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How sustainable development goals have transformed our world? Evolution of the ecological networks of the Italian economy

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ABSTRACT

This article focuses on modelling the structure of the Italian economy and its evolution from 2015 to 2019 using Physical Input-Output tables to understand its functioning in terms of biophysical and monetary exchanges. We considered energy extracted from natural resources within the country and embodied energy from natural resources extracted abroad. The model includes final demand (government, household, and gross capital formation) as endogenous factors. The results show that Agriculture, Advanced Manufacturing, and Tertiary industry are the main sectors consuming energy when considering the direct energy required to produce one unit of economic output. However, when assessing embodied energy, Tertiary Industry emerges as the leading consumer of energy. The findings demonstrate how the services sectors are highly dependant on the flow of energy-intensive resources. Ecological Network Analysis (ENA) was applied to identify the main sectors driving the Italian economy and their ability to obtain energy inflows from other sectors. The study found that the Tertiary industry, Final demand, and Manufacturing sectors were the main drivers of the Italian economy and had a higher ability to obtain energy inflows. The results also showed that exploitative or control relations dominated interactions between different economic sectors. Our results highlight that the dematerialization process at national level comes at environmental costs elsewhere.

1. Introduction

Global consumption of materials and energy as well as the associated environmental impacts have greatly increased in the last decades (Krausmann et al., 2017). Many sustainability issues related to the transgression of planetary boundaries are caused by the extraction, processing and discharge of energy and resources (Steffen et al., 2015). As a response to the unsustainable pathway of most countries, the United Nations elaborated the *Agenda 2030* setting 17 goals for sustainable development (UN, 2015). The Sustainable Development Goals (SDGs), despite being rightfully criticised by some due to their focus on economic growth and the contradictions between some goals (Hickel, 2019), provide a framework to assess the transition towards a more sustainable society from a social-ecological perspective. In particular, Goals 7, 9, 10, 11 and 12 are related to cities and countries compromise to improve the provision of sustainable energy to citizens, building a strong economy that reduces inequality while enhancing resilience; simultaneously, these changes should be accompanied by a transition to sustainable consumption and production patterns (UN, 2015). Since the SDGs are currently at a mid-term stage, it is timely to assess to what extent nations have transitioned towards a more sustainable pathway.

Since energy is required for any economic process to be carried out (Odum, 1996), the energy-money coupling can provide insightful information to assess the sustainability of a nation by putting together the biophysical requirements of any economy and its cultural component including human valuation. In this regard, social metabolism addresses the biophysical exchange processes between society and the environment, and the related sustainability problems. In such a way, social metabolism studies the biophysical basis of the economy and provides a framework to investigate patterns and dynamics of socio-economic material and energy flows and their drivers. This knowledge has proven to be useful to manage resource flows in a more sustainable way (Krausmann, 2017).

Social metabolism can be assessed with the use of Ecological Network Analysis (ENA) (Fath et al., 2007). ENA allows to study these material, energetic or monetary flows, providing information about the

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structure of a society, as well as the relation between its components, which has led to an increase of its use in the last decades (Borrett et al., 2018). ENA combines modelling and analysis to investigate the structure, function, and evolution of complex systems by tracing the movement of thermodynamically conserved energy or matter through the system (Borrett et al., 2018). The components and the exchanges between urban metabolic systems can be represented as a collection of flows, and the exchange of materials and energy through pairwise interaction resemble those in an ecological network (Fath and Patten, 1999; Zhang et al., 2014).

In the context of multiple industries interacting within the economic system, the relevance of production sectors and their contributions to sustainable development requires a measure that delineates both forward and backward linkages to empirically analyse the role of each industry and to evaluate the connections between economic sectors (Kay et al., 2007). Within this framework, linkages between sectors estimate interdependencies between them, as well as their contribution or dependence to the functioning of the economy (Ciaschini et al., 2022; Fath et al., 2007).

The goal of this study is to biophysically assess the Italian economy through Physical Input-Output fluxes between its economic sectors. These fluxes are measured in direct energy (energy extracted from natural resources within the country), and energetic products (energy extracted abroad and imported as energetic products). To this end, we aim to (i) build a model of the Italian economy and its economic sectors; (ii) determine the sectorial linkages, energy use intensity, utility relations and structural characteristics; (iii) analyse its evolution during the first five years after the implementation of the Sustainable Development Goals (2015–2019); and (iv) provide the implications of these attributes for system sustainability.

2. Material and methods

2.1. General model

According to Herendeen and Bullard (1974), a national economy can receive energy in three different ways: (i) energy extracted from natural resources within the country; (ii) energy products, i.e., energy produced from natural resources extracted outside the country; and (iii) energy incorporated into imported goods and services, i.e., non-energetic goods. In this study we considered the first two sources, since the third one requires a multi-regional perspective integrating world trade.

We used physical-monetary input-output tables to track the economic and environmental resources involved in the exchanges. To translate the economic data into physical data, the so-called 'embodied energy intensity factor' was used. The amount of energy that is involved in a product or process has been measured using a closed Input-Output System. The methodology used for this calculation was developed by Costanza (Costanza, 1980, 1979; Costanza and Herendeen, 1984) and has already been applied by many combined with ecological network analysis (Fath et al., 2007; Galychyn et al., 2022; Zhang et al., 2014).

The embodied energy intensity can be defined as follows:

$$E + eZ = e\widehat{X} \tag{1}$$

where E represents the energetic input inflow matrix, e represents the embodied energy intensity factor, Z is the transaction matrix and X is the economic output of the system. The hat on the X means that column vector is diagonalized in order to perform the operation. It is possible to solve for e, which is a row vector representing the embodied energy intensity per unit of X, in the following way:

$$e = E(\widehat{X} - Z)^{-1} \tag{2}$$

In essence, this factor quantifies the amount of energy used per unit of monetary value within the system, that is, its efficiency to transform energy into economic products. Using this measure, we can estimate how much energy, directly and indirectly, is consumed by the different sectors of a national economic system. To convert monetary data into energetic units, it is necessary to use the appropriate 'energy intensity coefficients' and multiply them with the corresponding flows. The product of the energy intensity coefficients and the gross output shows the total embodied energy, both direct and indirect, involved in the production of goods and services. Similarly, the e vector multiplied by the final demand allows us to calculate the embodied energy of the final demand. The total amount of energetic input should be equal to the sum of the results of the last multiplication, which ensures that the model is accurate and avoids double counting. This method is used to verify the model's accuracy, as already used in previous studies (Galychyn et al., 2022; Zhang et al., 2014). Guarino et al. (2023) employed the same model to examine the correlation between energy input and economic output. The correlation that emerges from the closure of the Input-Output model makes embodied energy a reliable indicator of prices, particularly for resources that lack a market. This raises the possibility of energy as an original factor of production (Missemer and Nadaud, 2020).

