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Towards nexus thinking in energy systems modelling: A multi-scale, embodied perspective

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ABSTRACT

The European Green Deal aims to decarbonise the EU by 2050. In alignment with that goal, the REPowerEU plan took Russia's invasion of Ukraine as an opportunity to address the security and sustainability of the EU's energy sector, by increasing energy efficiency and local energy production. While policy targets are often a political choice, models informing policies shape what dimensions are included in (or excluded from) sustainability discourses. The relations between the EU's energy system and other nexus elements of the social-ecological system, within the EU (local) and outside (embodied in imports) are underrepresented in models and policies. *Nexus thinking* highlights these relations. We present a framework to represent the energy system through a collection of local and embodied components across different scales, accounting for the nexus elements embodied in energy imports. The framework is explained through the examples of Spain, Sweden and the EU, for 2018. By focusing on the interactions between energy and local and embodied nexus elements, we show how synergies between security and sustainability are less linear than what REPowerEU would suggest. Our results point to the need of including embodied elements in policy agendas, to better account for the global nature of sustainability policies.

1. Introduction

Following Russia's invasion of Ukraine, the REPowerEU plan was launched as part of the European Green Deal (EC, 2022a, 2022b). The plan plays a crucial role towards the EU's goal of achieving carbon neutrality by 2050, aiming to reduce the dependence on Russian gas while simultaneously speeding up the green transition. Through a strengthening of the already existing trend of securitisation of energy policy (Natorski and Surallés, 2008), urgent measures were taken to reduce the EU's dependence on imported gas from Russia (EC, 2022c). In this policy framing, sustainability and security are seen as complementary: by producing local energy carriers, and diversifying the energy mix, imports can be reduced, greenhouse gas (GHG) emissions can be reduced, and green growth is stimulated.

This dominant framing, built on the synergies between security, sustainability, and green growth, minimises the role played by elements embodied in trade – not only GHG emissions, but also water flows, energy carriers, labour, and materials. Increasing local energy production may reduce direct energy carrier import dependence (e.g., gas), while increasing indirect dependence on that flow (e.g., gas embodied in electricity imports), and the dependence on other flows (e.g., batteries). This requires considering both the flows and impacts embodied in imports (e.g., the electricity embedded in battery production), and those associated with local production (e.g., the water use tied to producing fuels, rather than importing them). The global impacts of the European Green Deal are considered across various domains: the Carbon Border Adjustment Mechanism (CBAM) sets carbon prices for imported products, to avoid carbon leakage (European Parliament, 2023); global climate actions are financed through the EU, its Member States and the European Investment Bank (EC, 2023); and the Trade Policy aims to ensure that trade is fair and sustainable (EC, 2021). However, the relations between local and embodied impacts of EU policy measures are not considered when setting policy agendas.

Models have a part to play in shaping policy agendas and determining what is considered and what is excluded from dominant narratives (Ellenbeck and Lilliestam, 2019). Focusing on the energy sector, we present a framework that relates energy flows with local and embodied nexus elements across different scales. We do so by accounting for the

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nexus elements embodied in energy products – i.e., funds and flows tied to the imports of primary energy sources and energy carriers, such as the labour needed to extract imported uranium, or the GHG emissions tied to imported fuels.

The nexus (often short for water-energy-food-environment, or WEFE, nexus) has become increasingly popular since its introduction in mainstream sustainability discourses following the Bonn 2011 Nexus Conference (Hoff, 2011), as a lens to view the connections between different dimensions of social-ecological systems. Depending on how it is implemented, the nexus can either be used as a tool to push for win-win technological solutions (Stirling, 2015; Cairns and Krzywoszynska, 2016), or as a framework that highlights the impossibility of such solutions, pushing for a change in perspective. In this paper, we build on this second conception of the nexus, defined by Urbinatti et al. (2020) as a "way of viewing problems", with the potential to break down silos across policy domains (Wallis, 2015; Cabello et al., 2019). We refer to this perspective as *nexus thinking*.

Our results contribute to MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism), an existing framework aimed at characterising social-ecological systems across different scales of analysis. MuSIASEM describes energy systems as complex systems that transform energy to guarantee their own maintenance, reproduction and adaptation (Giampietro, 2023). Energy systems are open, exchanging material flows with other systems through imports, exports, and elements embodied in those imports and exports. They are also multi-scalar, since they can be viewed at different scales of granularity, and multiple scales are needed to guide decisions – e.g., observing the behaviour of individual power plants, and studying the electricity production curves generated from their aggregate patterns. MuSIASEM focuses on the relational aspect on the nexus, by highlighting: (i) relations across scales of the energy sector; (ii) relations between local and embodied processes and (iii) relations across elements of the social-ecological system. Through three examples using 2018 data from Spain, Sweden and the EU, we show the local and embodied nexus elements tied to different scales of the energy system, and their relations. In the examples, we include the nexus elements of land use, use of primary energy sources and energy carriers, water use, labour requirements, spent nuclear fuel and GHG emissions. Our results were developed within the Horizon-2020 project MAGIC, short for Moving Towards Adaptive Governance in Complexity: Informing Nexus Security (MAGIC, 2016). The goal of MAGIC was to check the quality of EU sustainability narratives from a multi-scale, nexus perspective, building on MuSIASEM. In terms of energy accounting, this paper expands on previous work describing the energy-nexus metabolism of Catalonia across scales (Di Felice et al., 2019) and quantifying embodied elements in the energy sector (Ripa et al., 2021).

The aim of the framework that we present, and its conceptual building blocks, is not to replace large models currently used at the science-policy interface, such as PRIMES. Rather, through a relatively simple description of the energy system, we point to the importance of accounting for embodied elements across different scales of analysis, complexifying the narratives that are underpinning REPowerEU and the European Green Deal.

In the next section (Section 2), we introduce the accounting framework, focusing on multi-scalarity and on embodied elements in the energy system. Section 3 summarises how the three examples were built. Results are presented in Section 4, highlighting the relations between local and embodied nexus elements across scales. The implications of the accounting framework for the science-policy interface are discussed in Section 5, pointing to pathways for future research grounded in nexus thinking. We conclude in Section 6 with our policy recommendation, that embodied nexus elements should be considered when setting sustainability policy agendas.

2. The relational accounting framework

Section 2.1 explains the multi-scale, embodied nexus perspective in MuSIASEM. In Section 2.2, we introduce the main tool used in the framework, i.e., the *metabolic processor*; in Section 2.3, the accounting method for embodied processors is explained, and in Section 2.4 we show how local and embodied processors are connected across multiple scales of analysis.

2.1. Background: a multi-scale, embodied perspective

Regional, national and supra-national energy systems are open: they are connected with other economies and environments through the imports and exports of energy products, both primary energy sources and energy carriers. *Embodied nexus elements in the energy sector are those elements tied to the imports of primary energy sources and energy carriers*, such as the water used to extract imported coal, or the labour used to produce imported electricity. While usually embodied energy is associated with other imported products, such as the energy embodied in the imports of manufactured goods, our focus is on *the nexus elements embodied in energy products themselves*. These embodied nexus elements can be considered across different scales of analysis. We refer to scale from an information perspective (short for "analytical scale") – i.e., as the chosen granularity used to observe a system (Diaconescu et al., 2021). Complex systems are systems that can be represented in multiple, non-reducible ways at different analytical scales (Giampietro and Mayumi, 2004). A minimum of three scales is necessary to understand the behaviour of a complex system: a focal level; a scale below it, explaining its structure; and one above, explaining its function (Salthe, 1993).

Taking the energy sector as our focal level of analysis, we propose three scales to understand its nexus interactions. We consider (i) a structural perspective, describing the infrastructure composing the energy sector; (ii) a functional perspective, providing a description of the different compartments of the energy sector, broken down based on what type of energy carrier they provide to society (electricity, heat, fuels or gas); (iii) a global perspective, describing the energy sector as a whole. For these three scales, going from more detailed to more aggregated, the description includes an accounting of the nexus inputs and outputs tied to local and embodied processes. On the structural scale this means, for example, accounting for the nexus inputs and outputs tied to coal mines in the EU, and to the mines producing the coal that is directly imported into the EU, or indirectly imported through other imports of energy products (e.g., the coal used to produce imported electricity). On the functional scale, a nexus description of "electricity production" in the EU aggregates all the structural processes (local and embodied) that are needed to produce electricity – e.g., coal mining, coal transport, and coal power plants. These three scales can be connected with consumption patterns, showing how different energy carriers are consumed by different sectors of society, representing the social and economic context of the energy sector. The energy sector constitutes the interface between production and consumption patterns, since it produces energy while consuming it, through its *autocatalytic loop*.

