a column vector set at 0 for each *i* except for *i=h2* that is equal to the additional production needed to obtain exogenous production(x^*_{h2}).

We can now calculate new production x^*_j as follows:

$$x^*_j = x_j + IC^{\forall}_{i,h2}$$

This new production x^*_j allows calculating new $IC_{i,j}$, new va_j and new imp_j via $A_{i,j}$, Ava_j and $Aimp_j$. However, as mentioned above, intermediate consumptions in the hydrogen sector C5, C2 and DZ are fixed:

$$IC^*_{h2,C5} = 0.6 \cdot x^*_{h2} \; ; IC^*_{h2,C2} = 0.3 \cdot x^*_{h2} \; ; IC^*_{h2,DZ} = 0.1 \cdot x^*_{h2}$$

These new intermediate consumptions result in the corresponding technical coefficients:

$$a^*_{h2,C5} = \frac{IC^*_{h2,C5}}{x^*_{h2}} \; ; a^*_{h2,C2} = \frac{IC^*_{h2,C2}}{x^*_{h2}} \; ; a^*_{h2,DZ} = \frac{IC^*_{h2,DZ}}{x^*_{h2}}$$

With $a^*_{h2,j} > a_{h2,j}$ because $x^*_j > x_j$ and by construction $A_{i,j} + Ava_j + Aimp_j$ = 1, hence the variation between $a^*_{h2,j}$ and $a_{h2,j}$ must be removed. We choose to remove it at the level of imp_j because the surplus of domestic hydrogen lowers the imports (of gas). Thus, we get $aimp^*_{h2,C5}$, as follows:

$$aimp^*_{h2,C5} = 1 - \sum A^*_{i,C5} + Ava_{C5}$$

Similar operations are made for $aimp^*_{h2,C2}$ and $aimp^*_{h2,DZ}$

Step 7. With these three new technical coefficients and import coefficients, we can obtain a new IOT, IOT4, which includes inter-industrial linkages of low carbon hydrogen sector like IOT3 but also *physically* (in TWh) as it ensures that the gas removed is equal to the hydrogen produced domestically.

Step 8. By means of the Leontief approach, we calculate multipliers and linkage indices to depict the way the sectors are connected. We use output-to-output multipliers, Backward Linkage Index (BLI) and Forward Linkage Index (FLI).

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

$$Otoj = \sum_{i=1}^{n} \propto^{*}{}_{i,j}$$

BLI 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. It is calculated as follows:

$$BLI_j = \frac{1/n \sum_i^n \propto^{*}{}_{ij}}{1/n^2 \sum_j^n \sum_i^n \propto^{*}{}_{ij}}$$

FLI measures how much an output from a specific sector will induce attempts to use this output as inputs by others sectors for their own production (Hirschman, 1958). But FLI from Leontief input output model 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 $\propto^{G}{}_{ij}$:

$$\propto^{G}{}_{i,j} = (I - A^{G}{}_{i,j})^{-1}$$

With $A^{G}{}_{i,j}$ the allocation coefficient matrix obtained by the following equation:

$$A^{G}{}_{i,j} = \frac{IC_{i,j}}{x_i}$$

FLI is next calculated as follows:

$$FLI_j = \frac{1/n \sum_j^n \propto^{G}{}_{ij}}{1/n^2 \sum_i^n \sum_j^n \propto^{G}{}_{ij}}$$

3. Results

The shock applied to the French economy represents 5% of gas import removal which means 25.5 TWh and 604.94 M€ ($\beta = 25$ TWh $= 604.94$ M€). Table 1 presents the model results in volume generated by a domestic low carbon hydrogen sector, and Table 2 shows the global economic results, in value. Under the hydrogen cost assumption of 6 €/kg H2 and electrolysis efficiency set at 70%, 25.5 TWh of gas represents 0.8 Mt of hydrogen, obtained through electrolysis based on low carbon electricity, and this further means a total cost of 4,587 M€ ($x^{*}{}_{h2} = 25.5$ TWh $= 4\,587$ M€). This hydrogen production would require the power generation of some 9 GW of offshore wind turbines, entirely being dedicated to the hydrogen production, which are rather significant, but not unrealistic, in line with recent scenarios of national decarbonisation strategy (see deployment targets in the range of 10-20 GW of wind turbines by 2035; RTE [2], 2022).

