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How robust is the circular economy in Europe? An ascendency analysis with Eurostat data between 2010 and 2018

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ABSTRACT

Considering its relatively low circularity rate (11.8% in 2019), the EU set several waste management targets as part of its roadmap to a circular economy yet the decision about which transition pathway to follow is not trivial. The maximization of circularity in human made systems is intended to function as a catalyst for this transition albeit at the risk of establishing fragile techno-economic systems. To provide insights for a balanced transition to a circular economy its link with the ecological concepts of *"resilience"* and *"robustness"* is illuminated by assessing the theoretical robustness of the material and energy flow networks of the EU27 countries between 2010-2018 using Eurostat data. Results show that despite the high degrees of order (efficiencies) which all European countries developed over the years studied, none of them achieved near-maximum robustness. The identified relationships between the average circularity rate and the average energy efficiency with the theoretical robustness of these material and energy flow networks (for the years studied), respectively, suggest that ascendency analysis is a credible tool for supporting policy making. Both on a national and on a local level for developing circular and robust urban waste management systems given data availability. The contribution to the underlying theory of ascendency analysis is the introduction of the concepts of *"technological boundaries"* and *"windows of efficiency"* of these human-made networks which are juxtaposed with the *"window of vitality"* that is often used to describe healthy natural ecosystems. Finally, the limitations of ascendency analysis and directions for future research are presented.

1. Introduction

The projected large migration flows to European cities in combination with prevalent unsustainable production and consumption patterns could push waste management systems to their limits. By 2050 the average number of inhabitants per square kilometer in several European functional urban areas[1] is projected to increase substantially (*e.g.* by 60% in Stockholm) whereas a decrease is expected elsewhere (*e.g.* by 38% in Alicante) due to demographic changes, economic growth, and the provision of high quality of life and services (Joint Research Centre, 2021).

Currently, out of the 750 million tonnes of waste generated annually in the EU only 50% is recycled and only 10% of those recycled materials are returned back to the economy (Hedberg & Šipka, 2020). When major mineral waste (due to mining, quarrying, and construction and demolition activities) are also considered then the total amount of EU waste (generated in 2018) reaches up to 5.2 tonnes per EU inhabitant or 2.2 billion tonnes (Eurostat, 2021a; Eurostat, 2021f) which is the estimated amount to be generated by all cities worldwide combined in 2025 (UN Environment Programme, 2021). As a responsible way to reduce waste generation, to retain the value of end-of-life products and materials in the economy, and to avoid pollution and costly externalities, the European Commission advocates that the EU follow a waste hierarchy approach where waste prevention is central and complemented by the principles of reuse, recycling, and energy recovery while landfilling should be avoided (Hedberg & Šipka, 2020). The aspiration of the EU is

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[1] Functional urban areas are defined as *"sets of contiguous local (administrative) units composed of a 'city' and its surrounding, less densely populated local units that are part of the city's labour market ('commuting zone')"* (Schiavina et al., 2019).

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to transition to a circular economy (CE) by setting, for example, common EU targets according to which by 2035 the recycling rates of municipal and packaging waste should reach 65% and 70%, respectively, while landfilling should be reduced to a maximum of 10% of municipal waste (European Commission, 2021b).

Material circularity initiatives during the past decade have been important but apparently not sufficient for addressing global environmental crises effectively likely due to a persistence on maximizing efficiency gains subjected to economic constraints rather than focusing on social and environmental goals, as well as due to a belief that markets will take care of such a transition *"naturally"* (Hinton, 2021). Haas et al. (2015) found that both the EU27 and the global economy in 2005 were far away from a CE due to the large amounts of processed materials used for energy purposes instead of recycling, as well as due to an increasing rate of socio-economic stocks, and suggested that the focus should shift from *"end of pipe"* solutions (which are limited due to the proportions of flows) towards the use of renewable energy, substantial reduction in societal stock growth, and decisive eco-design. The situation has not improved the last couple of years with the circularity of the world worsening from 9.1% in 2018 to 8.6% in 2020 (Haigh et al., 2021). The maximization of circularity in human made systems such as material and energy flow networks could, in theory, function as a catalyst for the transition to a CE albeit at the risk of establishing fragile techno-economic systems with potentially undesirable socio-ecological side-effects (*e.g.* increasing wealth inequality or generating dependency on critical resources). Interestingly, a portfolio theory approach suggests that the minimization of resource use via increased circularity does not translate into the maximization of eco-efficiency in practice *"where the aim is to make more with less"* (Figge et al., 2021). Despite its popularity, the concept of CE is still largely based on economics (Stahel, 2019; Webster, 2021), the latter focusing on GDP growth with no visible signs of decoupling from the global material footprint (Bauwens, 2021). If steps are not taken towards bolstering its modesty, concreteness, inclusion, and transparency then the concept of CE will be at risk of remaining an elusive promise for an idealized business-oriented world where linear practices could be rebranded as circular and, misleadingly, sustainable by default (Corvellec et al., 2021).

It is already well known from studies in natural ecosystems that over-constrained networks can become *"too efficient for their own good"* and therefore *"brittle"* to shocks (Ulanowicz, 2020). Whether this is the case also for human-made systems remains unclear. If CE is the way forward, then it should be paved with a holistic systems perspective that is considerate of *"ecosystemic relationships, the maintenance of capitals or stocks, the interdependence of different scales and the clear distinction between effective and efficient"* (Webster, 2021). Here, we argue that the adoption of an ecological perspective that builds on the concepts of resilience, efficiency, and robustness will support actors in the EU to consider complex aspects of multiple material and energy flows in their attempt to transition to a CE in more balanced ways. To illustrate the usefulness of these ecological concepts, we explore, for the first time to the best of our knowledge, the application of ascendency analysis to assess the robustness of the EU27 material and energy flow networks by reviewing readily available national statistics from Eurostat. We present two hypotheses to organize the study and we examine the implications of ascendency analysis at a national level to extract insights. Ultimately, these insights will contribute to the development of robust and circular waste management systems. The paper aims to answer the following research questions:

1 What is the robustness of the material and energy flow networks of the EU27 countries and how did it evolve between 2010 and 2018?
2 Is there a relationship between the reported values of the circularity rate by Eurostat with the robustness of the material flow networks, and between the calculated values of energy efficiency with the robustness of the energy flow networks of the European countries?
3 Do the robustness values of the studied European countries between 2010 and 2018 fall within the optimum *"window of vitality"* observed in natural ecosystems or are there different patterns?
4 What are the implications for developing waste management systems?

Section 2 presents a conceptual framework that links the concept of CE with those of ecological resilience and robustness that are typically used for the health assessment of natural ecosystems. Section 3 introduces ascendency analysis, the statistical analysis used, and an approach to re-construct robustness curves. Section 4 is an elaboration on the results where the *"technological boundaries"* and the *"windows of efficiency"* are brought in as novel concepts. We restrict our study to the years between 2010 and 2018 to illustrate the applicability of ascendency analysis but also because the relevant values for recent years were not always available for the complete set of indicators studied or they were being updated. Section 5 is a discussion on the implications of the *"windows of vitality and efficiency"* and on the limitations of ascendency analysis, it introduces the principle of *"Rebalance"* as an extension to the waste hierarchy framework, and it provides an outlook for future research. Finally, Section 6 presents the conclusions.

2. Theoretical background

To provide context and to support the bridging of the ecological concepts of resilience and robustness with those of circularity rate and energy efficiency in the context of circular urban waste management systems we conducted a search in Scopus, and we studied relevant literature. The work of Ulanowicz et al. (2009) and Fath et al. (2019) on the ecological concepts of robustness and resilience form the theoretical basis for this paper.

2.1. Circular economy and waste management

CE has become a contested concept (Korhonen et al., 2018) with various definitions (Appendix A). Regardless of the viewpoint, it is well established that on an overarching level the concept of CE deals with the development of strategies for the optimal management of material, energy, information and monetary flows and stocks within an economy. However, it is also becoming clear that the concept still fails to address social aspects sufficiently and is in need of a revised definition (Murray et al., 2017; Lemille, 2017; Walker et al., 2021). Inarguably, the shift towards a CE will begin to materialize only when various stakeholders with different functions and specializations in value chains start to form collaborative partnerships. This should be the case for many networked systems but particularly so for urban waste management systems since designing out waste and pollution is one of the three key pillars of a CE (Ellen MacArthur Foundation, 2019).

The decision about which CE related strategies, policies, and technologies should be adopted is critical as it can transform the dynamic interactions between all actors involved in an economy, including urban waste management networks. This transformation can lead to various unintended impacts, such as altering the ability of the newly formed networks to process different types of resources or waste and/or to distribute them internally thereby affecting the overall system's capacity to absorb shocks (*e.g.* due to pandemics, socio-economic crises, climate change etc.). There exists no *"perfect set"* of indicators that can capture the vast complexity of a transition to a CE but arriving at a consensus on which reporting rules and guidelines are relevant would, firstly, reduce the administrative burden on companies and organizations by knowing what to report on, and secondly, they would foster discussion to include different elements that are relevant for circularity (Pietikäinen, 2020).

A recent literature review has shown that commonly used circularity indicators tend to focus more on the *"nano"* (product) level for monitoring material and resource recovery strategies, and on the simultaneous assessment of environmental and economic aspects but they rarely address social repercussions, they cannot assess the sustainability performance of circular systems holistically (Oliveira et al., 2021), and they do not deliberately capture the resilience or fragility of the studied systems against shocks. However, resilience is recognized as a relevant concern for systems in transition, as is demonstrated by manifestation of the *"resilient city"* as a city label with its own theoretical foundations (de Jong et al., 2015). It has not been picked up policy-wise as this typically becomes relevant for policy making only once unambiguous quantification methods are ready for adoption (de Jong et al., 2015). One possible explanation of why the quantification has stalled, may be because the operationalization of the concept of city/urban resilience is generally difficult and it *"should be treated as a process of active, positive adaptation of urban systems to changing development conditions, to phenomena and processes that may constitute more or less predictable developmental threats, including natural disasters"* (Mierzejewska & Wdowicka, 2018). Given that resilience is a concept with distinct theoretical, empirical, and programmatic aspects of urban development and planning, quantification methods should be able to address the resilience of an urban system explicitly and distinctively from other metrics that relate to sustainability (Schraven et al., 2021). What these quantification tools should be is still unclear.

Here, we propose ascendency analysis as a quantification method to capture not only the resilience of material and energy flow networks of countries but also their efficiency and robustness from an ecological perspective. We explore how these concepts are related to the circularity performance of the material and energy flow networks at the national level which here is assumed to be sufficiently covered by two indicators. The first one is the circularity rate as reported by Eurostat for all EU27 countries which monitors the share of materials recovered and fed back into the economy, and it expresses a country's effort to recover waste and to contribute indirectly to the world wide supply of secondary raw materials rather than just measuring directly its capacity to produce them (Eurostat, 2021c). The circularity rate is closely related to material recycling, but as stated on the Eurostat website, it differs in two ways. Firstly, the circularity rate considers only recycling (and not backfilling) to be contributing to a CE as a waste operation that produces secondary raw materials, and secondly, it accounts both for imported and exported waste that are bound for recovery (Eurostat, 2021c). The second indicator is the energy efficiency (calculation based on Eurostat data is shown in Section 3) which shows the percentage of energy flowing through the various sectors of a country's economy, and which is ultimately delivered for a certain purpose (*e.g.* as final consumption or exports).

2.2. Concepts from ecosystems ecology and their use in ascendency analysis

Ascendency analysis stems from the work of Ulanowicz (1980) whereby ascendency was defined as a non-conservative, macroscopic variable which natural ecosystems were hypothesized to optimize as self-organizing, dissipative systems. The method is grounded on information theory and the concept of entropy (Ludwig Boltzmann and Claude Shannon), and has been developed to assess the health (*i.e.* sustainability) of natural ecosystems with the concepts of resilience, efficiency, and robustness (Fath & Scharler, 2018). Within ascendency analysis, an ecosystem is abstracted into a network *i.e.* a group of interconnected nodes (*e.g.* trophic levels or species) where the links between them represent mutually constrained flows of a circulating medium such as matter or energy (Ulanowicz, 2020). The concept of resilience refers to the network's diversity and ability to withstand perturbations whereas efficiency in this context is related to its potential to streamline material and energy flows between its various species across trophic levels (Fath, Asmus, et al., 2019). Both concepts are important and interdependent counterparts for the capacity of an ecosystem to develop since the *"development of new adaptive repertoires requires a cache of what formerly appeared as redundant, inefficient, incoherent and dissipative processes [whereas] greater constrained and efficient functioning always generates increased dissipation"* (Ulanowicz, 2020).