This study used the Input-Output tables provided by ISTAT on the Italian economy from 2015 to 2019 (ISTAT, 2020a). Symmetrical tables were used, constructed using the 'Technology by Branch' methodology. The tables record yearly monetary transactions between 63 sectors expressed in millions of euros. For the sake of simplicity, the sectors have been grouped into ten main categories. Appendix Table A1 shows the abbreviations, component names and sectors they comprise. Energy data were also obtained from ISTAT for the 2015–2019 period (ISTAT, 2020b). The 'Physical Energy Flow Account' (PEFA) records the consumption of energy flows according to the destination sector expressed in Terajoules.

2.2. Final demand as internal sector: government, household and gross capital formation

The model considers final demand and added value as internal sectors, e.g., as dummies sectors of the economy. Final demand is composed of 'government investment', 'household consumption' and 'gross capital formation'. In parallel, added value is composed of 'employee compensation', 'indirect business taxes' and 'capital depreciation'. Several studies suggest internalising household and government to analyse the interdependence between economic production and energetic inputs (Appelbaum, 1992; Costanza, 1980; Duchin and Steenge, 2007) and many others have already applied (Fath et al., 2007; Zhang et al., 2014). We also considered gross capital formation as endogenous (Costanza, 1979). This methodological process involves creating a balance between the taxes and wages of household and government consumption. According to the authors, these sectors receive goods and services from other sectors based on personal consumption and government spending. In turn, they provide services to other sectors based on employee compensation, indirect business taxes, and a percentage of property-type income. For the Italian economy, the government sector can be defined according to the categories provided by ISTAT (see Appendix Table A1) as follows:

$$\mathrm{OT} + \mathrm{X}_g * \mathrm{PTI} + \mathrm{TLCP} = \mathrm{FEPB} + \mathrm{GS} \tag{3}$$

where OT is the "Other Taxes". X_g is the coefficient of the value added for government sector. PTI is the "Property-type income" that is the "Rent from capital". $TLCP$ is the "Taxes less contribution on products". $FEPB$ is the "Final expenditure of public administration". GS is the "Government Salaries" that is "Taxes less contribution on profits".

In the same way for the household sector:

$$EC + X_h * \mathrm{PTI} + \mathrm{GS} = \mathrm{FCEH} + \mathrm{TLCP} \tag{4}$$

where EC is the "Employee compensation". X_h is the coefficient of the value added for household sector. PTI is the "Property-type income" that

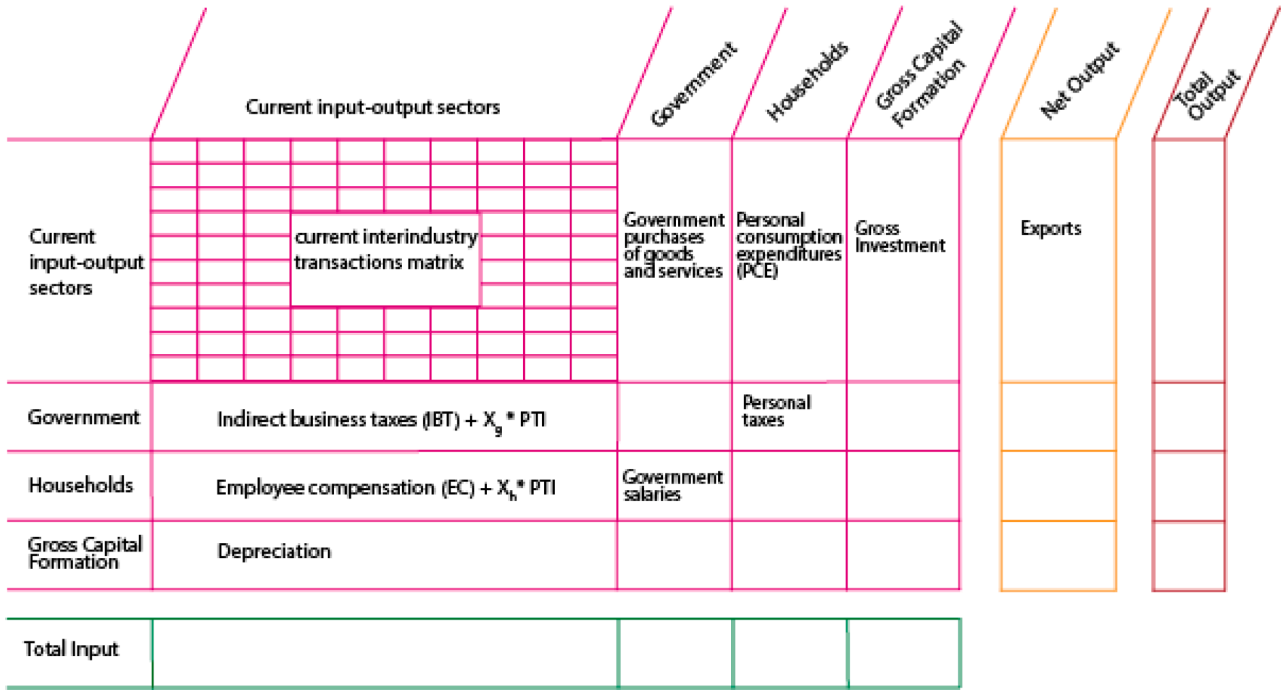

Fig. 1. Input-Output Table's considering Government, Households and Gross Capital Formation as internal transactions. In pink the matrix of domestic transactions, in orange the net output (i.e. exports), in red the economic output and in green the energy input.

is the "Rent from capital". *GS* is the "Government Salaries" that is "Taxes less contribution on profits". *FCEH* is the "Final consumption expenditure of households". *TLCP* is the "Taxes less contribution on products".