Table 1: Model results in volume, at 25 TWh gas shock

Hydrogen production (Mt)	0.8
Offshore wind turbines capacity (GW)	9.2
Electrolysers capacity (GW)	6.5
Electricity needed (TWh)	36.4

The GDP generated after the shock amounts to 3,961 M€, out of which 2,414 M€ are due to the hydrogen sector only.

Table 2: Economic indicators at 25 TWh gas shock, model results

	Hydrogen sector	National economy
Value added (M€)	2 414	3 961
Production (M€)	4 587	8 620

Table 3 represents all intermediate consumptions needed in the hydrogen sector. As a low carbon product, the main intermediate consumption is the electricity, needed for electrolysis process (DZ product); in value, the electricity represents a significant share in the hydrogen price as well. The second most important intermediate consumption comes from the C5 sector, mainly due to the manufacture of electrolysers, compressors and other equipments. Finally, the third most important intermediate consumption comes from the MN sector, i.e. R&D, which naturally fuels the hydrogen sector that is an emerging industry at an early stage of development, thus requiring massive innovation.

Table 3 : Hydrogen sector's intermediate consumptions for 4587 M€ output

AZ - Agriculture, forestry and fishing	1
DE - Mining and quarrying	6
DZ - Electricity, gas, steam and air conditioning supply	**961**
EZ - Water supply; sewerage, waste management and remediation activities	25
C1 - Manufacture of foodstuffs, beverages and tobacco products	3
C2 - Manufacture of coke and refining	9
C3 - Manufacture of electrical, electronic and computer equipment; machinery manufacturing	42
C4 - Manufacture of transport equipment	8
C5 - Manufacture of other industrial products	**312**
FZ - Construction	184
GZ - Wholesale and retail trade; repair of motor vehicles and motorcycles	166
HZ - Transport and storage	57
IZ - Accommodation and food service activities	10
JZ - Information et communication	32
KZ - Financial and insurance activities	49
LZ - Real estate activities	11
MN - Scientific and technical activities; administrative and support services	**257**
OQ - Public administration, education, human health and social action	27
RU – Other service activities	10

The Table 4 shows the magnitude of hydrogen consumed in the three main sectors absorbing the shock of gas imports: DZ mainly the gas sector and partly power-to-power applications; C2 refining; and C5 chemistry, steel industry and other energy intensive industries.

Table 4 : Hydrogen as intermediate consumption for 25 TWh gas shock

DZ - Electricity, gas, steam and air conditioning supply	C2 - Manufacture of coke and refining	C5 - Manufacture of other industrial products
459	1376	2752

Table 5 represents output to output multipliers, ranked in descending order. We notice that the H2 sector ranks first, with an output multiplier of 1.879, which means that an increase in the H2 production by 1M€, generates 1.879 M€ of output value in the whole economy: 1M€ as H2 outputs and 0.879 M€ as direct and indirect effects. The first rank that the H2 sector holds reveals the high growth potential that the product and the sector represent for the whole economy.

Table 5 : Output to output multiplier

Output to output	Output multiplier	Rang
H2 - Low carbon hydrogen	1.879	1
C1 - Manufacture of foodstuffs, beverages and tobacco products	1.772	2
DE - Mining and quarrying	1.716	3
IZ - Accommodation and food service activities	1.686	4
C3 - Manufacture of electrical, electronic and computer equipment; machinery manufacturing	1.582	5
GZ - Wholesale and retail trade; repair of motor vehicles and motorcycles	1.579	6
C4 - Manufacture of transport equipment	1.560	7
FZ - Construction	1.532	8
AZ - Agriculture, forestry and fishing	1.469	9
RU – Other service activities	1.454	10
C5 - Manufacture of other industrial products	1.451	11
EZ - Water supply; sewerage, waste management and remediation activities	1.449	12
C2 - Manufacture of coke and refining	1.441	13
HZ - Transport and storage	1.416	14
JZ - Information et communication	1.409	15
C3 - Manufacture of electrical, electronic and computer equipment; machinery manufacturing	1.622	16
RU – Other service activities	1.511	17
C2 - Manufacture of coke and refining	1.476	18
OQ - Public administration, education, human health and social action	1.298	19
LZ - Real estate activities	1.255	20