A simplified abstraction of a carbon flow network of various species inhabiting a cypress wetland ecosystem in South Florida illustrates the usefulness of ascendency analysis in assessing the networks' health and in highlighting the antagonistic tendencies of living ecosystems between effective orderly performance and resilience (Ulanowicz et al., 2009).

Among the several indicators that will be discussed in detail in Section 3, are the degree of order and the theoretical robustness which are the main outcomes of our analysis. The degree of order shows whether the efficient (ordered) part of the networked ecosystem is more dominant than its resilient (redundant) part or not. An ecosystem with a very high degree of order would be more efficient in processing the flows of the circulating medium of interest but at the expense of becoming *"brittle"* whereas an ecosystem with a low degree of order would be more redundant in its connections within its network but less efficient in directing flows in an orderly manner. Studies on ecological communities showed that natural ecosystems tend to obtain a range of values of the degree of order that are near the maximum theoretical robustness, a range that is known as the *"window of vitality"* (Zorach & Ulanowicz, 2003). This maximum robustness indicates a situation where *"all flows contribute equally towards sustaining the system in this propitious state. In other words, the system is acting as a coherent whole in endowing itself with fitness"* (Ulanowicz, 2009). Fath et al. (2019) proposed a comprehensive list of ten regenerative principles for developing healthy socio-economic systems that balance within this *"window of vitality"* and provided relevant metrics that include the degree of order and theoretical robustness.

Cases where ecological methods, including ascendency analysis, have already found applications outside the field of ecology include economic systems (Huang & Ulanowicz, 2014; Hu et al., 2016), trade flows (Kharrazi et al., 2017), supply chains (Allesina et al., 2010; De Souza et al., 2019; Chatterjee & Layton, 2020), urban-industrial ecosystems (Morris et al., 2021), socio-economic metabolisms (Gao et al., 2021), energy flows of cities (Zhu et al., 2019), and nutrient flows that can affect the food security of countries (Liang et al., 2020).

Ascendency analysis can be a valuable tool to bring back into perspective currently undervalued ecological principles to promote human development that is in balance with nature, and where *"everyone has a role to play in ensuring that human knowledge, ingenuity, technology and cooperation are redeployed from transforming nature to transforming humankind's relationship with nature"* (United Nations Environment Programme, 2021).

2.3. Conceptual framework

By following the aforementioned theoretical underpinnings of the ecological perspective to CE, we developed the conceptual framework shown in Figure 1. Here, we considered the concept of CE to be a subsystem of the natural environment assuming that the latter is a precondition for the former to exist. The framework is concerned with the flow of materials and energy within a CE both at the national as well as the urban level where a substantial amount of waste is typically generated, and which can have a negative impact on the environment (*e.g.* as pollution when mismanaged).

The framework illuminates the added value of an ecological perspective to CE. More specifically, the focus is on the links between circularity rate (as reported by Eurostat) and energy efficiency (calculated based on Eurostat values) with the corresponding values of theoretical robustness of material and energy flow networks of European countries. One naturally expects that a country with a high circularity rate and a high energy efficiency will not only be more efficient in recycling material and energy resources, but it will also be more resilient to disruption of supplies by becoming more independent from imports via the development of its internal material and energy flow networks.

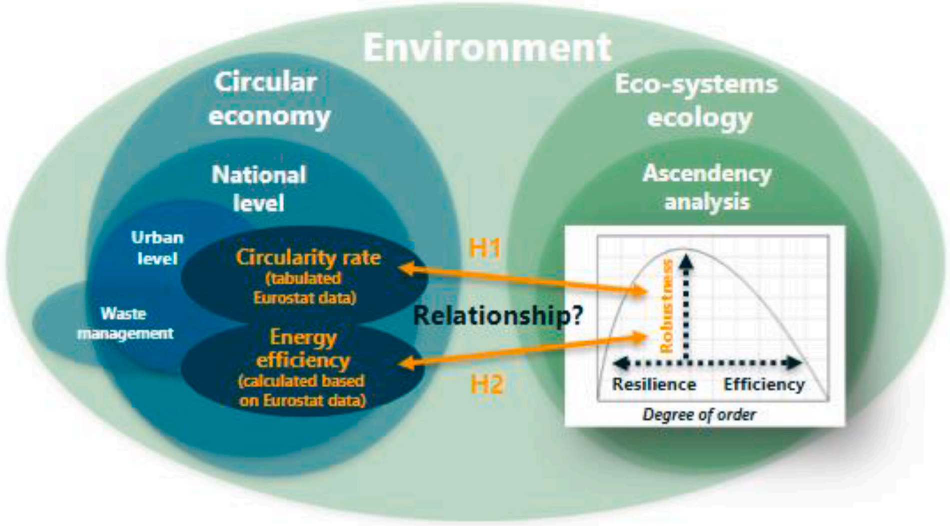

Figure 1. Conceptual framework to bridge the fields of circular economy and ecosystems ecology where H1 and H2 are the stated hypotheses.

However, from an ascendency analysis point of view, when very efficient processes are fixed in a network, the system can become more orderly yet fragile to shocks. To explore these relationships, we formulate the following hypotheses:

- *H1o: Circularity rate is not related to the theoretical robustness of material flow networks of the EU countries*
- *H1α: Circularity rate is related to the theoretical robustness of material flow networks of the EU countries*

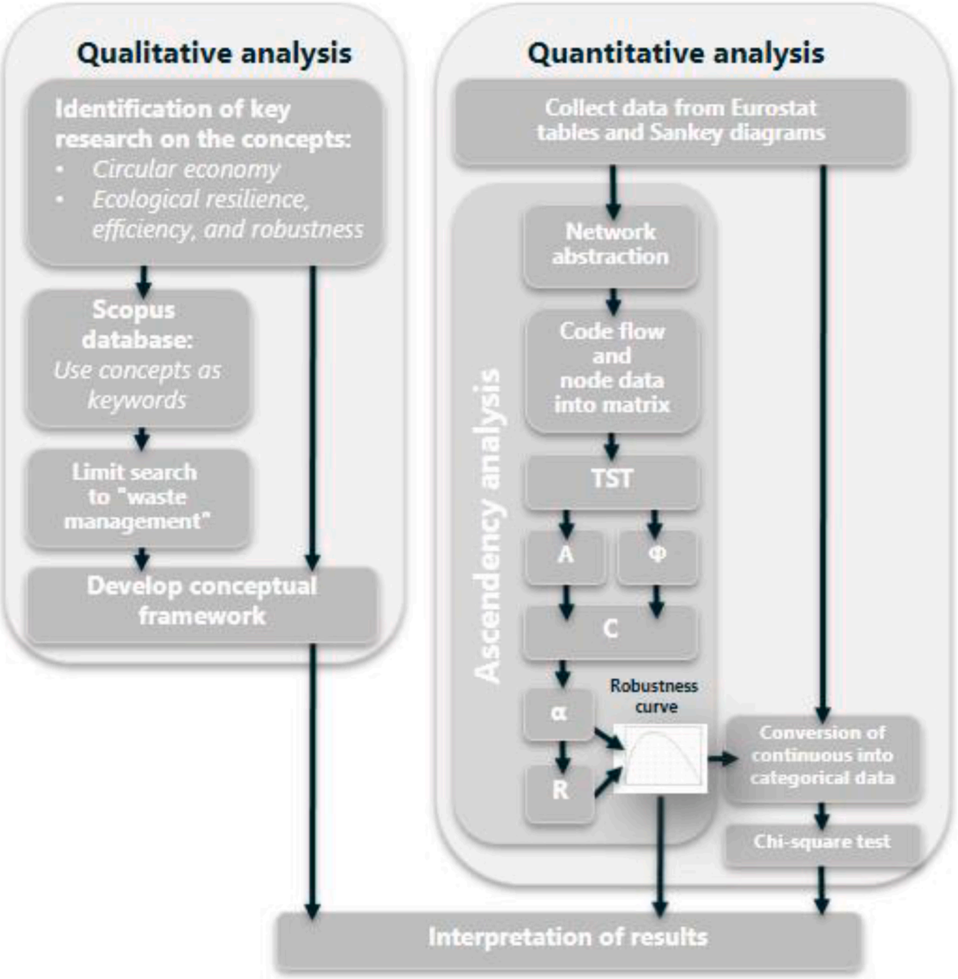

Figure 2. Research design where *TST* is the total system throughput of the network, *A* is the networks' ascendency, Φ is the networks' overhead, *C* is the networks' capacity for development, *α* is the degree of order of the network, and *R* is the theoretical robustness of the network.

- *H2o: Energy efficiency is not related to the theoretical robustness of energy flow networks of the EU countries*
- *H2α: Energy efficiency is related to the theoretical robustness of energy flow networks of the EU countries*

3. Methodology and data

Figure 2 shows the research design followed. The qualitative analysis led to relevant body of literature that allowed us to theoretically underpin all concepts that are relevant for this paper. To answer the first research question, we conducted an ascendency analysis of the material and energy flow networks of the EU27 countries between 2010 and 2018. For the second and third research questions, we conducted a Chi-square test, and we reconstructed the robustness curves for these networks, respectively. To answer the fourth research question, we drew insights from our previous findings, and we examined the Netherlands as an example.

3.1. Data collection from Eurostat

The quantitative analysis started with the collection of tabulated Eurostat data on the circularity rate (circular material use rate) *CMR (%),* and of the material and energy flows from the Sankey diagrams of the EU27 countries between 2010 and 2018 obtained on the 21st of May 2021 which can be found in the supplementary data (European Commission, 2021a; Eurostat, 2021d). Eurostat defines the circularity rate as the ratio of circular use of materials *U* over the overall material use rate *M*:

$$CMR = \frac{U}{M} = \frac{RCV_R - IMP_W + EXP_W}{DMC + RCV_R - IMP_W + EXP_W}$$

where RCV_R is the recovery/recycling on the basis of the treatment operations defined in the Waste Framework Directive 75/442/EEC, IMP_W is the amount of imported waste bound for recovery, EXP_W is the amount of exported waste bound for recovery, and *DMC* is the domestic material consumption (Eurostat, 2021c).

The energy efficiency η_{energy} (%) was calculated from the values of the reported energy flow Sankey diagrams (as they are shown in Appendix B.2.1) as the ratio of all the energy flow outputs [excluding the “Transformation losses” (y_{trl}), “Distribution and transmission losses” (y_{dtl}), and the “Statistical difference outflow” (y_{sto})] over all energy inputs [excluding the “Statistical difference inflow” (z_{stin})]:

$$\eta_{energy} = \frac{y_{fic} + y_{ceb} + y_{ina} + y_{mbu} + y_{stb} + y_{exp}}{z_{std} + z_{imp} + z_{pro}} \cdot 100$$

where y_{fic} is “Final consumption”, y_{ceb} is “Consumption of the energy branch”, y_{ina} is “International aviation”, y_{mbu} is “Marine bankers”, $y_{stb}$is “Stock build”, y_{exp} is “Exports”, z_{std} is “Stock draw”, z_{imp} is “Imports”, and $z_{pro}$is “Production”.

3.2. Ascendency analysis

The methodology of ascendency analysis is well reported in the work of Ulanowicz et al. (2009), Fath and Scharler (2018), and Fath et al. (2019).

First, information from Eurostat’s Sankey diagrams (i.e. names and number of processes) of the material and energy flows of the EU27 countries (left figure of Appendix B.2.1) are abstracted into networks of nodes and links (right figure of Appendix B.2.1). Next, the network information is encoded into matrixes where their rows and columns represent the network’s nodes (processes on the Sankey diagrams). The matrix elements correspond to the quantities reported by Eurostat on each one of the flows of these Sankey diagrams from one node to another (as tonnes per year for the material flow networks or TJ per year for the energy flow networks). In this matrix form, the data are used to calculate the following indicators in a progressive manner for each Member State and for each year between 2010 and 2018. All extracted data can be found in the supplementary material.