The existing tool most similar to this approach, when it comes to accounting for embodied elements, are EIO-LCAs (environmental input-output life cycle assessments), that combine input-output tables with LCAs (Sherwood et al., 2017; Usubiaga et al., 2017). EIO-LCAs use economic tables of monetary flows between industries to assess the upstream environmental impacts tied to a specific product, good or service. MuSIASEM, on the other hand, up-scales structural descriptions, rather than disaggregating from the top-down.[1] Another similar

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[1] In practice, for missing data points, benchmarks and averages were used to determine the structural description, rather than the other way around – full details on this are provided in the supplementary material.

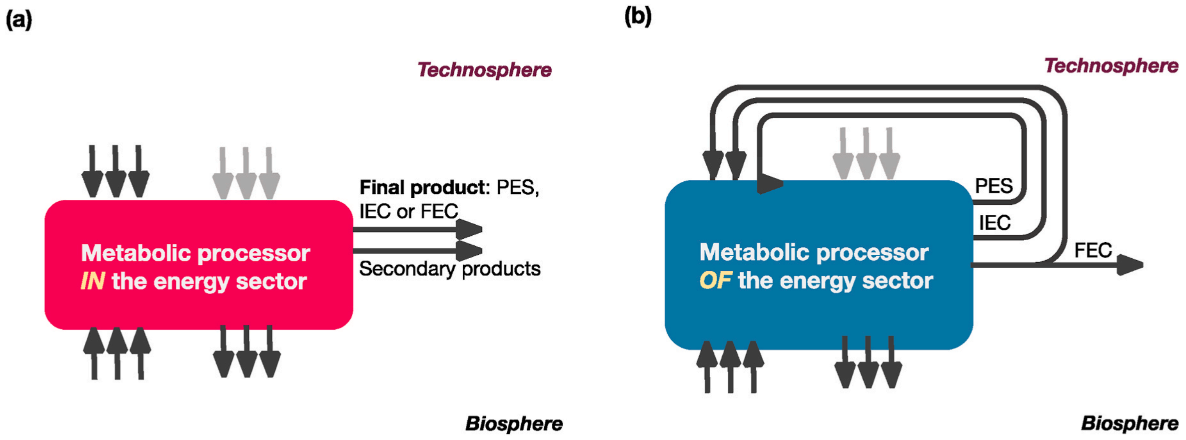

Fig. 1. Metabolic processor in the energy sector (a); and of the whole energy sector (b). Light grey arrows show fund elements, dark grey arrows show flow elements. PES: primary energy sources; IEC: intermediate energy carriers; FEC: final energy carriers. PES, IEC and FEC are outputs of the energy sector to the technosphere, while the outputs shown in the lower right side of the processor are those going to the biosphere.

approach is the ENBIOS environmental assessment model developed in the SENTINEL project (Martin et al., 2022); similar to our framework, ENBIOS combines principles from LCAs and MuSIASEM, but it does not include the accounting of embodied elements.

2.2. The metabolic processor for energy processes

In MuSIASEM, metabolic processors are devices used to describe the pattern of nexus inputs and outputs of processes. Fig. 1a shows how the processor is constructed. A set of inputs and outputs is associated with a final product – i.e., the primary output of the process. In energy processes, there are three types of primary outputs: primary energy sources (PES), intermediate energy carriers (IEC), and final energy carriers (FEC). PES are energy products that need to be converted before consumption, such as coal, crude oil, uranium, or wind. IEC are energy carriers (converted from PES), that are then converted again before being consumed as a final product. This category includes, for example, yellowcake that is used in nuclear power plants, or oil products that are converted into electricity (e.g., in diesel generators). The distinction between PES, IEC and FEC is determined by what the energy product is used for (its functionality), and not only by its material form. This means that the same energy product can be placed in different categories depending on the context. Gas, for example, can be consumed directly (as a FEC), or it can be converted to electricity through natural gas turbines (as an IEC).

The production of a unit of a PES, IEC or FEC is associated with a profile of inputs and outputs. The top half of the processor shows inputs from the technosphere, making the separation between flows and funds – flows are produced or consumed within the reference timeframe, while funds are maintained (Georgescu-Roegen, 1970). The bottom half shows biosphere inputs (on the left) and outputs (on the right). The biosphere inputs and outputs that we consider are all flows, although they are either taken from, or released into, funds – for example, a flow of water taken from a water body, where the water body is the fund needing to be maintained. We include processors tied to PES extraction, and to the generation of FEC – excluding the steps of transport, transmission and distribution. We do not include the steps of cultivation, fabrication and construction of infrastructure, which would be important to consider for scenarios of renewable transformations (Di Felice et al., 2018; Slameršak et al., 2022).

For each process, the following inputs and outputs are accounted for:

- Technosphere flow inputs: water from taps; IEC and FEC: coal products (such as coke oven coke), manufactured gases, nuclear fuel element, oil products, electricity, derived heat, biofuels and biogas. We combine energy products used as transformation inputs with those consumed in the process – e.g., the "oil product" category for a petroleum product plant includes the products converted to electricity and other oil products that are used throughout the process;
- Technosphere fund inputs: land use; labour; power capacity;
- Biosphere flow inputs: PES: coal, uranium, lignite, gas, oil, biomass, waste, other solid fossil fuels, other hydrocarbons; water taken from water bodies;
- Biosphere flow outputs: GHG emissions;
- Technosphere flow outputs: the primary output of the process (PES, IEC or FEC); secondary outputs of the process (PES, IEC or FEC); spent nuclear fuel.

Details on how these inputs and outputs are accounted for are included in Sections 1.1-1.3 of the supplementary material. All inputs and outputs are normalised by the primary output – e.g., kilograms of coal needed to produce 1 MJ of electricity. Outputs to the technosphere are those that are either consumed or converted before final consumption. In addition to a processor's primary output, the same energy process can produce secondary outputs (what is known as joint production). Similar to the distinction between PES, IEC and FEC, the distinction between primary and secondary outputs is also dependent on the case study and goal of the analysis. Processors describing specific energy processes can be aggregated to account for different parts of the energy sector (e.g., PES extraction), or the sector as a whole. Fig. 1b shows an example of a metabolic processor for a whole energy sector, including the autocatalytic loop. In this case, the only output going directly to the technosphere is a mix of FEC.

2.3. Local and embodied processors

Processors are split between local and embodied, depending on where the energy process takes place. Local processors are situated within chosen geographical boundaries – e.g., if the case study is the EU, energy processes that are physically located within EU borders. Embodied processors are materially connected to local ones by flows of direct or indirect imports. For example, coal can be imported directly and converted into electricity in a coal power plant, or indirectly through imports of coal-generated electricity. Since indirect imports can be calculated recursively, we set system boundaries at the processors for PES extraction needed for the IEC and FEC that are directly imported. This means that, if a country imports nuclear electricity, the processor for electricity production in the nuclear plant is accounted for, as well as the processor for uranium mining. The latter includes the input flows of FEC, such as the electricity consumed in the power plant, but the

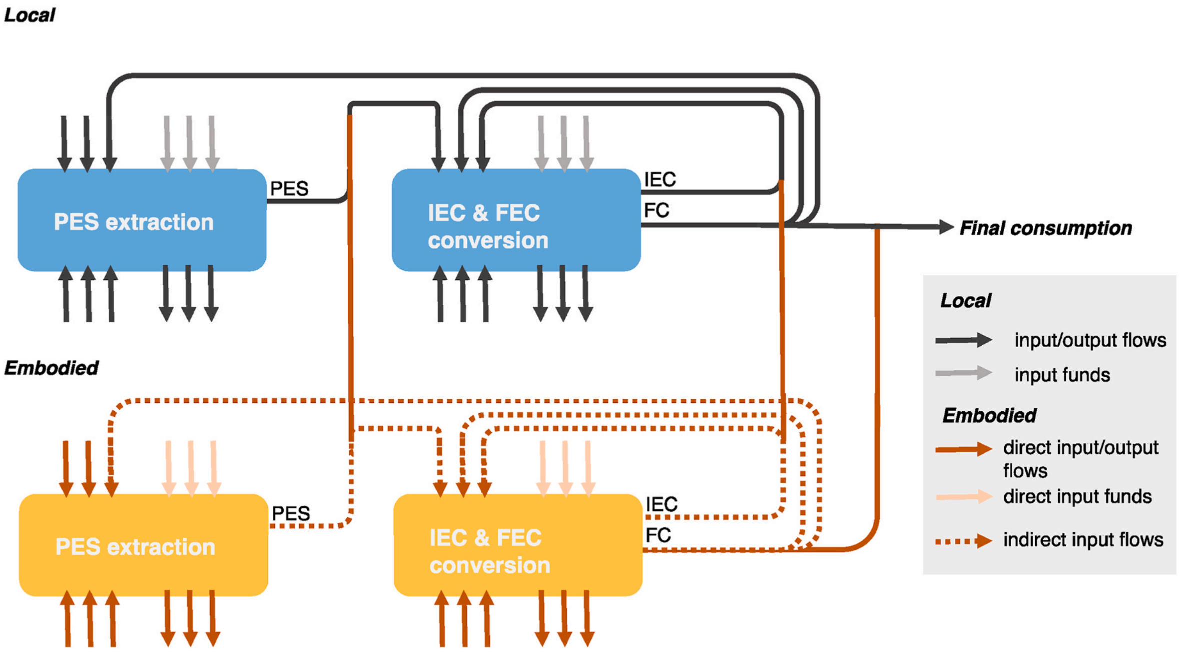

Fig. 2. Local and embodied energy processors. For the embodied processes (bottom half of the Figure, in yellow), dotted lines show indirect imports, full lines (connected to the local processors) show direct imports. Processors connected to one another form sequential pathways. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