Table 6 shows the backward linkage indices (BLI) of all sectors in the economy, ranked in descending order. The hydrogen sector ranks first again, which is quite expected as BLI is calculated by means of the output multiplier where H2 sector has shown the highest ranking. It means that H2 sector has a very significant potential to pull other industries upward through its high level of intermediate consumption. In other words, an increase in H2 sector output will lead to a significant increase in the output of the upstream industries. This result is triggered by the initial condition that H2 is produced with French electricity, equipment and innovation, without any import intermediate consumption. High BLI are then triggered by domestic production on one hand, and by the significant share that the energy sources hold in the economy, on the other hand.

Table 6 : Backward Linkage Index

Sector	**BLI**	**BLI (rank)**
H2 - Low carbon hydrogen	1.266	1
C1 - Manufacture of foodstuffs, beverages and tobacco products	1.194	2
DE - Mining and quarrying	1.156	3
IZ - Accommodation and food service activities	1.136	4
C3 - Manufacture of electrical, electronic and computer equipment; machinery manufacturing	1.066	5
GZ - Wholesale and retail trade; repair of motor vehicles and motorcycles	1.064	6
C4 - Manufacture of transport equipment	1.051	7
FZ - Construction	1.032	8
AZ - Agriculture, forestry and fishing	0.990	9
RU – Other service activities	0.980	10
C5 - Manufacture of other industrial products	0.977	11
EZ - Water supply; sewerage, waste management and remediation activities	0.976	12
C2 - Manufacture of coke and refining	0.971	13
HZ - Transport and storage	0.954	14
JZ - Information et communication	0.949	15
KZ - Financial and insurance activities	0.907	16
OQ - Public administration, education, human health and social action	0.857	17
MN - Scientific and technical activities; administrative and support services	0.848	18
LZ - Real estate activities	0.815	19
DZ - Electricity, gas, steam and air conditioning supply	0.811	20

Table 7 summarizes sectoral impacts linked to an increase of H2 output. For an increase of 1 M€ in H2 production, each sector will increase its output by *x* M€. For example, if H2 sector raises output by 1 M€, direct and indirect effects will lead the C5 sector to increase its production by 0.104 M€. Among the nineteen sectors, DZ, MN and C5 sectors are receiving the highest shares of low carbon hydrogen. It means that H2 sector can significantly pull these sectors upwards but is also significantly dependent on their production capacities; the cross-sector dependence can ultimately be a point of vulnerability in case of drop in production in these sectors. For example, the French electricity sector is currently subject to technical tensions, due to a lower availability of nuclear power plants. As hydrogen is produced by electrolysis, a lower production of DZ sector could strongly impact the H2 sector and, by domino effects, all the sectors that depend on hydrogen (direct industries and indirect industries relying on hydrogen-consuming sectors, etc.).

Table 7: H2 sector supply investment effects

Sector	**Effects**	**Rank**
DZ - Electricity, gas, steam and air conditioning supply	0.366	1
MN - Scientific and technical activities; administrative and support services	0.129	2
C5 - Manufacture of other industrial products	0.104	3
GZ - Wholesale and retail trade; repair of motor vehicles and motorcycles	0.058	4
FZ – Construction	0.055	5
KZ - Financial and insurance activities	0.034	6
HZ - Transport and storage	0.033	7
JZ - Information et communication	0.021	8
EZ - Water supply; sewerage, waste management and remediation activities	0.013	9
LZ - Real estate activities	0.013	10
C3 - Manufacture of electrical, electronic and computer equipment; machinery manufacturing	0.012	11
OQ - Public administration, education, human health and social action	0.011	12
IZ - Accommodation and food service activities	0.007	13
C2 - Manufacture of coke and refining	0.006	14
RU – Other service activities	0.005	15
C1 - Manufacture of foodstuffs, beverages and tobacco products	0.004	16
C4 - Manufacture of transport equipment	0.003	17
DE - Mining and quarrying	0.002	18
AZ - Agriculture, forestry and fishing	0.002	19
Total	0.879	-