The first indicator to be calculated is the total system throughput $T_{..}$ which indicates the total activity of the network in terms of its flows. Its units depend on the flowing medium. Here, the units of $T_{..}$ are million tonnes per year for the material flow network or TJ per year for the energy flow network.

$$T_{..} = \sum_{j=1}^{n} z_j + \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ji} + \sum_{i=1}^{n} y_i$$

where z_i, y_i, and f_{ij} (or T_{ij}) are the imports, exports, and intermediary flows between two nodes *i* and *j*, respectively, and constitute the elements of the constructed matrix.

Then, the average mutual information *X* is calculated which describes the organized part of the flows and is measured in bits:

$$X = \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) log_2 \left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right)$$

where *“the joint probability of a quantum of material ($p(a_i,b_j)$) flowing from species i to species j can be denoted as $T_{ij}/T_{..}$”* (Fath & Scharler, 2018). Here, a quantum refers to a discrete quantity of matter or energy, and the analogy with species or trophic levels is that of certain processes as reported by *Eurostat* (*e.g.* production, imports, transformation, final consumption, exports etc.).

The overhead H_c (also known as reserve or redundancy) is also calculated which describes the unorganized part of the flows and is also measured in bits:

$$H_c = -\sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) log_2 \left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right)$$

The sum of the overhead and the average mutual information equals the capacity of the system for development *H*:

$$H = X + H_c$$

These three indicators are scaled with *T..* to convey physical dimensions to the studied networks (Ulanowicz et al., 2009).

$$A = T_{..} \cdot X = T_{..} \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) log_2 \left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right)$$

$$\Phi = T_{..} \cdot H_c = -T_{..} \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) log_2 \left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right)$$

$$C = A + \Phi = -T_{..} \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) log_2 \left(\frac{T_{ij}}{T_{..}}\right)$$

where *A* is the ascendency of the system describing its efficiency in directing its flows through its network, Φ is the overhead of the system quantifying its flexibility via the redundancy of its network connections, and *C* is the scaled overall capacity of the system for development. All three scaled indicators are measured in million tonnes • bits per year (for the material flow networks) or in TJ • bits per year (for the energy flow networks), and are used to calculate the degree of order α (unitless) which mathematically, is the ratio of the ordered part of the ecosystem over its total capacity for development, and it indicates whether the studied network is leaning towards structures of higher efficiency (*e.g.* α>0.6) or of higher redundancy (*e.g.* α<0.4):

$$\alpha = \frac{A}{C} = \frac{X}{X + H_c}$$

Finally, the degree of order is used as the sole argument to the logarithmic function of the theoretical robustness *R* (unitless) of the network which is also defined as its *"maximum fitness for evolution"* (de Souza et al., 2019):

$$R = -\alpha \cdot ln(\alpha)$$

3.3. Constructing robustness curves

When the degree of order and the theoretical robustness are plotted against each other it is possible to construct a robustness curve and identify how far or close a given network is to the optimum state around which healthy natural ecosystems tend to balance. This optimum state corresponds with the maximum robustness value of 0.368 and a degree of order of approximately 0.4 around which natural ecosystems tend to cluster (Ulanowicz, 2009; Borrett & Salas, 2010; Panyam & Layton, 2019; Ulanowicz, 2020). The robustness curve is conspicuously tilted towards the left implying that in natural ecosystems redundancy is seemingly more important than efficiency (Ulanowicz, 2009). It is also worth mentioning that Fath et al. (2019) stress that a change in the values of the ascendency indicators *"does not necessarily indicate a change in the health of an ecosystem, unless the metric change is caused by a decrease or extinction of several species producing small flows as opposed to a decrease in large flows (usually originating from bacteria, phytoplankton, or detritus). However, the metrics serve to identify the changing state of a system. Whether a state change is detrimental or beneficial depends on the present state (e.g., natural, impacted), and on which flows caused the change in the metrics"*.

As an illustrative example of the application of ascendency analysis, the material and energy flow Sankey diagrams of Bulgaria for the years of 2010 and of 2018 are abstracted in their corresponding networks (Appendix B.2.1) to construct their network matrixes (Appendix B.2.2 to B.2.5), and to calculate all relevant indicators and plot them on a robustness curve (Appendix B.3). Appendix F provides a code developed in R which can be easily adapted to study other networks.

3.4. Chi-square test

Given the limited number of datapoints per country for the circularity rate, the energy efficiency, the degree of order, and the theoretical robustness, we converted these numerical variables into the categorical variables of *"above median"* or *"below median"*. We did so to conduct a Chi-square test at an alpha value of 0.05 to explore the existence of a relationship between these variables. For the conversion we used as a threshold value the median values calculated from the complete dataset of all countries for all years. For example, Belgium, having an average circularity rate (for the years between 2010 and 2018) of 17.4% and an average calculated theoretical robustness of its material flow network of 0.2556, was categorized as a country with a circularity rate that was *"above median"* and a robustness value in its material flow network that was *"below median"* when it was compared to the overall median values of 6.9% and 0.2563, respectively.

3.5. Re-constructing the robustness curves

We re-constructed the robustness curves for both material and energy flow networks of the EU27 for the years studied as follows:

1. First, we calculated the number of roles $n = 2^X$ where *"a role is, loosely speaking, a specialized function: it is a group of nodes that takes its inputs from one source and passes them to a single destination. The source and destination can be a group of nodes as well"* (Zorach & Ulanowicz, 2003). In other words, n is the number of transfers (logarithmic average) that a quantum of material or energy makes before leaving the network (Ulanowicz et al., 2009) *"gauging the effective number of trophic levels in the system and is directly related to throughput efficiency"* (Lietaer et al., 2010). The analogy between an ecosystem and the human-made material and energy flow networks is that n assumes the processes illustrated in the Eurostat Sankey diagrams to be *"trophic levels"*.
2. Secondly, we calculated the link density $c = 2^{\left(\frac{H_C}{2}\right)}$ which is the number of links (logarithmic average) that enter or leave each node in the material or energy flow network (Ulanowicz et al., 2009) *"measuring the effective connectivity of the system in terms of links per node which is directly related to resilience"* (Lietaer et al., 2010). The analogy between an ecosystem and the human-made material and energy flow networks is that c describes the links between the *"trophic level"* processes illustrated in the Eurostat Sankey diagrams.
3. Consecutively, we identified the lower and upper bounds of the averages of the calculated n and c values which we used to extrapolate the adjusted degree of order α_{adj} that corresponds to the maximum theoretical robustness calculated from the studied data.
4. The last step was to identify the most likely values of the parameters β and γ which adjust the shape and the height of the curve to match the maximum robustness value and the values of the degree of order that were already calculated from the studied data.

$$R_{adj} = -\gamma\left[\alpha^{\beta}\ln\left(\alpha^{\beta}\right)\right]$$

We used the generalized reduced gradient algorithm (GRG) of Excel to minimize the difference between the maximum robustness value of the reconstructed curve R_{adj} and the maximum robustness value that was calculated from the available data, subject to the constraint that both β and γ values should be positive.

4. Results

4.1. Ascendency analysis of the EU27 countries

Being aware of the difficulty to discern the underlying causes for each country individually, we examine only cases with extreme values for theoretical robustness to identify trends and to illustrate the usefulness of ascendency analysis. The tabulated results for all countries and years studied are shown in Appendixes C.1 and C.2. The figures presented below and in the Appendixes D.1 and D.2 illustrate the results of the countries which had the highest and lowest theoretical robustness values over the years studied.

The countries with the highest robustness values for material and energy flow networks (0.280 for Germany in 2015, and 0.302 for Estonia in 2016, respectively) are shown in green whereas the countries with the corresponding lowest robustness values (0.154 for Bulgaria in 2014, and 0.166 for Luxembourg in 2016, respectively) are shown in red. The other countries had degrees of order and robustness values which fluctuated somewhere in between and are shown in grey. The results for the EU27 are also presented in blue in all figures to identify the general performance of the European Union where the values presented are not calculated averages from the ascendency analysis of all countries, but separate results that have been calculated from reported data by Eurostat for the EU27 (as a whole). The Netherlands is also discussed as a particularly interesting case for three reasons: firstly, because it had the highest circular material use rates (%) between 2010 and 2018 as reported by Eurostat (European Commission, 2021a), secondly, because it was ranked as a frontrunner in CE after achieving a circularity metric of 24.5% in 2019-2020 (which, according to the Circularity Gap Report, could in theory be increased up to 70% in the future (PACE, 2020b)), and thirdly, because the Netherlands is one of the few European countries with the bold ambition to become fully circular by 2050 (Ministry of Infrastructure and the Environment, 2016).

Figure 3 shows that between 2010 and 2018 none of the countries for the years studied achieved robustness values that were within the optimum range of the *"window of vitality"*. The material flow networks of

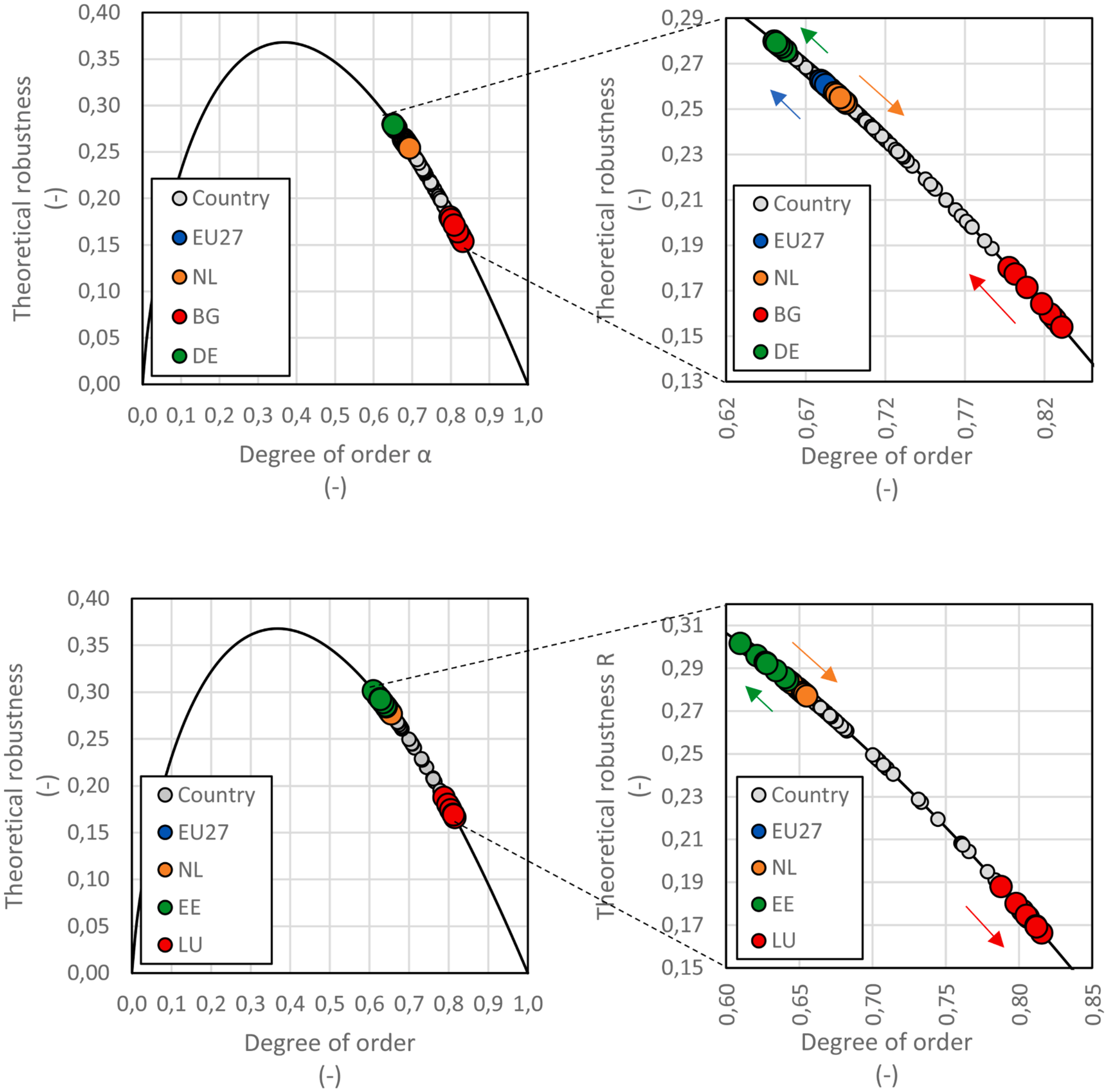

Figure 3. *Top left*: theoretical robustness (-) versus degree of order (-) of the material flow networks of EU27 (as a whole), the Netherlands (NL), Germany (DE), and Bulgaria (BG) between 2010 and 2018, *top right*: zoom-in of the material flow network results, *bottom left*: theoretical robustness (-) versus degree of order (-) of the energy flow networks of EU27 (as a whole), the Netherlands (NL), Estonia (EE), and Luxembourg (LU) between 2010 and 2018, bottom *right*: zoom-in of the energy flow network results. All other EU countries had values that ranged somewhere between the minimum and the maximum values of the degree of order and of the theoretical robustness and are represented in grey.

all EU27 countries were leaning towards the efficiency side of the robustness curve. Through the years, the EU27, Germany, and Bulgaria have been adopting lower degrees of order and higher robustness values to a varied extent, moving in the direction of the optimum *"window of vitality"*. For the Netherlands, however, the opposite trend was noticeable indicating that the network became more efficient in processing its material flows but at the latent expense of increased *"brittleness"* to shocks.