Then, it is possible to derive the coefficients through the following equations:

$$X_g = (FEPB + GS - OT - TLCP)/PTI \tag{5}$$

$$X_h = (FCEH + TLCP - EC - GS)/PTI \tag{6}$$

The remaining part of the added value is calculated by the difference, and it is called net profit.

$$X_e = 1 - X_g - X_h \tag{7}$$

To fully develop the model, it is essential to consider the part of the economic process that involves restoring and expanding the fixed assets that are consumed during the process itself. Therefore, we included gross investment as a column in our transaction matrix and depreciation as a row. This approach allows us to treat gross capital formation as a productive sector, like households and government sectors. As a result, the net output in the model is only made up of exports. Fig. 1 shows the basic form of the monetary-physical input-output table considered.

2.3. Ecological network analysis

Once the energy intensity factors have been calculated, we multiply them by the appropriate monetary flows in the transaction matrix. In this way, we have a matrix showing the embodied energy in transactions between sectors. For instance, the term f_{ij} denotes the embodied energy in the transaction between sector i and sector j. In order to perform Ecological Network Analysis, the model should meet steady-state requirements. In other words, it is necessary for the model to adhere to the principle of conservation of energy and mass, as stated in the first law of thermodynamics (Fath et al., 2001). The steady-state requirement is given by the following equation:

$$T_j = T_i \tag{8}$$

where T_i refers to the sum of all flows to each sector i and T_j refers to the sum of all outflows from each sector j. Hence, the system can be considered to be in a steady-state if the total amount of inputs and outputs from each compartment i and the environment, R_i, is equivalent to the total amount of outputs and inputs from each compartment i and the environment, Y_i. It is possible to rewrite the previous equation as the following:

$$f_{ij} + R_i = f_{ji} + Y_i \tag{9}$$

To proceed, the estimation of indirect and integral flows between each pair of system components is required. This can be achieved by determining the non-dimensional input-orientated transfer efficiencies along all pathways in the system. The elements of the non-dimensional output-orientated transfer efficiency matrix (G) can then be determined using the next equation:

$$g_{ij} = f_{ij}/T_i \tag{10}$$

In this equation, g_{ij} represents the total amount of energy (direct plus indirect) input flows to each sector i (T_i) required to produce 1 TeraJoule of energy flow from each sector j to each sector i (f_{ij}). In the ENA, the matrix (G) is known as an 'input-orientated non-dimensional ecological element exchange efficiency matrix' due to its focus on the non-dimensional input-orientated transfer efficiencies between the ecological components. The matrix illustrates the proportion of the initial input energy that is effectively utilized in the exchange process between each set of sectors. The computation of a dimensionless integral flow intensity matrix (N) can be carried out based on the direct flow (f_{ij}) between each pair of nodes. This represents the sum of the initial, direct and indirect transfer efficiencies.

$$N = G_0 + G_1 + G_2 + \cdots + G_n = (I - G)^{-1} \tag{11}$$

If we multiply the integral flow intensity matrix with the diagonal of the flow matrix, represented by diag(T_i), we can generate a matrix *Y* that indicates the relative contribution of each component:

$$Y = diag(T_i) * N \tag{12}$$

This information enables us to calculate the "integral pulling force weight (W_i)" and the "integral driving force weight (W_j)" (Fath et al., 2007; Galychyn et al., 2022; Zhang et al., 2014).

$$W_i = \sum_{j=1}^{n} y_{ij} \Big/ \sum_{i=1}^{n} \sum_{j=1}^{n} y_{ij} \tag{13}$$

$$W_j = \sum_{i=1}^{n} y_{ij} \Big/ \sum_{i=1}^{n} \sum_{j=1}^{n} y_{ij} \tag{14}$$

The numerators of the equations represent the total energy contributed by the system to sector *i* and the total energy contributed by sector *i* to the system, respectively. The "pull force weight" represents the ability of sector *i* to obtain energy inflows from other sectors through forward linkages (i.e., demand linkages). This factor reflects the extent to which sector *i* depends on other sectors in the system. The "driving force weight" indicates the capacity of sector *i* to offer energy support to other sectors through backward linkages (i.e., supply linkages). It assesses the level of influence that sector *i* exerts over other sectors in the system. We can consider them as upstream and downstream relations, respectively. By combining them, we can obtain the ecological hierarchy of the economic system. Zhai et al. (2019) explored the effects of indirect contributions, highlighting the need to determine and compare both indirect and direct pulling and driving force weights.

$$F_i = \sum_{j=1}^{n} e_{ij} \Big/ \sum_{i=1}^{n} \sum_{j=1}^{n} e_{ij} \tag{15}$$

$$F_j = \sum_{i=1}^{n} e_{ij} \Big/ \sum_{i=1}^{n} \sum_{j=1}^{n} e_{ij} \tag{16}$$

Fi and *Fj* are direct pulling and driving force weights, respectively. $\sum_{j=1}^{n} e_{ij}$ is the direct contribution by the system to sector *i* and $\sum_{i=1}^{n} e_{ij}$ is the direct contribution by sector *i* to system. It is possible to determine indirect pulling and driving force weights by subtraction:

$$E_i = W_i - F_i \tag{17}$$

$$E_j = W_j - F_j \tag{18}$$

Then, it is feasible to identify the type of relationship that exists between each pair of sectors. This can be done by computing the direct utility intensity matrix (D), and subsequently examining the integral intensity matrix (U). The matrix D is composed of the net flows between components *i* and *j*, as shown in the following equation.

$$d_{ij} = \left(f_{ij} - f_{ji}\right) / T_i \tag{19}$$

The D matrix only indicates the nature of the direct relationship, whereas the integral utility intensity matrix (U) provides insight into the complete advantages or disadvantages of any connection between any pair of components. In other words, it also takes indirect effects into account. The integral utility intensity matrix (U) is given by the next equation:

$$U = D_0 + D_1 + D_2 + \cdots + D_n = (I - D)^{-1} \tag{20}$$

Matrix U can have positive or negative values, which reveal whether the relationship is beneficial or harmful. We calculated five types of relationships: exploitation (+, -), where one component benefits more than the other; control (-, +), where one component's outputs are influenced by the other; competition (-, -), where both components are negatively affected; neutralism (0, 0), where there is no effect on either component; and mutualism (+, +), where both components benefit from the relationship. However, because control and exploitation are essentially the same relationship with reversed utility flow, they were combined into one category, leaving only four types of relationships. Determining the type of relationship between two components can provide insights into the overall system's structure and dynamics.