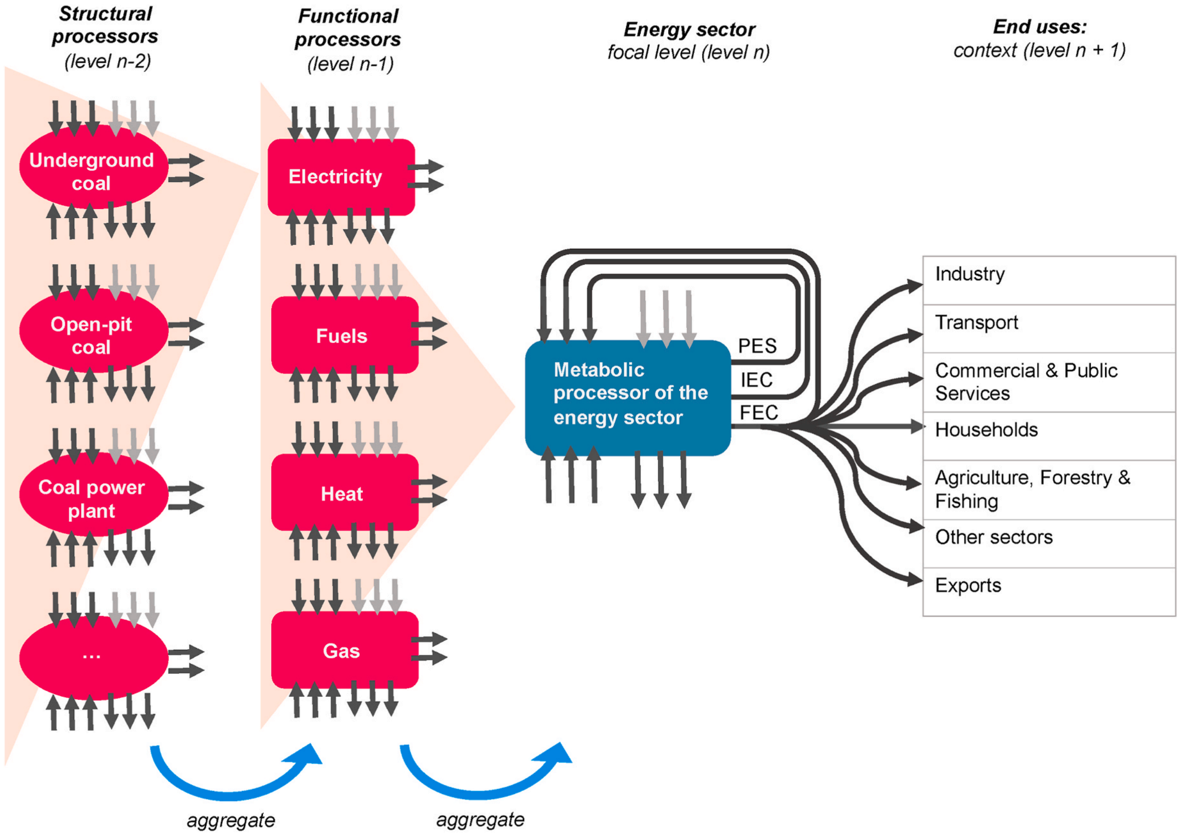

Fig. 3. Energy processors across scales. Structural processors are shown as ovals, and functional processors as rectangles; we show an example of structural processors that map onto the “electricity” function, in the case where electricity is produced by coal. Processors at each scale may also be connected through sequential pathways (e.g., the output of open-pit coal mining being the input of the coal power plant); however, the figure focuses on hierarchical pathways, aggregating processors across scales. The arrows of each processor represent nexus inputs and outputs.

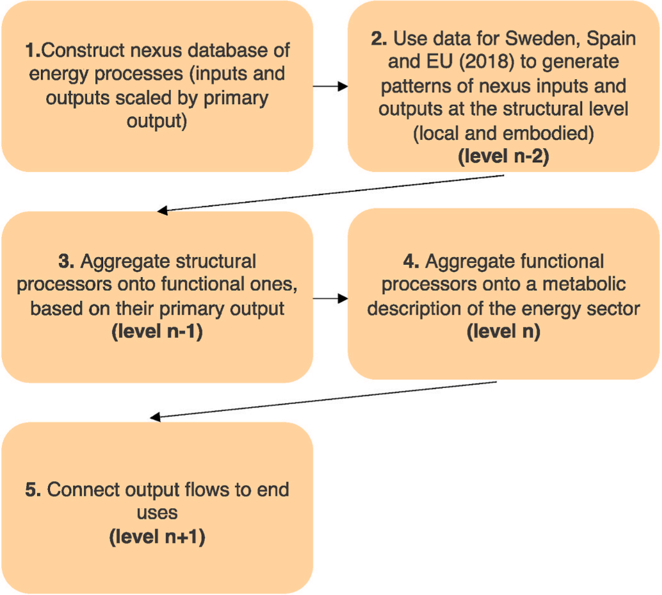

Fig. 4. Methodological flow.

processors for that electricity production are excluded. This is described in equations (1)–(3):

$$\mathrm{PES_{EMB}} = \mathrm{PES_{DIR}} + \mathrm{PES(EC_{DIR})} \tag{1}$$

$$\mathrm{EC_{EMB}} = \mathrm{EC_{DIR}} + \mathrm{EC(PES_{EMB})} \tag{2}$$

$$\mathrm{(In/Out)_{EMB}} = \mathrm{In/Out(PES_{EMB})} + \mathrm{In/Out(EC_{DIR})} \tag{3}$$

Equations (1)–(3). $\mathrm{PES_{EMB}}$, $\mathrm{EC_{EMB}}$ and $\mathrm{(In/Out)_{EMB}}$ are embodied PES, EC, and nexus inputs & outputs (such as water, GHG, etc.); $\mathrm{PES_{DIR}}$ and $\mathrm{EC_{DIR}}$ are direct imports of PES and EC; $\mathrm{PES(EC_{DIR})}$ are the PES needed to produce $\mathrm{EC_{DIR;}}$ $\mathrm{EC(PES_{EMB})}$ are the EC needed to extract $\mathrm{PES_{EMB}}$; In/Out ($\mathrm{PES_{EMB}}$) are the nexus inputs & outputs associated with $\mathrm{PES_{EMB}}$; In/Out ($\mathrm{EC_{DIR}}$) are the nexus inputs/outputs associated with $\mathrm{EC_{DIR}}$

Fig. 2 shows how local and embodied energy processors are connected to one another through material flows. The energy sector shown in Fig. 1b is an aggregation of these processors, combining local and embodied ones. Direct imports are materially connected with local processes, while dotted lines in the figure show indirect imports – i.e., PES used for embodied IEC and FEC conversion. When two or more processors are connected through material flows, they form a *sequential pathway*. In this paper, these material flows refer to energy flows, as cultivation, fabrication and construction of infrastructure are not considered. *Hierarchical pathways*, on the other hand, are those aggregations connecting processors across different scales. The processors shown in Fig. 2 are hierarchically aggregated onto the energy sector description of Fig. 1b.

2.4. Processors across scales

When representing an energy system, processes can be described at the structural scale, by characterising technologies, and at a functional scale, by considering the different compartments of the energy sector and what they do. We include both descriptions, aggregating processors from the bottom-up to reach a functional description (Fig. 3). At the lowest level (n-2, in Fig. 3), processors describe specific energy processes – e.g., the inputs and outputs associated with underground coal mining, for a chosen case study. These processes are then aggregated (through hierarchical pathways) onto functional compartments at the level n-1, where functionality is determined by what FEC is produced: electricity, heat, fuels or gas.