Regarding the energy flow networks, the EU27 fluctuated between a relatively small range of degree of order and of robustness values but with no distinguishable direction whereas Estonia showed an overall improvement. The Netherlands and particularly Luxembourg adopted increasing degrees of order that reduced the values of theoretical robustness, with an overall direction towards more rigid network structures. This is in line with recent research that showed that among other EU countries (where none of them were found to be energy self-sufficient between 2004 and 2018 due to *"a large variety of energy sources and the strict allocation of materials for specific needs"*), Luxembourg was found to be almost entirely dependent on external energy sources (Rokicki & Perkowska, 2021).

4.2. *Identifying relationships between circularity, energy efficiency, and robustness*

The substantial variation in the visual trends between the circularity rate and the degree of order and the theoretical robustness of the material flow networks, as well as between the energy efficiency and the degree of order and the theoretical robustness of the energy flow networks (Appendixes D.1 and D.2) illustrate that it is difficult to infer a generalized relationship between these variables for all EU countries.

Table 1 shows the results of the Chi-square test where the calculated expected values in the contingency matrixes were >5 and consequently the test was considered valid. The Chi-square value of the test for the relationship between the average circularity rate and the average theoretical robustness of the material flow networks was χ^2 (1, N=27) = 6.3123 with p=.012, and for the relationship between the average energy efficiency and the average theoretical robustness of energy flow networks it was χ^2 (1, N=27) = 8.3150, with p=.004. These p values

Table 1

Results of the Chi-square test where *N* is the sample size (number of EU countries), *df* is the degrees of freedom, χ^2 is the Chi-square statistic, and *p* is the p-value.

	N	df	χ^2	*P*	N	df	χ^2	*p*
	27	1	6.3123	0.012	27	1	8.3150	0.004
Country	Average circularity rate (%)	Average robustness of material flow networks	Average circularity rate as a categorical variable[1]	Average robustness of material flow networks as a categorical variable[2]	Average energy efficiency (%)	Average robustness of energy flow networks	Average energy efficiency as a categorical variable[3]	Average robustness of energy flow networks as a categorical variable[4]
Belgium	17.4	0.2556	Above median	Below median	87.4	0.2855	Above median	Below median
Bulgaria	2.7	0.1642	Below median	Below median	69.1	0.2893	Below median	Above median
Czech Republic	6.8	0.2623	Below median	Above median	72.7	0.2911	Below median	Above median
Denmark	7.9	0.2585	Above median	Above median	93.9	0.2976	Above median	Above median
Germany	11.2	0.2784	Above median	Above median	79.4	0.2851	Below median	Below median
Estonia	13.3	0.2661	Above median	Above median	68.3	0.2919	Below median	Above median
Ireland	1.8	0.2682	Below median	Above median	86.6	0.2813	Above median	Below median
Greece	2.3	0.2340	Below median	Below median	86.7	0.2774	Above median	Below median
Spain	9.0	0.2700	Above median	Above median	82.3	0.2887	Below median	Above median
France	18.1	0.2752	Above median	Above median	69.2	0.2884	Below median	Above median
Croatia	3.8	0.2452	Below median	Below median	93.1	0.2883	Above median	Above median
Italy	15.7	0.2628	Above median	Above median	85.9	0.2774	Above median	Below median
Cyprus	2.3	0.2300	Below median	Below median	76.7	0.2461	Below median	Below median
Latvia	4.1	0.2524	Below median	Below median	94.4	0.2753	Above median	Below median
Lithuania	4.0	0.2537	Below median	Below median	95.8	0.2640	Above median	Below median
Luxembourg	14.2	0.2626	Above median	Above median	96.1	0.1743	Above median	Below median
Hungary	6.1	0.2528	Below median	Below median	82.2	0.2875	Below median	Above median
Malta	5.5	0.2585	Below median	Above median	88.3	0.2100	Above median	Below median
The Netherlands	27.1	0.2602	Above median	Above median	95.4	0.2804	Above median	Below median
Austria	9.5	0.2710	Above median	Above median	90.3	0.2839	Above median	Below median
Poland	10.7	0.2512	Above median	Below median	80.1	0.2998	Below median	Above median
Portugal	2.1	0.2246	Below median	Below median	86.8	0.2808	Above median	Below median
Romania	2.2	0.1927	Below median	Below median	82.7	0.2896	Below median	Above median
Slovenia	8.6	0.2719	Above median	Above median	81.3	0.2684	Below median	Below median
Slovakia	4.9	0.2559	Below median	Below median	77.6	0.2866	Below median	Above median
Finland	9.3	0.2393	Above median	Below median	84.2	0.2916	Above median	Above median
Sweden	7.1	0.2389	Above median	Below median	80.3	0.2924	Below median	Above median

Thresholds for converting numerical variables into categorical ones ("Above median" or "Below median"):

[1] Median of circularity rate of the EU countries: 6.9%

[2] Median of the theoretical robustness of material flow networks of the EU countries: 0.2563

[3] Median of energy efficiency of the EU countries: 84.1%

[4] Median of the theoretical robustness of energy flow networks of the EU countries: 0.2857

show that there is sufficient evidence to reject the null hypothesis and suggest that there exists a statistically significant relationship between these variables.

4.3. Window(s) of efficiency

Here, we adopt the view that sustainable systems are defined as *"those that achieve a stable balance between efficiency and flexibility"* and given that *"it is likely that other types of sustainable systems might cluster elsewhere along the interval $0<a<1$"* (Ulanowicz, 2020), we explore whether the studied material and energy flow networks of the EU27 countries are following the same or a different pattern of behavior than what is encountered in natural ecosystems.

We define the *"technological boundaries"* as the boundaries within which the material and energy flow networks of the EU27 countries *"existed"* for the years studied and which were formed by the calculated minimum and maximum values for the number of roles n and the link density c (Appendix E). The values for the number of roles n indicate the lower and upper bounds in the number of nodes (processes) that were illustrated in the Eurostat Sankey diagrams. These processes (*e.g.* imports, transformation, final consumption etc.) serve as an analogy to the trophic levels encountered in natural ecosystems (*e.g.* producers, primary and secondary consumers, decomposers and scavengers), and their minimum and maximum values were $n_{min} = 3.82$ and $n_{max} = 4.92$ for the material flow networks and $n_{min} = 4.00$ and $n_{max} = 4.28$ for the energy flow networks, respectively. The link density c values indicate the lower and upper bounds in the number of links per node in the Sankey diagrams reported by Eurostat, and their minimum and maximum values were $c_{min} = 1.19$ and $c_{max} = 1.48$ for the material flow networks and $c_{min} = 1.18$ and $c_{max} = 1.54$ for the energy flow networks.

We juxtapose our results next to those of Ulanowicz *et al.* (2009) who discussed the upper and lower *"ecological boundaries"* and estimated the geometric center of the *"window of vitality"* of natural ecosystems to be located at $c = 1.25$ and $n = 3.25$ which translated into a degree of order α

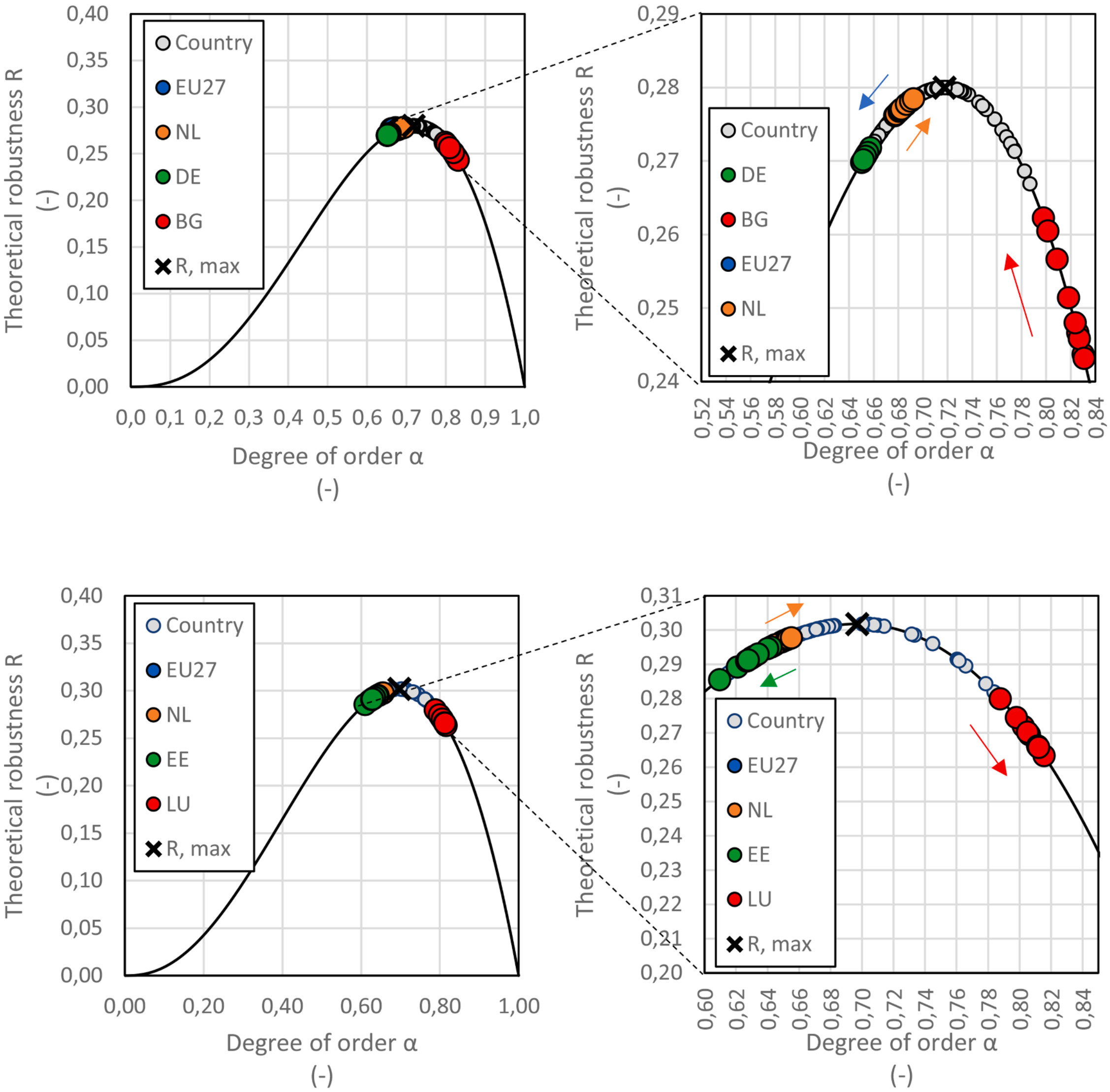

Figure 4. Adjusted robustness curves constructed based on the *"windows of efficiency"* of the material and energy flow networks of EU27 countries (more information on Appendix E). *Top left*: Maximum theoretical robustness value of 0.2800 (calculated from the original data of the material flow networks of the EU27 between 2010 and 2018) plotted against its corresponding *"apparent"* optimum degree of order of 0.7174. The value of β is estimated at 3.0114, and of γ at 0.7611. *Top right*: zoom-in of the material flow networks results. *Bottom left*: Maximum theoretical robustness value of 0.3018 is calculated from the original data of the energy flow networks of the EU27 between 2010 and 2018 and plotted against its corresponding *"apparent"* optimum degree of order of 0.6969. The value of β is estimated at 2.7689, and of γ at 0.8203. *Bottom right*: zoom-in of the energy flow networks results. All other EU countries had values that ranged somewhere between the minimum and the maximum values of the degree of order and of the theoretical robustness and are represented in grey.