Then, matrix U should be dimensionalized to obtain values of total benefits and costs from the relations between each pair of sectors in the system. The dimensionalized integral utility matrix (Y) is obtained from:

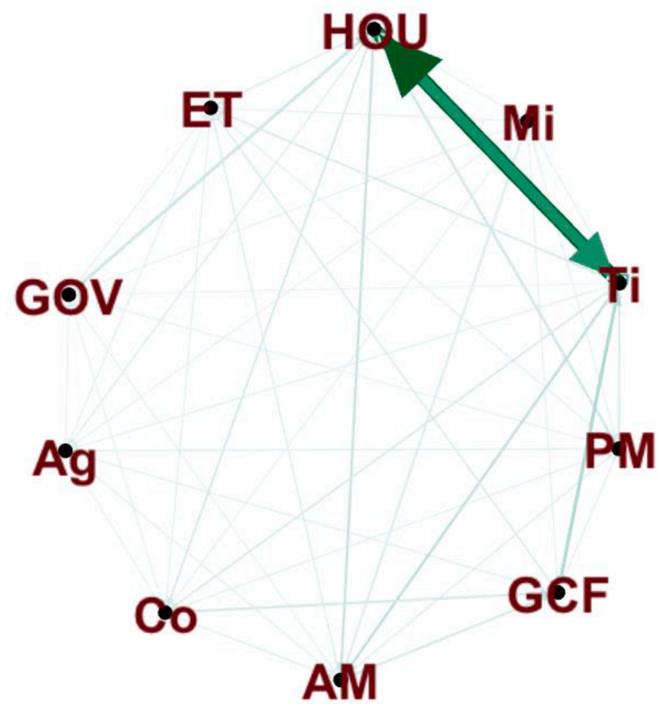

Fig 2. Network plot of the economic sectors of the Italian economy based on link strength of Energetic Products' weights 2019. Abbreviation code: HOU: household; Mi: mining; Ti: tertiary industry; PM: primary manufacturing; GCF: gross capital formation; AM: advanced manufacturing; Co: construction; Ag: agriculture; GOV: government; ET: energy and material transformation.

$$Y = diag(Ti) \times U \tag{21}$$

From this matrix mutualism index (M) and synergism index (S) can be estimated:

$$MI = \sum U(+) \Big/ \sum U(-) \tag{22}$$

$$SI = \sum Y(+) + \sum Y(-) \tag{23}$$

where $\sum$U(+) and $\sum$U(−) are sum of flows with positive and negative utilities, respectively. If MI is greater than 1, it means that the total benefits of interactions outweigh costs in the system and hence the system can be considered mutualistic and healthy (Tan et al., 2018). The synergism index is a ratio of integral flows with positive utilities to the integral flows with negative utilities (Tan et al., 2018). When $S > 0$, synergism is said to occur, i.e., systems have positive net benefits (greater benefits than costs) resulting from relations between each pair of sectors (Fath and Borrett, 2006; Zhang et al., 2016). All calculations have been made with MATLAB (version R2018A), and graphical representation with R (R Core Team, 2022).

3. Results

The Italian economic sectors are structured as depicted in Fig. 2. These links reflect exchanges of embodied energy between economic sectors, as well as the one recirculated within each of them.