Table 1
Energy processes (structural scale).

Category	Processes
Mining & Extraction	In situ leaching uranium mining Open pit uranium mining Underground uranium mining Underground coal mining Open pit coal mining Lignite mining Onshore light oil extraction Offshore light oil extraction Onshore medium oil extraction Offshore medium oil extraction Onshore gas extraction Offshore gas extraction
Intermediate PES conversion	Nuclear fuel element plant Coke oven
Derived heat plant	Biomass heat boiler/furnace Waste heat boiler/furnace Heat pump Other heat boilers/furnaces (Sweden) Natural gas heat boiler/furnace Coal heat boiler/furnace Other heat boilers/furnaces (EU)
Refinery	Biodiesel refinery Bioethanol refinery Hydroskimming refinery Medium conversion refinery Deep conversion w/coking refinery Deep conversion w/hydrocracking refinery
Combined Heat & Power (CHP)	CHP (Spain) Biomass CHP plant Waste CHP plant Other CHP plants (Sweden) Other CHP plants (EU) Coal CHP plant (EU) Natural gas CHP plant (EU) Lignite CHP plant (EU) Biomass CHP plant (EU) Waste CHP plant (EU)
Power plant	Natural gas turbines Solar PV Wind turbines Hydro Pumped hydro storage Nuclear plant Coal power plant Petroleum products plant Lignite power plant Other electricity (Spain) Other electricity (EU)

These functional compartments are then aggregated onto a full description of the energy sector, including all nexus inputs and outputs. The energy sector, with its autocatalytic loops, is the interface between production and consumption patterns – it aggregates lower-level production processes, and produces what is consumed by society, while also consuming a part of what it produces. Changes in the energy sector are driven by pressures on both sides: technologies shape practices, and practices shape technologies. These constraints are applied to each processor at each scale, and not just one way top-down or bottom-up: desirability concerns are also relevant for how structural processors are shaped (e.g., whether it is socially desirable to close a coal mine that is providing many local jobs), and technological/material constraints also apply to consumption patterns. In other words, material and social constraints are relevant all the way up, and all the way down.

Structural and functional components can be further broken down, or aggregated differently to what is shown in Fig. 3, depending on the purpose of the analysis – e.g., aggregating them based on a step in the energy sector's sequential pathway (such as "PES extraction"), or based on the output FEC, but with a higher granularity (e.g., making the distinction between baseload, peak and intermittent electricity, as in Di Felice et al. (2019)).

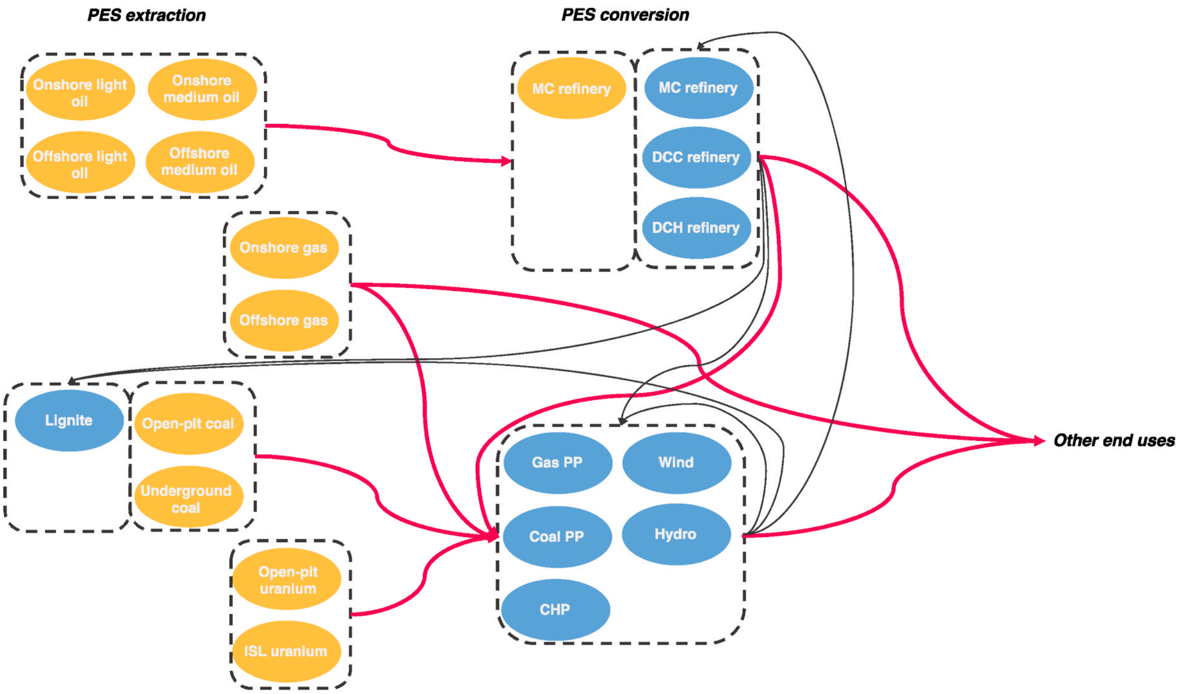

Fig. 5. Sequential pathways at the structural scale (level n-2), Spain (2018). Processors shown in yellow are embodied, while blue ones are local. Pink arrows show material flows connecting processes. Thin black arrows show hypercycle relations (energy-for-energy). MC: medium conversion; DCC: deep conversion with coking; DCH: deep conversion with hydrocracking; ISL: in-situ leaching; PP: power plant; CHP: combined heat & power. Note that raw natural gas is always processed before being distributed, and this is not included in the scheme. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Methodology

The methodological flow of the analysis is shown in Fig. 4. As a first step, a nexus database was compiled, describing the inputs and outputs of standard technological processes. These are taken from the Ecoinvent database version 2.2 inventories (Frischknecht et al., 2005) and other data sources, as explained in Section 2.1 and detailed in the supplementary material. The nexus database was used to describe the energy sectors of Spain, Sweden and the EU, starting with a description of relevant technological processes for each example. Structural processors were also built for embodied processes of the energy sector. Those structural processes were then aggregated onto functional ones, onto a full description of the energy sector, and connected to consumption patterns.

3.1. The nexus database

Inputs and outputs for different energy processes were collected into a nexus database, accessible as supplementary material.[2] Inputs and outputs are normalised by unitary outputs (e.g., hours of human activity by kilogram of coal extracted). This includes secondary outputs that are scaled by the primary output. Given the lack of a standardized database including nexus variables associated with energy processes, different data sources were used, including the Ecoinvent database, data from Eurostat and the NREL U.S. Life Cycle Inventory Database. Table 1 shows the processes included in the analysis. Full sources for each datapoint are included in the supplementary material, as well as details on how each section of the database was compiled.

3.2. Building the examples

To build each example from the nexus database, the first step was to take the standard processors and normalise them by their output, for both local and embodied processes. This required two types of data:

- Data on the outputs of each local process, e.g., how much lignite is mined in the EU and how much is imported. Most of these outputs were available from Eurostat, although some structural distinctions required data from other sources (e.g., how much gas is extracted onshore vs. offshore – see supplementary material for full details);
- Data on embodied processes, including: (i) the output of each embodied process (e.g., how much gas is imported by the EU, both directly and indirectly through other energy products); (ii) the origin of each embodied process, to determine the structural mix (e.g., how much of the gas imported within the EU is extracted offshore vs. how much is extracted onshore – depending on where the EU imports its gas from). For indirect imports, we assume that the same structural mix as direct imports applies.

Then, these structural processors were aggregated based on which FEC they produce: electricity, derived heat, gas or fuels (including oil products and biofuels). The FEC ‘gas’ refers only to the gas consumed by sectors such as households and services, and not to natural gas used as an IEC to produce other energy carriers, e.g., the gas used to produce electricity. We kept the distinction between local and embodied processors at the functional level. Finally, we aggregated processors for a nexus description of the energy sector and connected the final outputs to different economic sectors. In the nexus database, in addition to the structural inputs and outputs, all the data needed to produce these examples is provided (including the hierarchical pathways).

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[2] The database is also openly accessible on Zenodo, with DOI 10.5281/zenodo.4271324.

Table 2
Relations between structural processors for Spain, 2018. TI: transformation input; TO: transformation output.