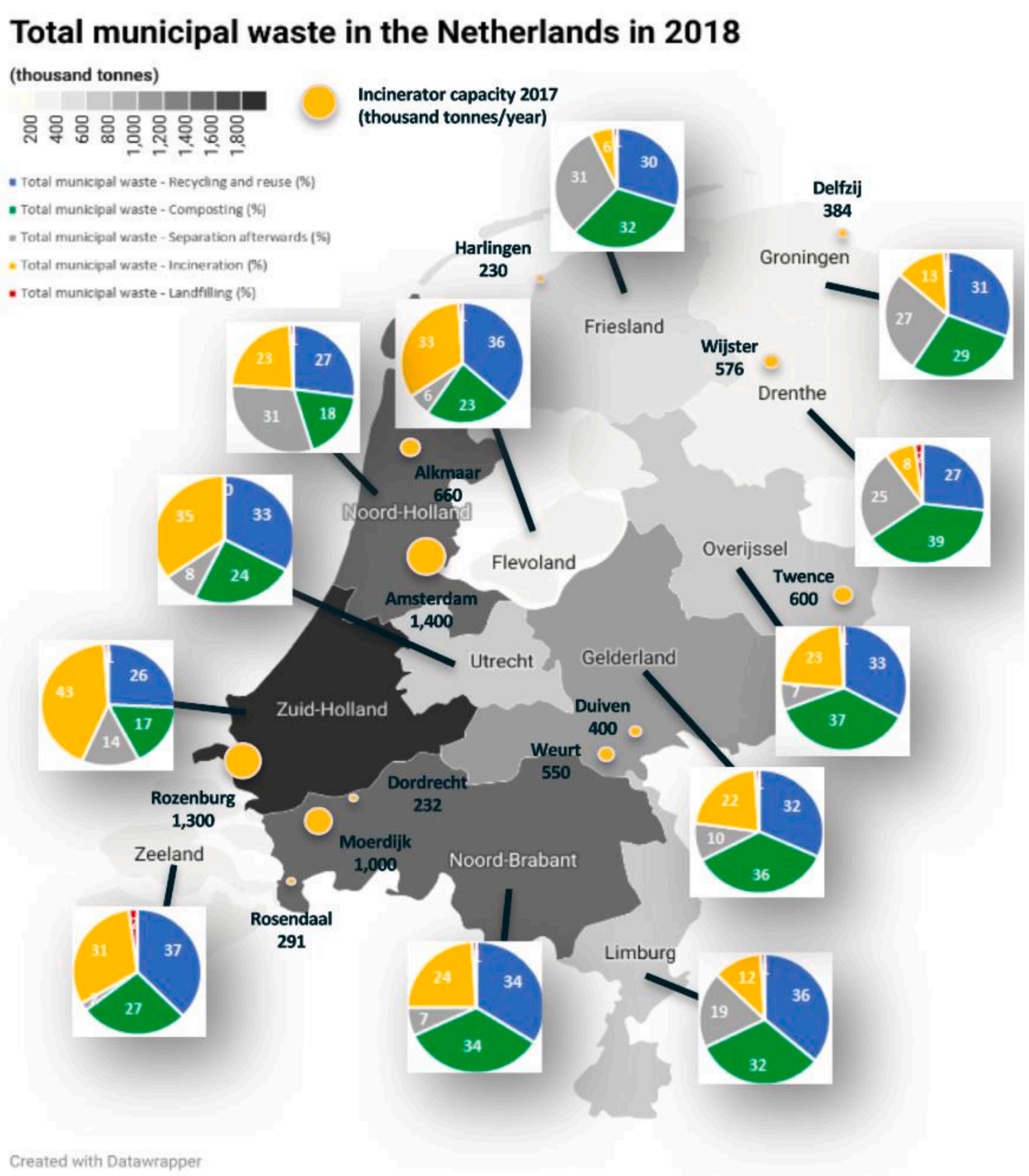

Figure 5. Distribution of municipal waste related activities across the twelve provinces of the Netherlands in 2018 where the total amount generated was about 9,519 thousand tonnes or about 6% of the total waste generation in the Netherlands that year which was about 145,241 thousand tonnes (Eurostat, 2021b). The rest were due to construction and demolition (70%), other economic activities (13.3%), manufacturing (9.6%), and energy (1.1%) whereas there was no contribution from mining and quarrying (0%) (Eurostat, 2021e). The pie charts represent the percentage of municipal waste per province that was recycled and reused (blue), composted (green), separated afterwards (grey), incinerated (orange), and landfilled (red) (Statistics Netherlands, 200). The size of the orange circles represents the relative capacity of the incineration plants (in thousand tonnes) across the country in 2017 (Confederation of European Waste-To-Energy Plants, 2017). The underlying map has been created with Datawrapper.

of 0.4596 and a β value of 1.288, and corresponded to their *"best possible configuration for sustainability"* (Ulanowicz et al., 2009). A *c* value of approximately 3 seems to be an upper *"ecological boundary"* in natural ecosystems implying that they can be strongly connected across a few links or weakly connected across many links; configurations of the opposite nature tend to fall apart (Ulanowicz et al., 2009). A *c* value of less than 1 sets the lower *"ecological boundary"* implying non-communicative networks (Ulanowicz et al., 2009). A *n* value larger than 2 describes complementary trophic pathways that exist in natural ecosystems such as oxidation/reduction processes (Ulanowicz et al., 2009). Finally, an *n* value of more than 5 is an *"ecological boundary"* that is still unexplained and arbitrarily defined because more than five trophic levels are rarely encountered in nature (Ulanowicz et al., 2009).

Figure 4 shows that the adjusted robustness curves shifted to the right. The parameters β and γ which were identified from the data of the EU27 for the studied years, were 3.0114 and 0.7611 for the material flow networks, and 2.7689 and 0.8203 for the energy flow networks, respectively. These parameters shifted the robustness curves to the right according to the calculated maximum theoretical robustness values which corresponded to a new *"apparent"* optimum degree of order α of

0.7174 for the material flow networks, and of 0.6969 for the energy flow networks, respectively. In the case of the material flow networks, the Netherlands and Bulgaria were now moving towards this new optimum state, Germany remained around stable values whereas the EU27 was only slightly becoming less robust. In the case of the energy flow networks, the Netherlands showed an improvement in its robustness whereas the EU27 remained stable. Both Estonia and Luxembourg drifted away from the new optimum, the former towards more redundancy and the latter towards more efficiency.

5. Discussion

5.1. Implications for developing urban waste management systems

Our analysis revealed that for the years studied, all Member States have developed a highly ordered part in their material and energy flow networks that favored efficiency over resilience. However, none of them achieved robustness values that were near the maximum observed in natural ecosystems. At first glance, this is not surprising since many human-made systems are typically developed to transfer materials and energy with full-throttle efficiency but likely at the risk of increased brittleness due to insufficient flow path diversity (Layton et al., 2015).

We also found statistically significant relationships (for the years studied) between the average circularity rate of the EU countries and the average robustness values of their material networks, and between their average energy efficiency and the average robustness values of their energy flow networks. This finding shows the potential relevance of ascendency analysis for assessing the robustness of material and energy flow networks both at a national and at an urban level. The analysis can support policy makers and businesses in developing waste management systems that are not just circular but also robust to shocks. Ascendency analysis could function as an *"alarm bell"* for both types of stakeholders by monitoring when certain processes which focus solely on the maximization of efficiencies within a waste management network (or within business ecosystems), would become dominant. This dominance of efficient processes could increase the risk of rendering cities or countries heavily dependent on a limited number of technologies or strategies that rely on waste generation and which could potentially lead to the emergence of fragile techno-economic networks.

Under this light, the adoption of variety of strategies and of new technologies that do not just focus on recycling, could in theory advance the European waste management sector both in terms of efficiency and of resilience. Some strategic examples come from consulting voices to the European Commission who advise governments and municipalities of Member States to follow an integrated approach to obtain high quality recyclable materials by establishing improved waste sorting technologies, by providing economic incentives to citizens for a more effective waste separation at households, by engaging in communication that highlights the importance of waste separation, and by legally enforcing penalties to citizens who do not comply (EY, 2021). Technological examples come from existing digitally-enabled solutions that include improved waste collection with real-time waste monitoring sensors, cloud-based and on-demand trash pickups, infrared technologies for advanced waste characterization, sorting, and recycling, blockchain technologies for real-time traceability of waste flows, and remote sensing and satellite technologies for assessing changes in the status of the environment (Hedberg & Šipka, 2020). However, to apply ascendency analysis in practice all stakeholders should have a common and clear conceptualization of what the studied network looks like (i.e. in terms of its main nodes and links), of how that conceptualization changes for each relevant flow (e.g. material, energy, monetary), and of which traceable data (over time and space) can be available per type of flow.

An example that illustrates this relevance is that of the Netherlands where the decision to recycle or to incinerate *"is one of the most important questions when managing waste"* (Pires & Martinho, 2019). Incineration, while being one of the least preferred ways of recovery in the waste hierarchy framework, it reduced the landfill rates of the country substantially by providing district heating and electricity, and it is regarded as part of the transition towards a circular economy yet with an uncertain role (Savini, 2021). However, incineration plants depend on a steady supply of waste which apparently is not available in sufficient amounts in the Netherlands to meet operational capacity constraints and is complemented with trans-national imports, indicating that a coupling exists between material and energy flows (Hollins et al., 2017; Savini, 2021). Data from Statistics Netherlands (2020) and the Confederation of European Waste-To-Energy Plants (2017) show (Figure 5) that the percent of waste incinerated across the twelve provinces in 2018 ranged between 6% (Friesland) and 43% (South Holland). Revisiting the target that is to be achieved by 2035 (i.e. 65% recycling rate of municipal waste), the Netherlands will have to divert a large part of incinerated waste to recycling (Hollins et al., 2017). This situation will challenge the country in maintaining long-term contracts with incinerators and in steering changes across its national energy transition strategies while simultaneously increasing the recycling rate (Hollins et al., 2017). Besides exacerbating the competition between incinerators, recyclers, and other emerging actors (e.g. start-up companies) who are engaged in the waste sector, this situation could also foster the emergence of a business ecosystem and a market that is locked in and ever-dependent on a constant supply of waste materials (Savini, 2021; Millicer, 2018). The results of ascendency analysis showed that both material and energy flow networks of the country had an increasing trend in their degrees of order between 2010 and 2018. This increase, on one hand, indicates that both networks became more efficient in streamlining material and energy flows which logically aligns with the technological advances in waste collection, recycling, and recovery as well as with achieving the highest circularity rate in Europe (30% in 2019). On the other hand, this high degree of order comes at the expense of relatively low theoretical robustness values which, in the context of ascendency analysis, could be interpreted as a warning of a national waste-to-energy system that is potentially *"brittle"* to shocks. Considering that the impact of the covid-19 pandemic increased not only the total amounts of bulky household waste but also the collection and processing costs by municipalities and private actors in the Netherlands by 10% to 15% compared to the previous year (Afvalgids, 2021), it is clear that waste management systems will have to become more robust to shocks. Ascendency analysis could support policy making as a diagnostic tool for tracking changes over time in the robustness values of the material and energy flow networks not only on a national but also on a local (urban) level given data availability.

Examples that could support a balanced transition to a CE include the creation of an enabling environment that is inclusive of a diverse set of actors, as well as the deployment of financial instruments and legal frameworks to strengthen the resilience of emerging networks and of multi-stakeholder collaboration initiatives, allowing for the adoption of a plethora of technologies and strategies for responsible innovation across multiple types of flows (*e.g.* material, energy, information, and monetary). In this way, both waste prevention activities that make use of higher *"R principles"* (*e.g.* Refuse, Rethink, Reduce, Reuse etc.) and waste management aspects (*e.g.* Recycle and Recover) could be addressed effectively to forestall undesirable lock-in situations.