3.1. Evolution of direct and embodied energy intensity across economic sectors

The flow analysis shows the direct (i.e., energetic unit) and

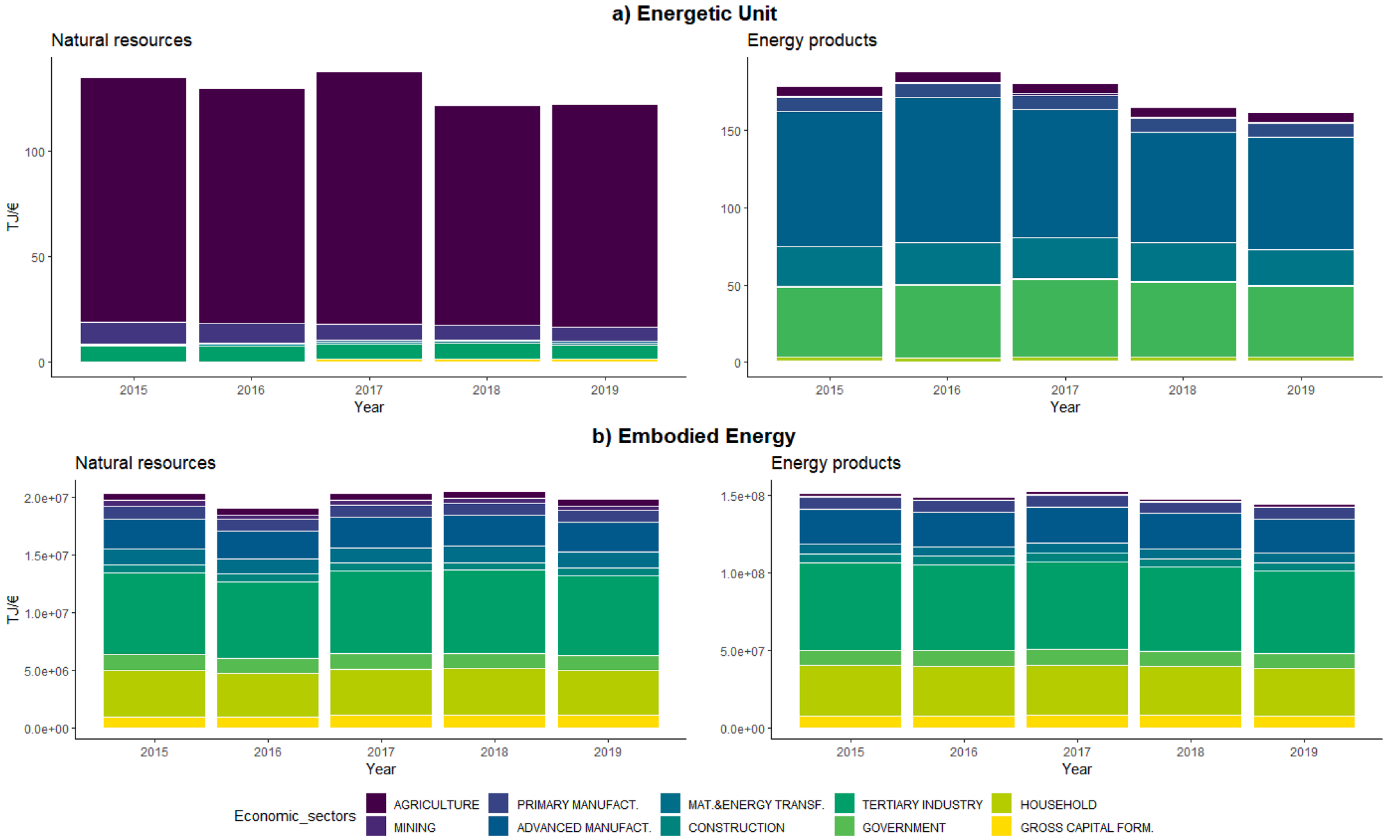

Fig. 3. Evolution of the energetic units (Fig. 3a) and embodied energy (Fig. 3b) required to produce one unit of economic output (TJ/€) for each economic sector. Each colour represents an economic sector.

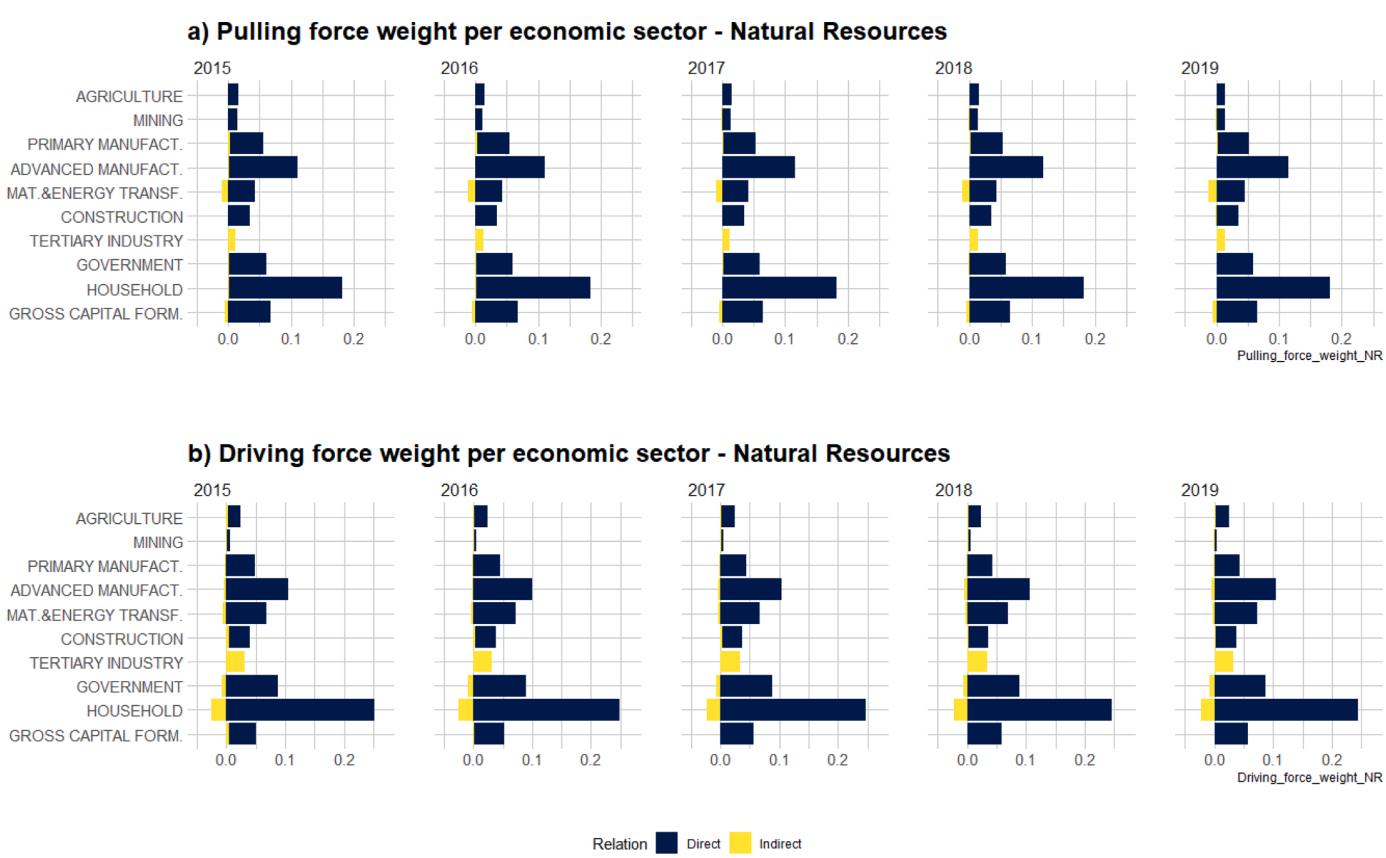

Fig. 4. Evolution of pulling (4a) and driving force weight (4b) for energy from natural resources.

embodied (direct + indirect) amount of energy required to produce one unit of economic output for each economic sector, considering local natural resources (NR) and energy products (EP). Our results show that, in terms of direct energy, the Agricultural sector, Advanced Manufacture and Tertiary Industry are the sectors that require higher quantities of energy per economic product; that is, in terms of direct energy these sectors have lower efficiency to transform energy into economic product (Fig. 3a). Moreover, while the Agricultural sector mainly uses local natural resources, both Manufacture and Tertiary industry rely on imported energy products. On the other hand, Final demand (grouping Government, Household, and Gross capital formation) does not directly consume energy from local natural resources and only few quantities of imported energy products (Fig. 3a). In Fig. 3b we can observe that, when accounting for the embodied energy, the configuration of the economic sectors changes. First, Tertiary industry turns out to be the most energy-intensive sector, mainly from energy products. The same can be said for Advanced Manufacturing. More specifically, subsectors such as Programming, IT consultancy and related activities are highly energy-intensive, accounting for 2.81% of the Tertiary industry, just as they represent 76% of the entire agricultural sector or 5 times the mining sector (further information available in Supplementary Material, Table S2).