PES extraction					
Process	Type	TO (type)	TO (quantity)	Indirect	Total
			Direct		
Onshore light oil extraction	Embodied	oil (t)	3,43 E+04	9,67 E+03	4,40 E+04
Offshore light oil extraction	Embodied	oil (t)	9,41 E+03	2,66 E+03	1,21 E+04
Onshore medium oil extraction	Embodied	oil (t)	1,75 E+04	4,93 E+03	2,24 E+04
Offshore medium oil extraction	Embodied	oil (t)	5,38 E+03	1,52 E+03	6,90 E+03
Off-shore heavy oil extraction	Embodied	oil (t)	6,72 E+02	1,90 E+02	8,62 E+02
Total oil	Embodied	oil (t)	6,72 E+04	1,90 E+04	8,62 E+04
Lignite mining	Local	lignite (t)	–	–	1,63 E+03
Open-pit coal mining	Embodied	coal (t)	1,27 E+04	3,91 E+02	1,30 E+04
Underground coal mining	Embodied	coal (t)	3,16 E+03	9,78 E+01	3,26 E+03
Total coal & lignite	Mixed	coal & lignite (t)	–	–	1,79 E+04
Onshore gas extraction	Embodied	gas (hm3)	1,35 E+04	0	1,35 E+04
Offshore gas extraction	Embodied	gas (hm3)	6,67 E+03	0	6,67 E+03
Total gas	Embodied	gas (hm3)	2,02 E+04	0	2,02 E+04
Open-pit uranium mining	Embodied	uranium (t)	9,03 E+01	0	9,03 E+01
ISL uranium mining	Embodied	uranium (t)	3,87 E+01	0	3,87 E+01
Total uranium	Embodied	uranium (t)	1,29 E+02	0	1,29 E+02
PES conversion					
Process	**Type**	**TI (type)**	**TI (quantity)**	**TO (type)**	**TO (quantity)**
Hydroskimming refinery	Local	oil (t)	4,03 E+06	oil product (TJ)	1,75 E+05
Hydroskimming refinery	Embodied	oil (t)	2,25 E+06	oil product (TJ)	1,06 E+05
Medium conversion refinery	Local	oil (t)	2,06 E+07	oil product (TJ)	1,96 E+05
Medium conversion refinery	Embodied	oil (t)	1,65 E+07	oil product (TJ)	7,70 E+05
Deep conversion w/coking refinery	Local	oil (t)	1,97 E+07	oil product (TJ)	8,44 E+05
Deep conversion w/hydrocracking refinery	Local	oil (t)	2,36 E+07	oil product (TJ)	1,02 E+06
Gas power plant	Local	gas (hm3)	6,55 E+03	electricity (TJ)	1,08 E+05
Coal power plant	Local	coal (t)	1,62 E+07	electricity (TJ)	1,33 E+05
Wind turbines	Local	–	–	electricity (TJ)	1,83 E+05
Solar PV	Local	–	–	electricity (TJ)	2,84 E+04
Hydropower	Local	–	–	electricity (TJ)	1,26 E+05
Pumped hydro storage	Local	–	–	electricity (TJ)	6,62 E+03
Nuclear plant	Local	nuclear fuel element (t)	1,37 E+02	electricity (TJ)	2,01 E+05
Petroleum products plans	Local	oil products (t)	2,48 E+06	electricity (TJ)	4,01 E+04
CHP	Local	gas (hm3)	4,25 E+03	electricity (TJ)	100609,2
CHP	Local	coal (t)	4,20 E+04	electricity (TJ)	972,0
CHP	Local	oil products (t)	4,64 E+05	electricity (TJ)	12106,8
CHP	Local	biomass (TJ)	7,61 E+03	electricity (TJ)	3355,2
CHP	Local	biogas (TJ)	5169,0	electricity (TJ)	658,8
CHP	Local	waste (TJ)	3084,0	electricity (TJ)	676,8
Other electricity production	Local	–	–	electricity (TJ)	3,77 E+04

4. Results

Section 4.1 describes the sequential pathways, hierarchical pathways, and consumption patterns for the three examples of Spain, Sweden and the EU; and Section 4.2 shows the EU local and embodied nexus patterns at the functional scale, and at the scale of the energy sector.

4.1. Processors across scales for Spain, Sweden and EU

For each example we start with a structural description of the energy sector, mapping sequential pathways. Fig. 5 shows a simplified example for the case of Spain, with data in Table 2, split between PES extraction and PES conversion. The table collects transformation inputs and transformation outputs of each process (for PES extraction processes, only transformation outputs); for embodied processes, data for direct and indirect imports is included. The database also includes the intermediate processes that are not shown in Fig. 5 and Table 2, such as coke ovens. The sequential pathways of Fig. 5 show the connections between categories (e.g., from "oil" to "refineries"), since we did not map how different types of extraction connect to different types of conversion processes. For example, while we know how much gas is extracted onshore vs. off-shore in Spain, we do not know how much of the onshore gas goes directly to consumption and how much is used in gas turbines. For this level of detail, a lower-scale analysis would be necessary, including a GIS interface to track the commodities flowing between each individual technology, while our mapping connects technological types.

The structural description is compiled taking the processors from the database and applying them to the local and embodied outputs of the technologies of each example. Then, processors are hierarchically aggregated based on which FEC they provide. Fig. 6a, 6b and 6c show the hierarchical relations for Spain, Sweden and the EU, respectively. The blue lines connecting processes are hierarchical pathways. CHP processes are mapped onto the "electricity" function in Spain, and the "heat" one in Sweden, based on the quantity of the primary output. This means that, for Spain, the primary output of CHP processes is electricity, with a secondary output of heat; and the other way around for Sweden. Table 3 shows the relative split of each structural mix for the three examples, and Table 4 shows their consumption patterns. Exports are included as a consumption category, since they can be seen as an economic sector where PES and FEC are traded for money, and they constitute an important element of the openness of the energy system.

On the production side (Table 3), for all three examples there are similar trends in what is produced locally and what is imported, with PES extraction being almost entirely embodied, and refineries and power plants almost entirely local. At the EU level, approximately 20% of gas is extracted locally, and lignite, while other PES are mostly imported.[3] For renewable electricity production, wind turbines and

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[3] Note that these results use data from 2018, prior to Russia's invasion of Ukraine.

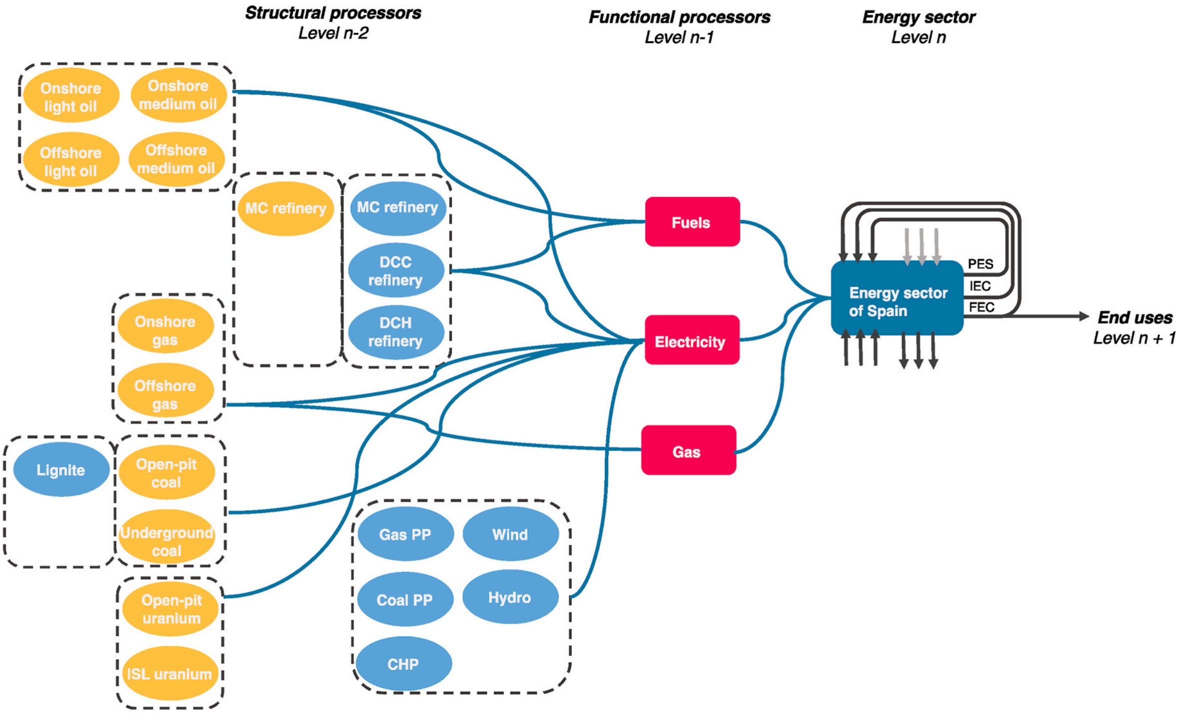

Fig. 6a. Hierarchical relations, Spain (2018). MC: medium conversion; DCC: deep conversion with coking; DCH: deep conversion with hydrocracking; ISL: in-situ leaching; PP: power plant; CHP: combined heat & power.