5.2. Two opposing perspectives on the transition to a circular economy

Natural ecosystems that strike a balance within the *"window of vitality"* are sustainable in the sense that they manage to preserve resources and to withstand shocks in the long term. Their resilience is inherently embedded and interminably endowed by the inclusion of a diverse set of interacting species and the maintenance of natural cycles.

Human-made systems, however, often focus on adapting to the current conditions in the short term by making processes as efficient as possible. Interestingly, Morris et al. (2021) suggested that industrial systems (which are part of human-made systems) can be, in general, less robust than natural ecosystems not only due to their overly constrained processes (as it was the case in our analysis) but also due to their excessive redundance in their network connections (leaning towards the left side of the *"window of vitality"*). Surely, there must exist numerous examples of human-made networks that are designed top-down with resilience in mind. But often, resilience in this context is artificially implemented as dormant redundancy only to be activated as a security measure when a shock occurs (*e.g.* as a mechanism to respond effectively to cyber-attacks or as a back-up generator to provide power during black-outs etc.). Our analysis showed that both reconstructed robustness curves of the material and energy flow networks of the EU27 for the years studied were found to be located away from the *"window of vitality"* that encloses natural ecosystems, and this is why we termed them as *"windows of efficiency"*. These *"windows of efficiency"* reflect the situation of these two types of human-made networks for the years studied, and it is questionable whether they should dictate the future direction for a transition to a CE. The status of the Sustainable Development Goals supports the argument that continuing the *"business as usual"* is not an option. Despite the substantial progress made over the past decade in some key environmental areas such as clean water, sanitation, and energy, other areas such as biodiversity loss and climate change have continued to deteriorate for a number of reasons including the capacity limitations in collecting, disseminating and effectively using environmental data, as well as the inherent trade-offs of achieving some SDG goals or targets at the expense of others (UN Environment Programme and the Convention on Biological Diversity, 2021).

However, recent studies on different topics suggest that, to a certain degree, it is possible to design human-made systems that are both efficient in processing material and energy flows, as well as resilient due to redundancy in their network connections (and therefore*,* robust). For example, Panyam and Layton (2019) identified network configurations of thermodynamic cycles in thermal systems where both their thermal efficiency and their ecological robustness could be improved. In another example, Morris et al. (2021) have addressed cases of human-made nutrient networks involving nitrogen, phosphorus, and carbon flows that could achieve very high robustness values within the *"window of vitality"* likely due to their similarity to natural cycles (Morris et al., 2021). Another study on smallholder farms in different regions of Nepal suggested that increasing on-farm biomass production could be the way forward for sustainable farm intensification by reducing their dependency on external fertilizer input and by providing more resilience and higher balance (robustness) in the local nitrogen flow networks (Alomia-Hinojosa et al., 2020). However, this might not be true for all human-made nutrient networks, as in the case of the phosphorus flow network in China where, among other findings, its resilience was found to be largely and negatively affected by dietary changes towards the consumption of more animal-based foods (Liang et al., 2020).

At any rate, nature is the best source of sustainability examples from which one can draw insights, guidelines, and inspiration for developing inclusive urban waste management systems that could potentially be balanced in ways that allow them to be both circular and robust. Considering that circularity is the bedrock of ecosystems where the *"cycling [of flows] at one scale is structural at another"* (Fath et al., 2001) giving rise to emergent structural and recurring patterns, the inclusion of *"detrital"* actors in reuse and recycling activities of a CE could be a promising way to prevent path dependencies from occurring by allowing for the structural cycling of waste flows in bio-inspired networks (Williams et al., 2019). This reasoning is also in line with the work of Tate et al. (2019) who argued that business ecosystems are currently hosting mainly producers and consumers but lack the presence of sufficient detrital actors that are typically observed in natural ecosystems. They proposed six biomimetic principles the first of which states that *"in order to transition to a circular value system, the [business] ecosystem needs an appropriate balance of actors"* (Tate et al., 2019). Contemplating the above, we hypothesize that if nature is seen as a library of guiding principles for sustainability, then the transition to a more balanced CE could be facilitated by developing policies that promote the transition from the *"technological boundaries"* of the *"windows of efficiency"* towards the *"ecological boundaries"* of the *"window of vitality"*. These concepts can advance the way the transition to a CE is viewed both in terms of its implementation difficulty as well as of emergent trade-offs between pace acceleration and system balancing. Too fast acceleration could potentially lead to early lock-ins and irreversible transitions on critical points of uncertainty.

Nevertheless, it is impossible to conclude from our analysis that either window will lead to a future society that, besides being more robust in some respect, will also be more sustainable or desirable in others as this can be system and context dependent, and potentially subject to other factors that have not been addressed here (*e.g.* upper thermodynamic limits of technological processes, socio-economic and political contexts, the possibility of transitioning successfully to sustainable dystopias etc.). Finding a stable balance seems to be key for achieving sustainability where the appropriate mix between specialism in efficiency and diversity of actors for resilience is likely to be context dependent.

5.3. Limitations of this research

The ascendency analysis presented here poses several limitations. A few have been addressed by Kharrazi et al. (2017) who studied the resilience of global trade networks. They proposed caution in the interpretation of theoretical robustness by arguing that a maximum value might not necessarily lead to desirable network structures, and they pointed out the inability of the method to differentiate against different types of shocks. It is also questionable whether a theoretical robustness value of, for example, 0.28 is substantially better than a value of 0.27. However, its relative change could always be expressed in percentage points for monitoring purposes.

Furthermore, the analysis neither differentiates nor guarantees the robustness against different types of shocks. The robustness of a given network is only theoretical by acknowledging that, like in every modelling exercise, ascendency analysis inevitably makes use of assumptions and reduces the complex and innumerable relationships that can exist between the studied interacting species or actors with each other and with the environment. Ascendency analysis is useful for providing a new viewpoint for the transition to a CE but only up to a certain extent as there are many other complex social aspects that can't be captured and require the support of qualitative methods.

Another important limitation is that the material and energy flow networks abstracted here have a static number of nodes that represent various types of processes occurring at a country level (*e.g.*

transformation processes where natural gas is converted into electricity at power plants), and the data reported summarize an entire year which misses the dynamics of what happens in between. Hence, this analysis as such does not fully reflect a dynamically evolving system. Furthermore, some of the processes abstracted here (*e.g. "statistical difference inflow"*) are arguably difficult to conceptualize as trophic levels. This network abstraction was chosen to match the reporting viewpoint of Eurostat. We theorize that the *"windows of efficiency"* in general (and not just the ones identified in this paper) are likely to be dynamic, evolving their *"technological boundaries"* in time subject to the network structure of the actors that *"inhabit"* it, and to the types and sizes of the circulating media (be it material, energy, monetary or other types of flows).

Here, we also stress that the estimated β, γ, and α values for the re-constructed robustness curves should be handled with care because the main drawback of the GRG non-linear programming solver is that it cannot guarantee that a global optimum solution has been reached. Nevertheless, the corresponding re-constructed curves seem to closely match the analyzed data.

To conduct the Chi-square analysis, we converted numerical into categorical variables by arguing that their categorization could be facilitated in an unbiased and transparent way by selecting as a threshold their median values (instead of using, for example, their averages because those could be largely affected by extreme values). Perhaps an alternative way of selecting this threshold could lead to different results for this analysis. Moreover, despite the statistical significance found in our results, the Chi-square analysis does not reveal anything about the underlying mechanisms of the studied relationships meaning that it is not possible to infer causality between the studied variables. The Chi-square test merely gives information about how rare the results are in a *"world where the null hypothesis is true"*, and only within the context of this study. It is mainly the logic behind the theory of ascendency analysis that may allow us to provide some plausible explanation to support the alternative hypothesis.

5.4. *Future research*

Future research could expand on the presented results of Appendixes C.1 and C.2 by exploring relationships with socio-economic indicators (*e.g.* GDP per capita or the Gini coefficient). Case studies on ascendency analysis should aim at studying networked systems at multiple levels (*e.g.* at a region or city level) by considering the inclusion of multiple stakeholders that are active in the socio-economic and natural context (Zhang et al., 2017). A multi-level approach can be enlightening because *"as with many analyses, sometimes there are interesting differences at one level that disappear in the summary at another level of analysis. […] Selecting the appropriate level of analysis, and above all regularly using multiple levels, may be a critical analytical decision"* (Niquil et al., 2020).

Besides, different stakeholders can have very different perspectives and interests in different types of flows even when addressing the very same system. By calculating and perhaps by weighting or normalizing the theoretical robustness of urban waste management systems across a multitude of flows and a plurality of actors, more insights could be obtained on their capacity to absorb shocks over time. However, the limited availability of data on the urban metabolism of cities (Voskamp et al., 2017) can be a serious obstacle. Attempts to integrate the analysis of material stocks and flows with spatial analysis have been proposed (Liu et al., 2019) yet the establishment of a consistent and objective way to digitize urban environments and their various spatial and temporal dynamic flows into assessable networks that can be comparable, still remains a challenge. Furthermore, data should account for the embodied material and energy content, and environmental impact of imports, as well as for the different ways that renewable sources are produced, managed, and consumed because they are not always sustainable by default (Navare et al., 2021).

In any case, before taking any actions, each city will have to first define what circularity means for itself (Paiho et al., 2020), and any efforts to address the triple-bottom line sustainability in general should consider both local and cultural contexts (Virtanen et al., 2020). In this way the power of ascendency analysis could be unlocked to offer policy makers a better grip in measuring the effective robustness of networks of interest during their transition to a CE.

6. Conclusions

We assessed the theoretical robustness of material and energy flow networks of EU countries between 2010 and 2018 by reviewing Eurostat data via ascendency analysis. We found that European countries have developed a highly organized part in their material and energy flow networks that favors efficiency over resilience yet none of them achieved near-maximum robustness for the years studied. Furthermore, we identified the *"technological boundaries"* of these two networks, and we used them to reconstruct robustness curves along with their *"windows of efficiency"* (for the years studied).

Despite its limitations, we argue that ascendency analysis can be a highly relevant methodology for studying the robustness not only of European countries but also of urban waste management systems considering that statistically significant relationships were found between the average circularity rate and the average theoretical robustness of material flow networks, and between the average energy efficiency the average theoretical robustness of energy flow networks of the EU27 for the years studied. However, the usefulness of the method at an urban level will become apparent once data on a plurality of resource flows and stocks will be traceable and openly accessible.

The transition of the EU to a CE will require all actors, from policy makers and researchers to the private sector and non-governmental organizations, to obtain a new perspective; one that considers the capacity of a system to develop in a balanced way, both in terms of its efficiency in streamlining multiple resource flows as well as in terms of its ability to include a diversity of actors for enhanced resilience, and in ways that match the local context and environment. To facilitate this process, the waste hierarchy framework could be enriched with one more strategy: the principle of *"Re-balance"*.

If what needs to be done for the Earth to remain well below the 1.5 °C threshold is to transition to a CE then there should be a clear conceptualization of what possible futures could look like, and what realistic strategies can be identified to achieve (or to avoid) them in balanced ways that are not only environmentally regenerative and robust to a multitude of shocks but, most importantly, they should also drive inclusive prosperity through democracy, diversity, and social equity.

Author Contributions

F.K.Z. conceived of the idea of the research, compiled the document structure, conducted the data collection and the ascendency analysis, and wrote the text as the main author. D.S. and M.d.J. both provided guidance, constructive criticism, and suggestions on parts of the methodology as well as on ways to bridge the various concepts, and they reviewed the text. All authors contributed significantly to this work by reading, knowledge-sharing, and editing. All authors have read and agreed to the published version of the manuscript. The authors are

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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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.106032.

Appendix A

An indicative (and certainly not exhaustive) list of definitions and viewpoints of CE.

“An industrial system that is restorative or regenerative by intention and design (see Figure 6 in Chapter 2). It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models” (Ellen Macarthur Foundation, 2013).

“A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and be- yond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations” (Kirchherr et al., 2017).

“An economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being” (Murray et al., 2017).

“A sustainable development initiative with the objective of reducing the societal production-consumption systems’ linear material and energy throughput flows by applying materials cycles, renewable and cascade-type energy flows to the linear system. CE promotes high value material cycles alongside more traditional recycling and develops systems approaches to the cooperation of producers, consumers and other societal actors in sustainable development work” (Korhonen et al., 2018).