Table 8 represents forward linkage indices (FLI) of all sectors in the economy, ranked in descending order. According to this indicator, H2 ranks first, meaning that the demand for H2 is high in the economy, namely as intermediate consumption, based on the assumption that hydrogen should be domestic such as to improve the country energy security after gas import removal. Further on, H2 being consumed only as intermediate consumption, with no export options here, this reinforces even more the linkages.

Table 8: Forward Linkage Index

Sector	**FLI**	**FLI (rank)**
H2 - Low carbon hydrogen	1.586	1
DZ - Electricity, gas, steam and air conditioning supply	1.416	2
DE - Mining and quarrying	1.358	3
KZ - Financial and insurance activities	1.302	4
MN - Scientific and technical activities; administrative and support services	1.230	5
EZ - Water supply; sewerage, waste management and remediation activities	1.215	6
AZ - Agriculture, forestry and fishing	1.160	7
HZ - Transport and storage	1.100	8
C2 - Manufacture of coke and refining	1.004	9
JZ - Information et communication	0.981	10
C5 - Manufacture of other industrial products	0.969	11
C1 - Manufacture of foodstuffs, beverages and tobacco products	0.848	12
GZ - Wholesale and retail trade; repair of motor vehicles and motorcycles	0.824	13
IZ - Accommodation and food service activities	0.815	14
LZ - Real estate activities	0.776	15
FZ - Construction	0.757	16
RU – Other service activities	0.724	17
C3 - Manufacture of electrical, electronic and computer equipment; machinery manufacturing	0.689	18
C4 - Manufacture of transport equipment	0.636	19
OQ - Public administration, education, human health and social action	0.610	20

4. Conclusions

The paper provided a first methodological framework for the assessment of the energy security issue. In line with the French strategy of low carbon industrial development, it is estimated an energy policy of gas import removal, entirely replaced by domestic low carbon hydrogen. We use input-output model to identify the way that the hydrogen sector is linked to the other industries in the economy. Results show that the H2 domestic production can be considered as a leading sector with a significant economic potential, as shown by high output-to-output multiplier, and this leader position is further confirmed by high levels of BLI and FLI obtained for the H2 sector.

This research opens further work perspective, related to the hydrogen infrastructure necessary to build a national industry made of local clusters of hydrogen production and transport and distribution points. These are the necessary conditions such as to substitute a mature industry of gas storage, transport and distribution at large scale. Additional documentation is needed in order to finely model those H2 consuming sectors which already have the infrastructure ready to consume the hydrogen in priority in order to limit the switching costs of the energy transition.

Next model development will extend the demand for hydrogen to the final user and to exports, where additional cost will be accounted for the distribution infrastructure in case of mass deployment of end-user engines, such as the heavy mobility. Sensitivity will be run to test the resilience of the economy to the hydrogen cost, here set at 6 €/kg H2, whereas in practice it might decrease due to electrolysis technological progress or it might increase due to electricity cost increase.

Finally, input-output models contain intrinsic limitations due to linear calculation, static representation of impacts of the transition, and exogenous innovation. Yet the model gives useful insights into the energy role in the economy, in the costs and benefits structure from producing domestic source (electricity) and vector (hydrogen) of energy that reduce the country dependence. As any industrial development, the State intervention is crucial at this stage and the French government has already designed massive support initiatives that amount to 7 Bln € (NHS, 2020), with milestones of 10% clean hydrogen for 2023 and 20-40% for 2028.

Beyond national policies, implementation of targets requires decentralized actions and further research is necessary to understand the most appropriate drivers to cumulate and combine sector synergies. Decentralized hydrogen deployment, based on concepts of innovation system (Piirainen 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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