Regarding the evolution of the energy intensity from 2015 to 2019, all sectors remained almost constant for both direct and embodied energy (Fig. 3). In terms of direct energy, Agriculture, Mining and Advanced manufacture show a decreasing trend. For the first two sectors, this is due more to a reduction in the consumption of local natural resources than to energy products. For Advanced manufacture the opposite is true. However, Tertiary industry shows a slight increase in energy products (Fig. 3a). On the other hand, the embodied energy of the local natural resource is fairly stable during the whole period. As for embodied energy of energy products, Tertiary industry and Advanced Manufacturing have a moderate decline (Fig. 3b). Considering the importance and number of sub-sectors involved in the tertiary industry, an internal classification can be found in Appendix Table A1. The implications of this results will be deepened in the discussion section.

3.2. Ecological network of the Italian national economy

3.2.1. The contribution and dependence of economic sectors to the national economy

The capacity of each economic sector to capture resources from (Fig. 4a) and contribute to (Fig. 4b) the Italian economy remained constant over the studied period. Due to the similarity between the pull and driving force weights of natural resources and energy product, we show here the first one, while the latter is available in the Supplementary Material. The structure of the economy is determined by small pull and driving forces from the primary sectors (Agriculture and Mining) and strong for the tertiary sector and private consumption (Tertiary industry, Final demand – mainly Household –, and Manufacturing). Therefore, Fig. 4 shows an inverted pyramid structure with primary sectors on the top.

All weights show direct values higher than indirect values despite indirect values account for feedback loops and relationships between sectors (Fig. 4). The sectors showing the lowest indirect pull force values for local natural resources are the Material and Energy Transformation, with the minimum value of −1.12% in 2019, and the Gross Capital Formation sector, with the minimum value of −0.57% in 2016. Meanwhile, regarding energetic products, the Mining sector, with the minimum value of −0.91% in 2015, the Material and Energy Transformation sector, with the minimum value of −0.49% in 2019, and the Advanced Manufacturing sector, with the minimum value of −0.23% in 2015, are the sectors with lowest indirect pull force weights. This implies that the demand for the services provided by these three sectors exceeds the level of investments made into them.

Regarding the driving force weight, results show a gradual increase in weights as we move from primary to tertiary sectors and into final demand (Fig. 4b). The sectors with the highest values include Tertiary industry, with over 35% if direct and indirect effects are considered; Household, with over 30% direct but around −5% indirect; and Advanced manufacturing, just above 10%. Moreover, when we consider final demand jointly, it turns out to be the leading sector driving the Italian economy. Indeed, Household sector has the lowest indirect weights for local natural resources and energy products, with values of −5.46% and −5.58%, respectively, both reported in 2016.

Table 1
Ecological relations between economic sectors.

	Year	Ecological Relations (%) Mutualism	Exploitative or Control	Competition
Natural Resources	2015	15.6	71.1	13.3
	2016	13.3	75.6	11.1
	2017	15.6	71.1	13.3
	2018	15.6	71.1	13.3
	2019	15.6	73.3	11.1
Energy Products	2015	20.0	62.2	17.8
	2016	20.0	62.2	17.8
	2017	20.0	62.2	17.8
	2018	20.0	62.2	17.8
	2019	20.0	66.7	13.3

3.2.2. Ecological relations between economic sectors

The 45 interactions (pairwise linkages of the 10 sectors) between different economic sectors resulted in a majority of exploitative or control relations (between 60 and 69%) followed by mutualistic (between 18 and 24%) and competition (between 11 and 16%) relations (Table 1). Moreover, as it can be observed, there was almost no difference in the ecological relations between sectors during the studied period.

Our results show that the Construction sector has the largest number of mutualistic relationships, with five out of eight mutualistic relationships in term of local natural resources. These relationships are with the Agriculture, Mining, Primary Manufacturing, Material and Energy Transformation, and Tertiary Industry sectors. For energy products, the mutualistic relationships rise to six by including the Government sector. Considering local natural resources, the Advanced Manufacturing sector is found to have the largest number of extractive/control relationships with other sectors, including all other sectors in the study, for all years considered. When considering the final demand combined, it has the second largest number of extractive/control relationships. Although the sector has mutualistic relationships with the Government, Household, and Gross Capital Formation sectors, its only mutualistic relationship with other sectors is with the Tertiary Industry sector. Regarding energy products, the Advanced Manufacturing sector maintains the largest number of extractive/control relationships, with a competitive relationship with the Government sector for all years. Finally, for local natural resources, the Government sector is in competition with the Agriculture, Primary Manufacturing, and Advanced Manufacturing sectors. In contrast, the Government sector is only in competition with the Advanced Manufacturing and Primary Manufacturing sectors for energy products. Two other sectors, the Primary Manufacturing and Tertiary Industry sectors, have two competitive relationships. The first relationship involves the Tertiary Industry and the Government sectors, while the second relationship involves the Mining and Primary Manufacturing sectors. All the matrices of sectors ecological relations are available in the Supplementary Material.

These ecological relations between economic sectors resulted mutualistic and healthy outcomes (MI > 1), which remained constant from 2015 to 2019 (Fig. 5). On the other side, the SI showed that the economic sectors are benefitted from their pairwise interactions (SI > 0), which increased from 2018 to 2019 (Fig. 5).