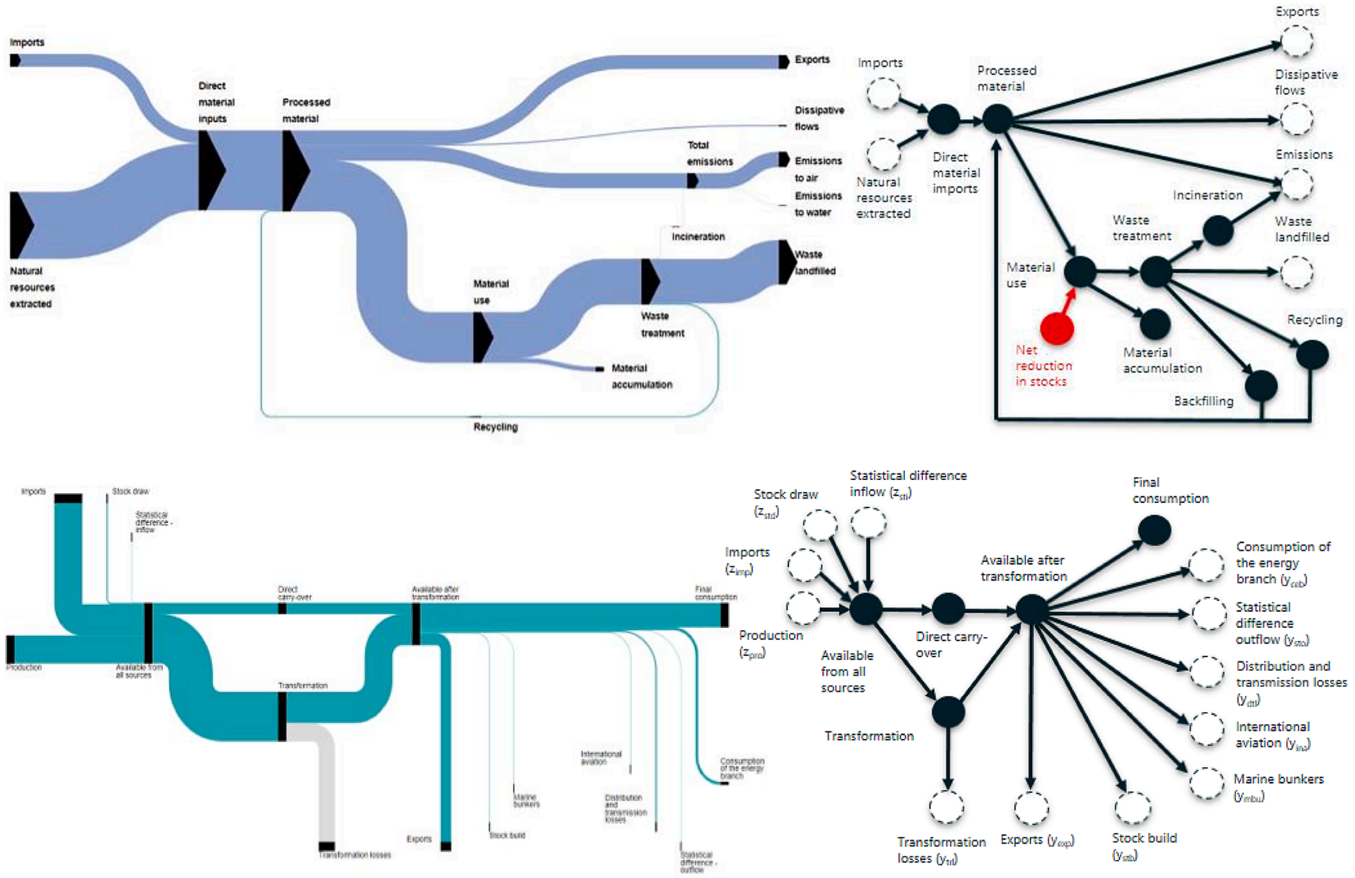
“A closed-loop process where optimization and implementation has measurable and specific limits” (Terry & Lalinde, 2019).

"The circular industrial economy is about economics; the overarching principle should therefore be economics! Environmental and social benefits will be a result, but only exceptionally the decision criteria" (Stahel, 2019).

“Circular economy mainly focuses on “planet” (natural capital) and “profit” (financial capital). Unlike what the name suggests, the circular economy is not always about “making circles”. Of the four material types used for production (biomass, fossil fuels, metals and non-metallic minerals), only the material cycles of metals and non-metallic minerals can be closed. Biomass and fossil fuels on the other hand are by definition not “circular”, in the sense that they can only be consumed once: once you eat an apple or use a gallon of gasoline the value drops to zero”. That does not mean that activities related to biomass and fossil fuels do not fit in the concept of a circular economy. However, circularity for these materials is about: 1. Ensuring that the level of consumption does not exceed the earth’s regenerative capacity (biomass); 2. Substitution with renewables (fossil fuels); 3. Higher resource efficiency and less waste” (ING Economics Department, 2020).

Appendix B.2.1

Network abstraction of *top:* material and *bottom:* energy flow Sankey diagrams of Bulgaria in 2010 as an example (Eurostat, 2021d). For the definition of each node and the composition of each flow, the reader is referred to the website of Eurostat. The *“net reduction in stocks”* has not been considered as a node in the material network analysis but its values were incorporated in the flow from the node *“processed material”* towards the node *“material use”* in the cases where that was necessary (*i.e.* for Greece between 2012 and 2016, for Bulgaria between 2010 and 2018, and for Romania in 2010). It is important to note that the material flow Sankey diagrams show only the annual amount of waste treated where *“waste treatment is on the basis of the treatment operations defined in the Waste Framework Directive 75/442/EEC”*, but not the of the total amount of waste generated (Eurostat, 2021b).


Imports
Natural resources extracted
Direct material inputs
Processed material
Exports
Dissipative flows
Total emissions
Emissions to air
Emissions to water
Incineration
Waste landfilled
Material use
Waste treatment
Material accumulation
Recycling
Exports
Imports
Processed material
Dissipative flows
Direct material imports
Natural resources extracted
Emissions
Incineration
Waste treatment
Waste landfilled
Material use
Net reduction in stocks
Material accumulation
Recycling
Backfilling
Imports
Stock draw
Statistical difference - inflow
Direct carry-over
Available after transformation
Final consumption
Production
Available from all sources
Transformation
International aviation
Consumption of the energy branch
Marine bunkers
Distribution and transmission losses
Stock build
Exports
Transformation losses
Statistical difference - outflow
Statistical difference inflow (z_{sti})
Stock draw (z_{std})
Imports (z_{imp})
Production (z_{pro})
Final consumption
Available after transformation
Direct carry-over
Available from all sources
Transformation
Consumption of the energy branch (y_{ceb})
Statistical difference outflow (y_{sto})
Distribution and transmission losses (y_{dtl})
International aviation (y_{ina})
Marine bunkers (y_{mbu})
Transformation losses (y_{trl})
Exports (y_{exp})
Stock build (y_{stb})

Appendix B.2.2

Values of the material flow network of the Bulgaria for 2010 in million tonnes.

	Im ports	Natural resources extracted	Direct material inputs	Pro cessed material	Ex ports	Dissi pative flows	Total emis sions	Mate rial use	Waste treat ment	Material accu mulation	Incine ration	Waste land filled	Re cycling	Back filling	$T_{i.}$
Imports	0	0	22	0	0	0	0	0	0	0	0	0	0	0	22
Natural resources extracted	0	0	118.5	0	0	0	0	0	0	0	0	0	0	0	118.5
Direct material inputs	0	0	0	141	0	0	0	0	0	0	0	0	0	0	140.5
Processed material	0	0	0	0	20	3	42	160	0	0	0	0	0	0	225
Exports	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dissipative flows	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total emissions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Material use	0	0	0	0	0	0	0	0	160	0	0	0	0	0	160
Waste treatment	0	0	0	0	0	0	0	0	0	0	0.12	158	2	0	160.12
Material accumulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Incineration	0	0	0	0	0	0	0.12	0	0	0	0	0	0	0	0.12
Waste landfilled	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recycling	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2
Backfilling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$T_{.j}$	0	0	140.5	142.5	20	3	42.12	160	160	0	0.12	158	2	0	828.24

Appendix B.2.3

Values of the material flow network of Bulgaria for 2018 in million tonnes.

	Im ports	Natural resources extracted	Direct material inputs	Pro cessed material	Ex ports	Dissi pative flows	Total emis sions	Mate rial use	Waste treat ment	Material accumu lation	Incine ration	Waste land filled	Re cycling	Back filling	$T_{i.}$
Imports	0	0	27	0	0	0	0	0	0	0	0	0	0	0	27
Natural resources extracted	0	0	144	0	0	0	0	0	0	0	0	0	0	0	144
Direct material inputs	0	0	0	171	0	0	0	0	0	0	0	0	0	0	171
Processed material	0	0	0	0	28	3	37	116	0	0	0	0	0	0	184
Exports	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dissipative flows	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total emissions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Material use	0	0	0	0	0	0	0	0	117	0	0	0	0	0	117
Waste treatment	0	0	0	0	0	0	0	0	0	0	0.43	113	3	0	116.43
Material accumulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Incineration	0	0	0	0	0	0	0.43	0	0	0	0	0	0	0	0.43
Waste landfilled	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recycling	0	0	0	3	0	0	0	0	0	0	0	0	0	0	3
Backfilling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$T_{.j}$	0	0	171	174	28	3	37.43	116	117	0	0.43	113	3	0	762.86

Appendix B.2.4

Values of the energy flow network of Bulgaria for 2010 in PJ.

	Imports	Production	Stock draw	Stat. dif. Inflow	Available from all sources	Direct carry-over	Transformation	Transformation losses	Available after transformation	Final consumption	Consumption of the energy brancjh	Stat. dif. Outflow	Distribuition and transmission losses	International aviation	Marine bunkers	Stock build	Exports	$T_{i.}$
Imports	0	0	0	0	492	0	0	0	0	0	0	0	0	0	0	0	0	492
Production	0	0	0	0	438	0	0	0	0	0	0	0	0	0	0	0	0	438
Stock draw	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	21
Stat. dif. Inflow	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Available from all sources	0	0	0	0	0	174	777	0	0	0	0	0	0	0	0	0	0	951
Direct carry-over	0	0	0	0	0	0	0	0	174	0	0	0	0	0	0	0	0	174
Transformation	0	0	0	0	0	0	0	286	492	0	0	0	0	0	0	0	0	777
Transformation losses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Available after transformation	0	0	0	0	0	0	0	0	0	382	48	6	23	7	4	7	189	665
Final consumption	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Consumption of the energy branch	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stat. dif. Outflow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution and transmission losses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
International aviation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marine bunkers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stock build	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exports	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$T_{.j}$	0	0	0	0	952	174	777	286	665	382	48	6	23	7	4	7	189	3519

Appendix B.2.5

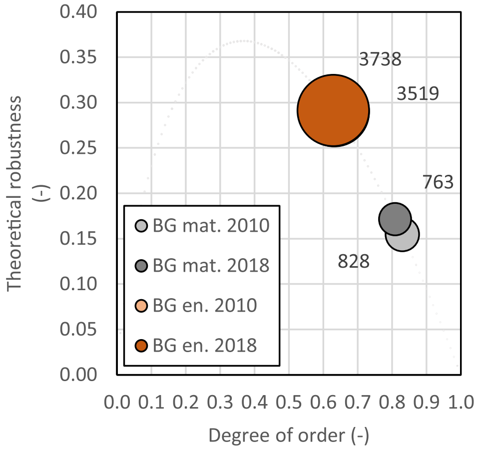
Values of the energy flow network of Bulgaria for 2018 in PJ.