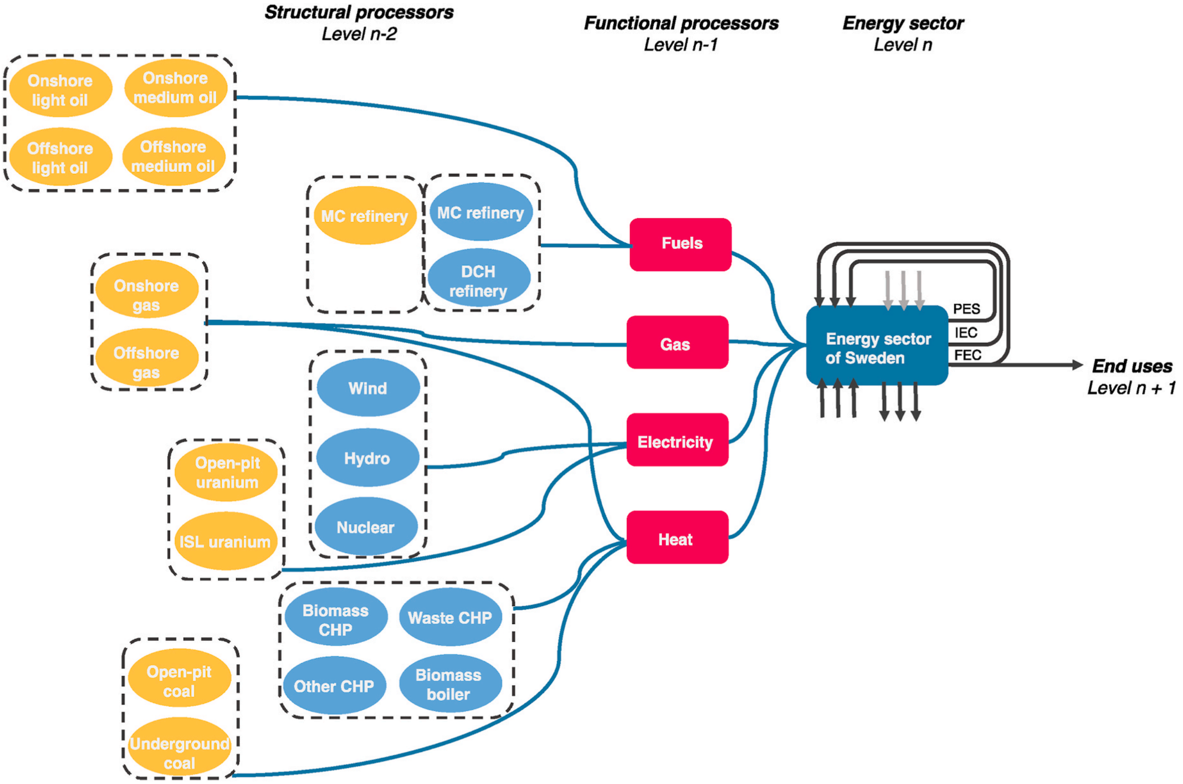

Fig. 6b. Hierarchical relations, Sweden (2018). MC: medium conversion; DCC: deep conversion with coking; DCH: deep conversion with hydrocracking; ISL: in-situ leaching; PP: power plant; CHP: combined heat & power.

hydropower are the only technologies producing a significant share of the final output (12% each), while for heat production, biomass, waste and other CHP plants produce over 80% of the final derived heat. Looking at consumption patterns (Table 4), there are some large-scale similarities across the three examples. Industry and households consume the largest share of electricity, and the transport sector is the largest local consumer of fuels. In Sweden and the EU, households consume the most heat, while in Spain this is substituted by gas, since

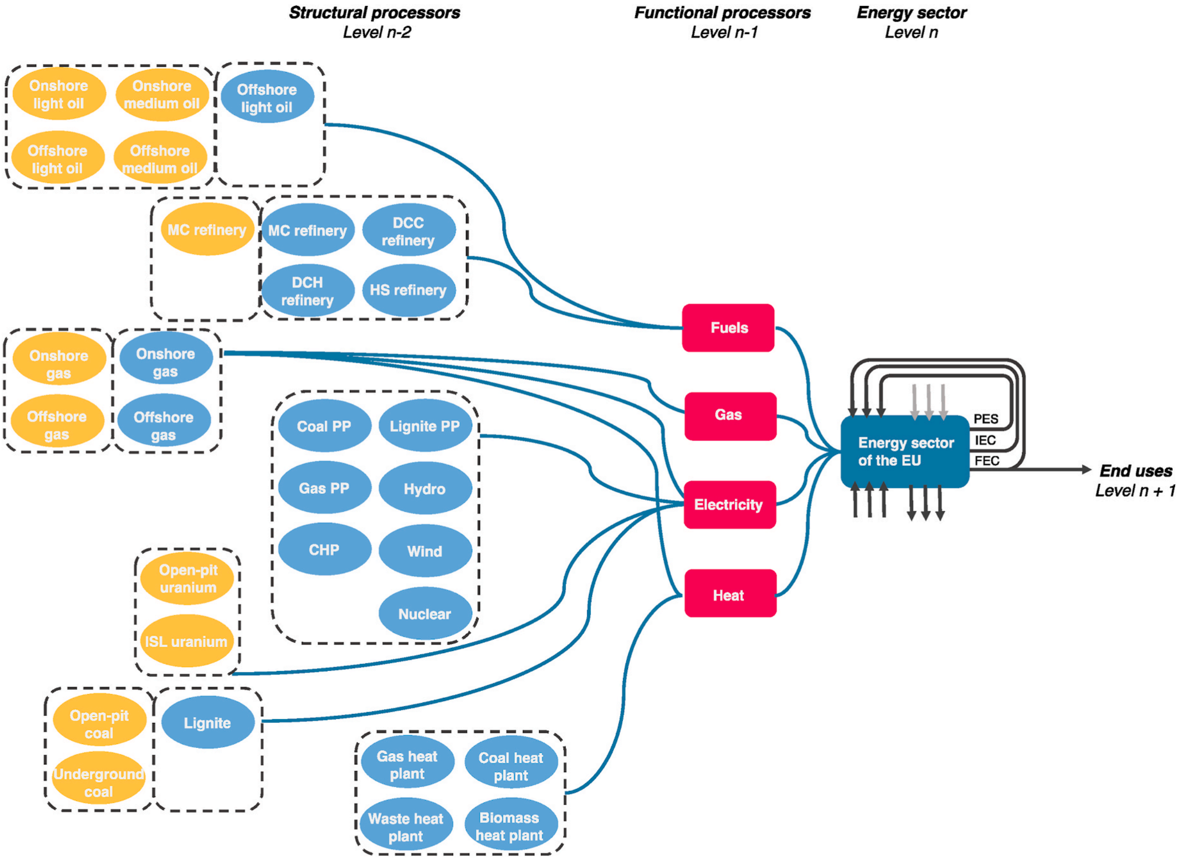

Fig. 6c. Hierarchical relations, EU (2018). MC: medium conversion; DCC: deep conversion with coking; DCH: deep conversion with hydrocracking; ISL: in-situ leaching; PP: power plant; CHP: combined heat & power.

there is no district heating. Given Sweden's structural mix for heat production, the country is less reliant on gas than Spain, and consumes most of its gas imports in the industry sector (almost 80%), while for Spain this figure drops to 50%, with an EU average of 30% (since the EU is also an important exporter of gas, and consumer of gas in the household sector).

As with Fig. 5, each processor in Fig. 6 is also associated with a set of nexus inputs and outputs. At the functional level, data is generated both for the full compartment (e.g., "electricity generation in the EU"), and for the local and embodied components of that compartment, as shown in Section 4.2.