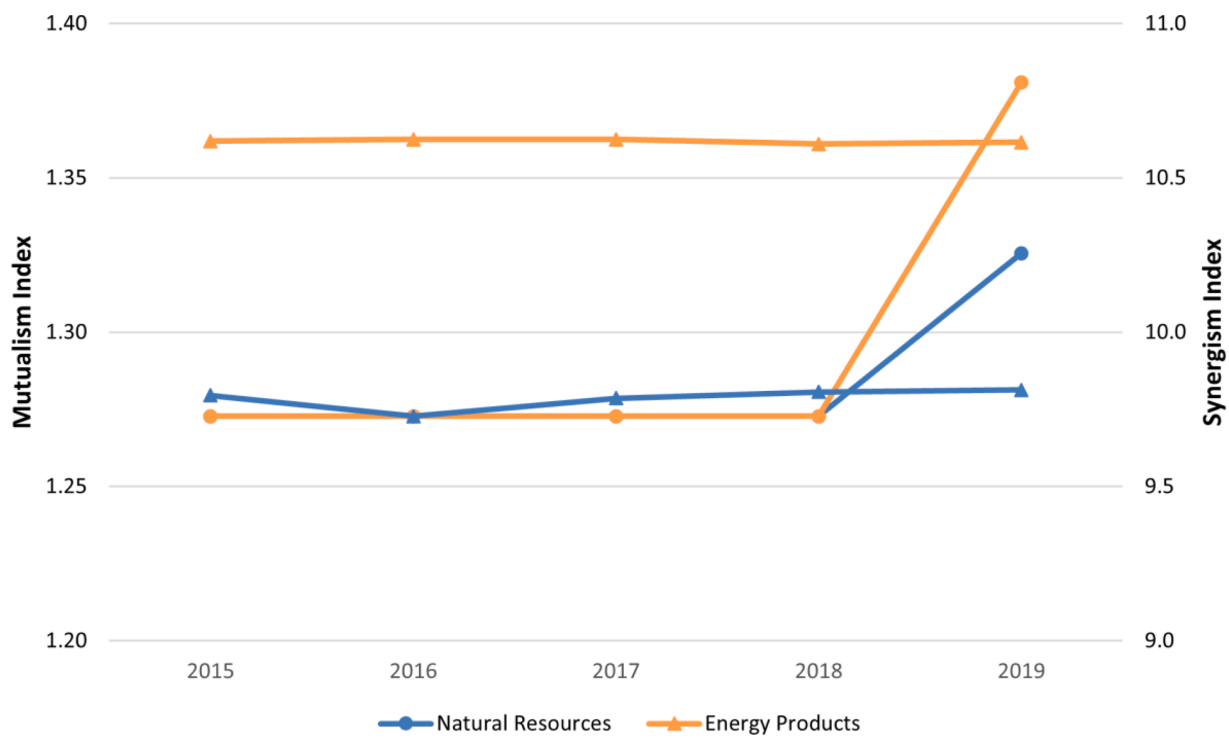

Fig. 5. Evolution of the Mutualism and Synergism index from 2015 to 2019. Circular marker refers to Mutualism and triangle marker to Synergism; Blue colour refers to Natural Resources and orange to Energy Products.

4. Discussion

The Sustainable Development Goals aimed to transform the world by 2030 (UN, 2015) but, to what extent has this objective been achieved when half of the time has already passed out? This article contributes to fill this gap in the literature by analysing the structure and functioning of the Italian economy in coupled biophysical-monetary terms from 2015 to 2019.

4.1. Structure and evolution of the Italian economy

In classical ecology, the food web is depicted as a pyramid where primary producers and decomposers form the base, followed by primary, secondary and tertiary producers, and predators on the top. In this web, energy, matter, and information fluxes and recirculates across the different compartments (Odum, 2002). In terms of direct energy use, the Italian economy presents primary producers (that is, Agriculture and Extractive industry) as the base, while predators, that is, final demand (Household, Government and Gross Capital Formation) are at the top with minimum direct energy use (ISTAT, 2020b). This information would suggest that the structure of the Italian economy is coherent with that of natural ecosystems. However, this perception completely changes when embodied energy is considered. By doing so, our results reveal hidden energy flows that are often ignored in classical and neoclassical economic models (Hornborg, 2019; Jorgenson et al., 2009). Our findings show that some sectors, such as Programming, IT consultancy and related activities; information service activities, which may seem less energy-intensive than others, actually require a significant amount of energy to maintain the infrastructure necessary for their operations. This is evidenced by the fact that this single sector has the same embodied energy as the entire Agricultural sector. These results confirm the so-called "tertiarization" of developed economy, whereby there is a shift away from agricultural and industrial production towards services (Deleidi et al., 2020; Ellger and Scheiner, 1997). Similarly, previous studies have found a prevalence of the tertiary industry as a top energy-intense sector of the economy in industrialized cities, like in Beijing (China) and Vienna (Austria) (Galychyn et al., 2022; Zhang et al., 2014). Little is known yet about this process in countries or cities from the global south. However, given the known dynamics of ecologically unequal exchange between northern and southern countries (Hickel et al., 2022), it could be expected that either natural resources are traded and manufactured in third countries or that energy products are exported and consumed elsewhere rather than capitalized by the national tertiary sector. Moreover, despite in economic analysis manufacturing and services sectors are considered the main drivers of economies (Ciaschini et al., 2022), we observed that manufacture (both primary and advanced) presented higher ability to benefit from other economic sectors than to push them when using a hybrid biophysical-monetary perspective.

Regarding the effect of the commitment to the *Agenda 2030*, our results show that the Italian economy has remained unchanged after the first five years. Despite stability is commonly a measure of systems' health, a resilient socio-ecological systems should also be able to prepare for future constraints, whether external (e.g., energy crisis after Covid-19 pandemic) or self-imposed (e.g., voluntary transition towards sustainability). Indeed, the large amounts of energy required to sustain the Italian economy from imported energy products highlights the challenges faced by the country in developing a sustainable energy policy. This represents an element of dependence on other countries in terms of both economic and environmental impact. Beyond that, it has important implications for the evaluation of the SDGs in Italy. Specifically, these results suggest that the SDGs may have not been effective yet in promoting significant changes in the energy consumption patterns of the Italian economy. If the recommendations and warnings synthesized from the last IPCC report (IPCC, 2022) are to be heard and followed, there is a long way forward that must be travelled fast.

4.2. Strengths and limitations of our modelling approach

Despite the rapid increase of ENA studies assessing the urban metabolism of cities (Borrett et al., 2018), to our knowledge, this is the first study analysing the functioning and structure of a national economy and its evolution over time. Through this approach we incorporate the thermodynamic constraint into economic models, which is crucial to achieve a more sustainable economy within planetary boundaries. As such, energy analysis appears to be a promising common ground for both ecological and economic sciences (Odum, 2007). By recognizing the true costs of economic activities in terms of energy consumption, we can identify areas where improvements can be made to reduce energy consumption and improve efficiency, ultimately leading to a more sustainable functioning.

Furthermore, the findings have important implications for ecological network analysis. Economic systems are complex and interconnected, and their stability is essential for maintaining the overall health of ecosystems (Odum and Odum, 1976). Therefore, understanding the factors that contribute to transition is critical for developing effective strategies for managing natural resources and promoting sustainable development. The results of this study suggest that further research is needed to identify specific factors that can drive meaningful changes in the economy and contribute to achieving SDGs. By understanding the interconnections between economic systems and ecological networks, researchers can better understand the complex relationships that underlie sustainable development and develop more effective policies and strategies for achieving it.

We identified one major limitation of our study that could be influencing the final outcome of mutualism and synergism indexes: we analysed the Italian economy alone. We are aware that all economies are interconnected, and fluxes of materials, energy, information and power govern their relations. This shortcoming does not invalidate our analysis of the relation of the economic sector within Italy, but calls for a contextualization that we provide in the following section. Furthermore, the analysis could be extended by examining the composition of natural resources and energy products, as well as exploring other environmental metrics such as emergy or exergy (Liu et al., 2010; Odum, 1996). Moreover, incorporating the embodied energy in imported goods and services into the analysis would provide a more comprehensive understanding of the energy flows within the Italian economy (Herendeen and Bullard, 1974).

4.3. Implications for global sustainability

A major principle of the *Agenda 2030* is its global perspective of leaving no one behind (UN, 2015). This principle demands the application of systemic perspectives that are aware of indirect relations and interactions which could result in undesired trade-offs. Our study contributes to this goal by considering not only the direct use of energy, but also the energy imported in energy products and the embodied energy. Thus, it is commonly assumed that extraction, conversion and industry sectors (that is, manufacture) are highly polluting industries with demand large energy consumption (Liu et al., 2011). This being so, our results point to the tertiary industry and final demand as the main drivers of the economy and capturers of resources from other economic sectors, that is, these "deindustrialized" sectors are the main explanatory cause of other sectors necessity to continue providing them with the necessary energy and materials. This inverted pyramid structure reveals the existence of sectors that hinder the systems' functioning. In particular, it appears that sectors positioned higher in the hierarchy lack sufficient national support for the development of lower-tier producers (Zhai et al., 2019, 2018).

The tertiarization process mentioned above is closely related to the narratives of dematerialization and decoupling economic production from environmental impact (Esposito et al., 2018) and, likewise, it seems to fall into the same theoretical pitfalls. That is, suggesting a tertiarization of a national economy comes at environmental (as much as social and economic) degradation elsewhere (Hornborg, 2009). Therefore, despite from a national perspective a tertiarization process could seem a prosperous strategy to satisfy both economic development and reduction of environmental degradation, from a global perspective, this

Table A1
– NACE Code Economic sectors, categories and abbreviations used in the text.

NACE - Sub-sector	Sector name	Sector
Produzioni vegetali e animali, caccia e servizi connessi; Silvicoltura e utilizzo di aree forestali; Pesca e acquicoltura	**Agriculture**	**AG**
Attività estrattiva	**Mining**	**MIN**
Industrie alimentari, delle bevande e del tabacco; Industrie tessili, confezione di articoli di abbigliamento e di articoli in pelle e simili; Industria del legno e dei prodotti in legno e sughero, esclusi i mobili; fabbricazione di articoli in paglia e materiali da intreccio; Fabbricazione di carta e di prodotti di cartaStampa e riproduzione su supporti registrati	**Primary Manufacturing**	**PM**
Fabbricazione di coke e prodotti derivanti dalla raffinazione del petrolio Fabbricazione di prodotti chimici Fabbricazione di prodotti farmaceutici di base e di preparati farmaceutici Fabbricazione di articoli in gomma e materie plastiche Fabbricazione di altri prodotti della lavorazione di minerali non metalliferi Attività metallurgiche Fabbricazione di prodotti in metallo, esclusi macchinari e attrezzature Fabbricazione di computer e prodotti di elettronica e ottica Fabbricazione di apparecchiature elettriche Fabbricazione di macchinari e apparecchiature n.c.a. Fabbricazione di autoveicoli, rimorchi e semirimorchi Fabbricazione di altri mezzi di trasporto Fabbricazione di mobili; altre industrie manifatturiere Riparazione e installazione di macchine e apparecchiature	**Advanced Manufacturing**	**AM**
Fornitura di energia elettrica, gas, vapore e aria condizionata; Raccolta, trattamento e fornitura di acqua; Gestione delle reti fognarie; attività di raccolta, trattamento e smaltimento dei rifiuti; recupero dei materiali; attività di risanamento e altri servizi di gestione dei rifiuti	**Energy and Material Transformation**	**EMT**
Costruzioni	**Construction**	**CO**
Commercio all'ingrosso e al dettaglio e riparazione di autoveicoli e motocicli; Commercio all'ingrosso, escluso quello di autoveicoli e di motocicli; … ; Attività di famiglie e convivenze come datori di lavoro per personale domestico; produzione di beni e di servizi indifferenziati per uso proprio da parte di famiglie e convivenze	**Tertiary Industry**	**TI**
Spesa per consumi finali	**Household**	**HOU**
Investimenti Lordi	**Government**	**GOV**
Variazione delle scorte e oggeti di valore	**Gross Capital Formation**	**GCF**

evolutionary process not only do not help achieving the so-called environmental SDGs, but also hampers the achievement of other SDGs (e.g., goals 1, 2 and 3) (Hornborg, 2019; Jorgenson, 2012).

5. Conclusions

This study assessed the structure and evolution of the Italian economy from 2015 to 2019 using ecological network analysis. Our results show that the structure of the Italian economy has remained unchanged after five years from the implementation of the SDGs. This could be interpreted as a call for policymakers to strengthen efforts towards a sustainability transition.

Furthermore, the study shows the potential of ecological network analysis as a tool for evaluating policy changes and monitoring the progress towards SDGs. Moreover, the consideration of embodied energy allowed to unmask economic dynamics that run unnoticed in classical analysis, like the high energy demand of the tertiary sector. In that way, our study helps understanding that there has not been a dematerialization of the economy, but a relocation of the primary industries to foreign countries from where energy is lately imported in the form of energy products.

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CRediT authorship contribution statement

Raffaele Guarino: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Writing – original draft. **Giulio Corsi:** Conceptualization, Supervision, Validation. **Enrique Muñoz-Ulecia:** Conceptualization, Project administration, Visualization, Writing – review & editing.

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

I have shared the link to my code in the attachments, while raw data are open-access.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2023.110474.

Appendix

Table A1.

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