4.2. Nexus patterns

The nexus inputs and outputs associated with each technology are mapped onto local and embodied functional processors, as well as a description of the whole energy sector, for each example. Fig. 7 shows a selection of nexus patterns for the case of the EU – full local and embodied patterns for each case study can be found in Tables S4, S5 and S6 of the supplementary material. The figure shows nexus patterns for the energy sector and for its four functional compartments, although structural descriptions can also be generated (e.g., nexus patterns for "coal and lignite mining"), and processors can be aggregated differently, depending on the goals of the analysis. The three graphs on the left of the figure show examples of two inputs (human activity and technosphere water) and one output (GHG emissions). In all three cases, the embodied component is non-negligible, and especially so in the case of human activity, although in absolute terms the investment of labour in the energy sector is minor compared to other economic activities. Accounting for embodied GHG emissions raises the energy sector's emissions by over 20%, mostly associated with the fuel processor. Similarly, fuels consume the most embodied water. On the right-hand side, we show a subset of the hypercyclic relations of the energy sector. Fuels require oil products across their sequential chain, and a significant share of these products (25%) is embodied. This is similar for electricity – the compartment requires electricity to function, as shown in panel *e*. In this case, however, electricity is produced locally. Gas is consumed by all functional compartments of the energy sector (not only by the gas compartment) and most of the gas needed to sustain the EU's energy sector and each of its functional compartments is embodied.

5. Discussion

REPowerEU frames sustainability and security as two synergistic goals. Nexus thinking complexifies this narrative, showing the relations between: (i) different scales of the energy sector; (ii) local and embodied elements; (iii) the energy sector and other nexus elements. We focused on the nexus elements embodied in the energy sector, showing how accounting solely for the local dimension hides part of the impacts of the EU's current energy mix, and of possible future energy mixes; how accounting for impacts beyond GHG emissions generates a broader representation of sustainability; and how making the distinction between structural and functional elements of the energy system allows checking the impact of technologies and of the aggregations of energy carriers that they produce, generating descriptions that can be more or less detailed depending on their purpose.

The EU's efforts to monitor the impacts of its global supply chain include the Due Diligence Act, monitoring impacts on human rights and the environment (EC, 2021a); and the CBAM, monitoring carbon leakage (EC, 2021b). However, these approaches are not well integrated within energy models themselves. Particularly, what is lacking is a view beyond GHG emissions, and an understanding of the energy-for-energy

Table 3
Output of main processes for each example, and structural mix. The structural split shows ratios (numbers for each category and country sum to 1).

Process	Type	Output	ES	SE	EU
Oil extraction	Mixed	oil (t)	8,64 E+07	2,75 E+07	9,84 E+08
Gas extraction	Mixed	gas (hm3)	2,02 E+04	1,14 E+03	6,74 E+05
Uranium mining	Embodied	uranium (t)	1,29 E+02	1,59 E+02	1,89 E+03
Coal & lignite mining	Mixed	coal & lignite (t)	1,79 E+07	3,02 E+06	7,20 E+08
Refineries	Mixed	oil products (TJ)	3,11 E+06	1,43 E+06	4,20 E+07
Biorefineries	Mixed	biofuels (TJ)	1,87 E+06	7,61 E+04	1,01 E+06
Power plants	Local	electricity (TJ)	8,69 E+05	5,88 E+05	9,32 E+06
Heat plants	Local	heat (TJ)	0,00 E+00	4,52 E+04	6,99 E+05
CHP plants	Local	electricity (TJ)	1,18 E+05	5,60 E+04	2,46 E+06
CHP plans	Local	heat (TJ)	0,00 E+00	1,41 E+05	1,66 E+06
Structural split					
Onshore light oil extraction	Embodied	oil (%)	0,51	0,51	0,46
Offshore light oil extraction	Embodied	oil (%)	0,14	0,14	0,14
Onshore medium oil extraction	Embodied	oil (%)	0,26	0,26	0,25
Offshore medium oil extraction	Embodied	oil (%)	0,08	0,08	0,08
Offshore heavy oil extraction	Embodied	oil (%)	0,01	0,01	0,01
Offshore light oil extraction	Local	oil (%)	0,00	0,00	0,06
Offshore medium oil extraction	Local	oil (%)	0,00	0,00	0,01
Onshore gas extraction	Local	gas (%)	0,00	0,00	0,15
Offshore gas extraction	Local	gas (%)	0,00	0,00	0,06
Onshore gas extraction	Embodied	gas (%)	0,67	0,67	0,40
Offshore gas extraction	Embodied	gas (%)	0,33	0,33	0,40
Open-pit uranium mining	Embodied	uranium (%)	0,70	0,70	0,70
ISL uranium mining	Embodied	uranium (%)	0,30	0,30	0,30
Open-pit coal mining	Embodied	coal & lignite (%)	0,73	0,65	0,39
Underground coal mining	Embodied	coal & lignite (%)	0,18	0,35	0,10
Lignite mining	Local	coal & lignite (%)	0,09	0,00	0,51
Medium conversion refinery	Embodied	oil products (%)	0,19	0,24	0,32
Hydroskimming refinery	Embodied	oil products (%)	0,03	0,03	0,04
Medium conversion refinery	Local	oil products (%)	0,24	0,11	0,16
Deep conversion w/ coking refinery	Local	oil products (%)	0,23	0,00	0,16
Deep conversion w/ hydrocracking refinery	Local	oil products (%)	0,27	0,48	0,24
Special refinery	Local	oil products (%)	0,00	0,14	0,00
Hydroskimming refinery	Local	oil products (%)	0,05	0,00	0,08
Coal power pant	Local	electricity (%)	0,14	0,00	0,06
Lignite power plant	Local	electricity (%)	0,00	0,00	0,06
Gas power plant	Local	electricity (%)	0,11	0,00	0,10
Hydropower	Local	electricity (%)	0,13	0,35	0,12
CHP	Local	electricity (%)	0,12	0,09	0,21
Wind turbines	Local	electricity (%)	0,19	0,09	0,12
Nuclear	Local	electricity (%)	0,20	0,38	0,25
Other	Local	electricity (%)	0,11	0,09	0,09
Gas heat boiler	Local	heat (%)	0,00	0,00	0,13
Coal heat boiler	Local	heat (%)	0,00	0,00	0,04
Biomass heat boiler	Local	heat (%)	0,00	0,15	0,07
Waste heat boiler	Local	heat (%)	0,00	0,02	0,02
Biomass CHP	Local	heat (%)	0,00	0,41	0,12
Waste CHP	Local	heat (%)	0,00	0,06	0,08
Other CHP	Local	heat (%)	0,00	0,29	0,50
Other	Local	heat (%)	0,00	0,07	0,03

loops that are inherent in the complex energy sector (as can be seen from the way gas is used in all functional compartments of the EU's energy sector – Fig. 7f).

Models interact with decision-making at different stages of the policy cycle, from agenda setting to policy evaluation (Süsser et al., 2021). An embodied, multi-scalar approach can be used in both stages: agenda setting, to define sustainability targets that account for embodied effects; and policy evaluation, to check the nexus interactions of chosen goals, inspect the interactions between structure and function, and adjust as needed. Our multi-level accounting method is relatively simple, and we do not aim to replace large-scale models that are used to check the detailed effects of different policy pathways. Rather, we view these representations as vehicles for thought experiments and for narrative building, and through our exercise we call for the inclusion of embodied elements and of a multi-scalar perspective of energy, focusing on the functionality of different types of energy carriers. As pointed out by Ellenbeck and Lilliestam (2019), "(…) it is unlikely that the newest mathematical finesse will have a profound impact on the policy strategy chosen, but it is very likely that the broad strokes that are already included but hidden behind myriads of largely intransparent but discursively shaped modeler decisions will" (p. 75). The transparent methodology presented shows that energy systems look different at different scales, that these scales can be connected with one another but cannot be reduced to one another, and that local and embodied nexus interactions paint a non-linear picture of sustainability.

There are two barriers to the inclusion of local and embodied nexus elements in EU policy processes. One is the lack of data (Voelker et al., 2022): the lack of a standardized, open-access nexus database and of statistics on embodied elements makes these kinds of calculations inexact and hard to compile (see Larsen et al., 2019, for water-for-energy data). Transparency of data and assumptions is particularly important for agenda setting. Ideally, statistical bodies such as Eurostat would include details on the nexus impacts of energy flows, as this data is currently mostly available at the LCA level, based on benchmarks generated from specific technologies in specific locations that are not transparent, and in many cases outdated. Statistics, like evidence, is also policy-based to some extent, so the inclusion of this data needs to come from a political intention. This brings us to the second barrier, which is institutional and political. As nexus practitioners have pointed out, better data does not necessarily lead to better policy, and nexus thinking can bring forth knowledge that is uncomfortable to policymakers (Rayner, 2012; Voelker et al., 2022), pointing to tensions across hierarchical scales, temporal scales, and geographies.

When placed within a static set of dominant narratives, these tensions become problematic. However, if the possibility of adapting goals

Table 4
Consumption patterns for each case study.

	ES	SE	EU	ES	SE	EU
Heat (TJ)				%		
Industry	8,09E+03	2,18E+04	6,59E+05	0,26	0,09	0,27
Transport	0,00E+00	0,00E+00	0,00E+00	0,00	0,00	0,00
Commercial & Public Services	1,64E+04	5,38E+04	5,78E+05	0,54	0,22	0,24
Households	6,08E+03	1,08E+05	1,09E+06	0,20	0,45	0,46
Agriculture, Forestry & Fishing	0,00E+00	3,00E+02	1,02E+04	0,00	0,00	0,00
Other Sectors	2,17E+00	5,66E+04	6,09E+04	0,00	0,24	0,03
Exports	0,00E+00	0,00E+00	7,60E+01	0,00	0,00	0,00
Total	3,05E+04	2,40E+05	2,40E+06	1,00	1,00	1,00
Electricity (TJ)				%		
Industry	2,83E+05	1,83E+05	3,40E+06	0,31	0,32	0,26
Transport	1,46E+04	9,26E+03	2,11E+05	0,02	0,02	0,02
Commercial & Public Services	2,68E+05	1,01E+05	2,66E+06	0,30	0,18	0,20
Households	2,70E+05	1,62E+05	2,55E+06	0,30	0,29	0,19
Agriculture, Forestry & Fishing	1,81E+04	4,28E+03	3,00E+06	0,02	0,01	0,23
Other Sectors	4,42E+03	0,00E+00	8,88E+03	0,00	0,00	0,00
Exports	4,65E+04	1,06E+05	1,31E+06	0,05	0,19	0,10
Total	9,05E+05	5,65E+05	1,31E+07	1,00	1,00	1,00
Fuels (TJ)				%		
Industry	2,08E+05	2,35E+05	2,51E+06	0,07	0,18	0,07
Transport	1,34E+06	2,84E+05	1,16E+07	0,44	0,21	0,34
Commercial & Public Services	6,15E+04	1,46E+04	6,22E+05	0,02	0,01	0,02
Households	1,96E+05	4,10E+04	3,33E+06	0,06	0,03	0,10
Agriculture, Forestry & Fishing	8,18E+04	2,08E+04	7,79E+05	0,03	0,02	0,02
Other Sectors	7,64E+03	3,99E-01	6,82E+04	0,00	0,00	0,00
Exports	1,16E+06	7,44E+05	1,55E+07	0,38	0,56	0,45
Total	3,06E+06	1,34E+06	3,44E+07	1,00	1,00	1,00
Gas (TJ)				%		
Industry	3,56E+05	2,11E+04	3,41E+06	0,49	0,78	0,31
Transport	8,50E+03	4,78E+02	1,47E+05	0,01	0,02	0,01
Commercial & Public Services	7,93E+04	3,27E+03	1,58E+06	0,11	0,12	0,14
Households	1,53E+05	1,37E+03	3,37E+06	0,21	0,05	0,30
Agriculture, Forestry & Fishing	6,54E+03	2,09E+02	1,44E+05	0,01	0,01	0,01
Other Sectors	1,35E+02	0,00E+00	2,54E+03	0,00	0,00	0,00
Exports	1,18E+05	5,50E+02	2,49E+06	0,16	0,02	0,22
Total	7,21E+05	2,69E+04	1,11E+07	1,00	1,00	1,00
Total (TJ)				%		
Industry	8,55E+05	4,61E+05	9,99E+06	0,18	0,21	0,16
Transport	1,36E+06	2,93E+05	1,20E+07	0,29	0,14	0,20
Commercial & Public Services	4,25E+05	1,73E+05	5,45E+06	0,09	0,08	0,09
Households	6,25E+05	3,12E+05	1,03E+07	0,13	0,14	0,17
Agriculture, Forestry & Fishing	1,06E+05	2,56E+04	3,94E+06	0,02	0,01	0,06
Other Sectors	1,22E+04	5,66E+04	1,41E+05	0,00	0,03	0,00
Exports	1,33E+06	8,51E+05	1,93E+07	0,28	0,39	0,32
Total	4,71E+06	2,17E+06	6,11E+07	1,00	1,00	1,00

and values is considered, these tensions could generate collective discussions and negotiations on desirable energy futures. Discussions may make more sense at the local and regional level, giving the difficulty of coordinating different DGs driven by powerful policy narratives (Voelker et al., 2022). While EU energy policy follows the principle of subsidiarity, this principle has mostly been invoked for Member State's autonomy in relation to the EU, and regional and local actors have asked for this principle to be extended to their scale (Palle and Richard, 2022). Discussing local and embodied nexus interactions at different governance levels may be an effective way to build alternative narratives that challenge reductive views on sustainability problems. In addition to discussions across different governance levels, intra-sectorial discussions are also necessary, and can be facilitated by nexus thinking, as it allows focusing on the relations among sectors.

Our examples are illustrative of the framework and the quantitative results are not meant to inform policy, but we provide the elements needed to build an embodied, multi-scale nexus analysis. A research agenda grounded in nexus thinking could consider:

- Looking at the openness of the energy sector not only in terms of imports but also in terms of exports. In 2018, 45% of the fuels produced in the EU were exported, and 22% of gas (Table 4). The sustainability implications of fossil fuel exports are currently not discussed by EU policy. This would call for a global sustainability perspective that accounts for impacts both within and outside of governance boundaries.
- Connecting nexus elements to end uses through their sequential pathways, accounting for how each sector generates local and embodied impacts (e.g., the water embodied in electricity consumed in the household sector). For now, we have shown how economic sectors consume different energy carriers, so this connection would be straightforward to make, and would enrich collective discussions, allowing different stakeholders to value nexus dimensions depending on what the energy carriers are used for – building on the notion that "not all GHG emissions are the same" (Jasanoff, 2007).
- Expanding the analysis beyond the energy sector, looking at embodied nexus elements in agricultural products, goods, etc. This would allow discussing nexus interactions while also taking into perspective the goals and priorities of different sectors, and processors across scales could be used as building blocks for this kind of comprehensive analysis.

6. Conclusions and policy implications

EU energy policy is informed by large-scale models, such as PRIMES and GAINS, using data and assumptions that are not available to the public. While target setting in policies can often be a political decision that is not supported by models (Süsser et al., 2021), models have a part to play in showing what elements are relevant for sustainability, the relations among those elements, and the scale at which to consider phenomena. Nexus thinking is relational: describing the energy system

Fig. 7. A selection of nexus patterns for the case of the EU.

from a nexus perspective means looking at the relations between energy and other social-ecological elements; at the relations between local and embedded elements; and at the relations between different scales – i.e., levels of granularity that can be used to observe and aggregate energy flows. The European Green Deal and the REPowerEU plan align sustainability and security goals under a green growth umbrella. The nexus interactions of energy with other social-ecological elements are not central to these policies, that focus on GHG emissions; and the global impacts of policies are considered with ex-post mechanisms, rather than forming part of agenda setting.

By providing a framework, and through three examples, we showed how the energy system can be described through a collection of local and embodied nexus elements in a simple way. The examples themselves have limitations, including approximations and simplifications due to data availability, and the lack of uncertainty estimations, which would be required for further implementations of the method to chosen case studies. Beyond the quantitative assessments, we recognise that the science-policy interface is complex, and that accounting methods may not lead to institutional change, regardless of whether that change is local or at the EU level, due to political barriers. However, this should not discourage experts from producing models of energy systems that can provide different sustainability perspectives and add nuance to dominant narratives, by diversifying knowledge (Turnhout, 2019).

The policy implications of our approach are tied to the three types of relations that we highlighted. First, the relations between energy and other social-ecological elements call for a sustainability agenda that goes beyond GHG emissions; second, the relations between different scales of the energy system, with a focus on functionality, call for a combination of models at different scales, not only considering technologies (e.g., renewable electricity generation), but also how the energy carriers produced by those technologies are used by different sectors; third, the relations between local and embodied elements call for including a global perspective of sustainability within energy models themselves, in order to better interact with existing mechanisms such as the CBAM.

Taking these three types of relations into account would complexify the information landscape used to make decisions, pointing to tensions that could generate collective discussions on energy futures. These collective discussions should be carried out simultaneously across different sectors at the local and regional scale, challenging and diversifying the European Commission’s powerful policy narratives.

CRediT authorship contribution statement

Louisa Jane Di Felice: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laura Pérez-Sánchez:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Michele Manfroni:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Mario Giampietro:** Supervision, Methodology, Funding acquisition, Conceptualization.

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.

Data availability

Full data has been shared in the supplementary material link. Data can be used to reproduce results, and to build new case studies

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2024.114052.

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