	Imports	Production	Stock draw	Stat. dif. Inflow	Available from all sources	Direct carry-over	Transformation	Transformation losses	Available after transformation	Final consumption	Consumption of the energy brancjh	Stat. dif. Outflow	Distribuition and transmission losses	International aviation	Marine bunkers	Stock build	Exports	$T_{i.}$
Imports	0	0	0	0	486	0	0	0	0	0	0	0	0	0	0	0	0	486
Production	0	0	0	0	510	0	0	0	0	0	0	0	0	0	0	0	0	510
Stock draw	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	9
Stat. dif. Inflow	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Available from all sources	0	0	0	0	0	236	769	0	0	0	0	0	0	0	0	0	0	1005
Direct carry-over	0	0	0	0	0	0	0	0	236	0	0	0	0	0	0	0	0	236
Transformation	0	0	0	0	0	0	0	281	487	0	0	0	0	0	0	0	0	769
Transformation losses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Available after transformation	0	0	0	0	0	0	0	0	0	429	45	12	18	11	3	10	195	723
Final consumption	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Consumption of the energy branch	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stat. dif. Outflow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution and transmission losses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
International aviation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marine bunkers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stock build	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exports	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$T_{.j}$	0	0	0	0	1005	236	769	281	723	429	45	12	18	11	3	10	195	3738

Appendix B.3

Illustrative example of ascendency analysis for the material and energy flow networks of Bulgaria for 2010 and 2018 (Appendix B.2.1). From the values of Appendixes B.2.2 – B.2.3 we calculate the $TST_{..}$ of the material flow networks for 2010 and 2018 at 828 and 763 million tonnes, respectively. Then we calculate the X, H_c, and H at 2.299, 0.471, and 2.770 bits for 2010, and at 2.295, 0.542, and 2.838 bits for 2018, respectively. By scaling these values by $TST_{..}$ we calculate A, Φ, and C at 1904, 390, and 2290 million tonnes • bits for 2010, and at 1751, 414, and 2165 million tonnes • bits, respectively. Then we use the scaled values to calculate the degree of order for 2010 and 2018 at 0.830 and 0.809, respectively. Finally, the degree of order is used to calculate the theoretical robustness for 2010 and 2018 at 0.155 and 0.172, respectively.

The same approach is used for the energy flow networks by using the values of the Appendixes B.2.4 -B.2.5, and the results are plotted in the figure below. The ΔT.., Δα, and ΔR values between 2010 and 2018 for the material flow network were, -8%, -2.5%, and 10.9%, while for the energy flow network were 6%, -0.4%, and 0.5%, respectively. We observe that for the years 2010 and 2018 both types of networks of Bulgaria were more efficient than resilient and nowhere near the maximum robustness. Moreover, we can also see that the material flow network had a relative reduction in its total system throughput and its degree of order but a substantial increase in its theoretical robustness. On the other hand, the energy flow network had an increase in its total system throughput, a reduction in degree of order, and a minor increase in its theoretical robustness (difference is not visible due to the overlapping of the two similarly sized bubbles of $TST_{..}$).



Theoretical robustness versus the degree of order for the material (grey) and energy (brown) flow networks of Bulgaria (BG) for the years 2010 and 2018 where the size of the bubble represents the total system throughput $TST_{..}$ in million tonnes and in PJ, respectively.

Appendix C.1

Ascendency analysis of the material flow networks of the EU countries between 2010 and 2018 where CMR is the circularity rate reported by Eurostat, $T_{..}$ is the total system throughput in million tonnes, X is the average mutual information in bits, H_c is the overhead in bits, H is the capacity for development in bits, A is the ascendency (X scaled by $T_{..}$) in million tonnes • bits, Φ is the overhead (H_c scaled by $T_{..}$) in million tonnes • bits, C is the capacity for development (H scaled by $T_{..}$) in million tonnes • bits, α is the degree of order (unitless), R is the theoretical robustness (unitless), n is the number of roles (unitless), c is the link density (unitless). The results are based on Eurostat data that have been obtained on the 21st of May 2021. According to Eurostat (personal communication), the values displayed on the Sankey diagrams at the website change every time that one of the following data set sources change: (env_ac_mfa), (env_wassd), (env_ac_sd) where the last two data sets integrate other sources, and therefore, the number of times that a value changes depends on the flow.

Country	Year	CMR (%)	$T_{..}$ (million tonnes)	X (bits)	H_c (bits)	H (bits)	A (million tonnes • bits)	Φ (million tonnes • bits)	C (million tonnes • bits)	α (-)	R (-)	n (-)	c (-)
EU27	2010	10.7	29141	2.1858	1.0027	3.1885	63696	29220	92916	0.6855	0.2588	4.5498	1.4155
	2011	10.2	30679	2.1849	0.9823	3.1672	67032	30136	97168	0.6899	0.2561	4.5471	1.4056
	2012	11.0	28806	2.1901	1.0167	3.2068	63088	29286	92374	0.6830	0.2604	4.5634	1.4224
	2013	11.2	28213	2.1892	1.0263	3.2156	61765	28956	90721	0.6808	0.2617	4.5607	1.4272
	2014	11.1	28553	2.1877	1.0237	3.2114	62465	29229	91694	0.6812	0.2615	4.5557	1.4259
	2015	11.2	28530	2.1865	1.0286	3.2152	62382	29347	91728	0.6801	0.2622	4.5521	1.4283
	2016	11.4	28577	2.1847	1.0315	3.2163	62433	29478	91911	0.6793	0.2627	4.5464	1.4298
	2017	11.5	29505	2.1826	1.0246	3.2072	64398	30231	94629	0.6805	0.2619	4.5397	1.4263
	2018	11.6	30066	2.1845	1.0174	3.2019	65679	30589	96268	0.6822	0.2609	4.5456	1.4228
Belgium	2010	12.6	1172	1.9637	0.8603	2.8240	2301	1008	3310	0.6954	0.2526	3.9006	1.3474
	2011	13.5	1234	1.9883	0.8768	2.8650	2454	1082	3535	0.6940	0.2535	3.9676	1.3551
	2012	16.7	1194	1.9986	0.8992	2.8978	2386	1074	3460	0.6897	0.2562	3.9960	1.3657
	2013	17.1	1181	1.9981	0.9017	2.8998	2360	1065	3425	0.6890	0.2566	3.9947	1.3669
	2014	18.2	1185	1.9952	0.8971	2.8923	2364	1063	3427	0.6898	0.2561	3.9868	1.3647
	2015	18.4	1173	1.9977	0.9062	2.9040	2343	1063	3406	0.6879	0.2573	3.9937	1.3690
	2016	18.3	1185	1.9961	0.8997	2.8959	2365	1066	3432	0.6893	0.2565	3.9893	1.3659
	2017	20.4	1209	1.9894	0.8974	2.8868	2405	1085	3490	0.6891	0.2566	3.9708	1.3648
	2018	21.8	1216	1.9807	0.8831	2.8638	2408	1074	3482	0.6916	0.2550	3.9467	1.3581

(*continued on next page*)

(*continued*)

Country	Year	CMR (%)	$T_{..}$ (million tonnes)	X (bits)	H_c (bits)	H (bits)	A (million tonnes • bits)	Φ (million tonnes • bits)	C (million tonnes • bits)	α (-)	R (-)	n (-)	c (-)
Bulgaria	2010	2.1	828	2.2988	0.4711	2.7699	1904	390	2294	0.8299	0.1547	4.9204	1.1774
	2011	1.8	865	2.3021	0.4866	2.7887	1992	421	2413	0.8255	0.1583	4.9319	1.1837
	2012	1.9	849	2.3024	0.4824	2.7848	1955	410	2365	0.8268	0.1573	4.9327	1.1820
	2013	2.5	876	2.3004	0.4931	2.7935	2016	432	2448	0.8235	0.1599	4.9260	1.1864
	2014	2.7	917	2.3062	0.4701	2.7763	2116	431	2547	0.8307	0.1541	4.9459	1.1769
	2015	3.1	865	2.3070	0.5133	2.8203	1997	444	2441	0.8180	0.1643	4.9485	1.1947
	2016	4.4	746	2.2967	0.5826	2.8792	1714	435	2148	0.7977	0.1803	4.9133	1.2237
	2017	3.5	762	2.2940	0.5686	2.8626	1748	433	2181	0.8014	0.1774	4.9043	1.2178
	2018	2.5	763	2.2952	0.5424	2.8376	1751	414	2165	0.8089	0.1716	4.9083	1.2068
Czech Republic	2010	5.3	838	2.0379	0.9389	2.9768	1708	787	2495	0.6846	0.2594	4.1065	1.3846
	2011	5.4	886	2.0394	0.9335	2.9728	1807	827	2634	0.6860	0.2585	4.1106	1.3820
	2012	6.3	812	2.0331	0.9571	2.9903	1651	777	2428	0.6799	0.2623	4.0930	1.3933
	2013	6.7	814	2.0403	0.9697	3.0099	1661	789	2450	0.6778	0.2636	4.1133	1.3994
	2014	6.9	844	2.0393	0.9649	3.0043	1721	814	2536	0.6788	0.2630	4.1105	1.3971
	2015	6.9	879	2.0469	0.9731	3.0200	1799	855	2655	0.6778	0.2636	4.1321	1.4011
	2016	7.6	870	2.0476	0.9846	3.0323	1781	857	2638	0.6753	0.2651	4.1343	1.4067
	2017	7.9	878	2.0551	0.9873	3.0424	1804	867	2671	0.6755	0.2650	4.1558	1.4080
	2018	8.0	906	2.0657	0.9585	3.0242	1872	868	2740	0.6831	0.2604	4.1865	1.3940
Denmark	2010	8.0	582	2.0457	0.9633	3.0090	1191	561	1751	0.6799	0.2623	4.1287	1.3963
	2011	7.1	645	2.0489	0.9331	2.9820	1322	602	1923	0.6871	0.2579	4.1379	1.3818
	2012	6.5	642	2.0551	0.9224	2.9774	1319	592	1912	0.6902	0.2559	4.1556	1.3767
	2013	7.8	617	2.0601	0.9527	3.0128	1271	588	1859	0.6838	0.2599	4.1701	1.3912
	2014	9.1	626	2.0694	0.9520	3.0213	1295	596	1891	0.6849	0.2592	4.1971	1.3909
	2015	8.4	642	2.0717	0.9346	3.0063	1330	600	1930	0.6891	0.2566	4.2039	1.3825
	2016	8.1	657	2.0693	0.9286	2.9979	1360	610	1970	0.6902	0.2559	4.1968	1.3797
	2017	8.0	686	2.0742	0.9557	3.0298	1424	656	2080	0.6846	0.2594	4.2110	1.3927
	2018	8.2	691	2.0847	0.9583	3.0430	1441	662	2103	0.6851	0.2591	4.2419	1.3939
Germany	2010	11.0	6422	2.1158	1.1292	3.2450	13588	7252	20840	0.6520	0.2789	4.3344	1.4790
	2011	10.4	6873	2.1176	1.1039	3.2215	14554	7587	22141	0.6573	0.2758	4.3397	1.4661
	2012	10.7	6632	2.1137	1.1183	3.2320	14018	7417	21435	0.6540	0.2777	4.3280	1.4734
	2013	10.9	6633	2.1169	1.1240	3.2409	14041	7456	21497	0.6532	0.2782	4.3376	1.4763
	2014	10.8	6841	2.1204	1.1176	3.2380	14506	7645	22151	0.6549	0.2772	4.3483	1.4730
	2015	11.6	6599	2.1190	1.1406	3.2595	13983	7527	21510	0.6501	0.2800	4.3439	1.4848
	2016	11.7	6678	2.1213	1.1413	3.2627	14166	7622	21788	0.6502	0.2799	4.3510	1.4852
	2017	11.5	6944	2.1228	1.1280	3.2508	14741	7833	22573	0.6530	0.2783	4.3555	1.4783
	2018	12.0	6793	2.1252	1.1377	3.2629	14436	7728	22165	0.6513	0.2793	4.3626	1.4833
Estonia	2010	9.1	190	2.2002	1.0560	3.2562	417	200	618	0.6757	0.2649	4.5956	1.4419
	2011	14.6	214	2.2023	1.1250	3.3273	470	240	711	0.6619	0.2731	4.6022	1.4768
	2012	19.3	222	2.2108	1.1559	3.3667	490	256	746	0.6567	0.2762	4.6294	1.4927
	2013	14.8	235	2.2523	1.0805	3.3328	529	254	782	0.6758	0.2648	4.7645	1.4542
	2014	11.4	212	2.2098	1.0203	3.2301	468	216	684	0.6841	0.2597	4.6260	1.4242
	2015	11.8	204	2.2080	1.0265	3.2346	450	209	660	0.6826	0.2606	4.6205	1.4273
	2016	12.2	204	2.1962	1.0356	3.2318	448	211	659	0.6796	0.2625	4.5827	1.4318
	2017	12.6	235	2.1955	1.0606	3.2561	515	249	764	0.6743	0.2657	4.5804	1.4442
	2018	13.8	253	2.1949	1.0719	3.2668	555	271	825	0.6719	0.2672	4.5787	1.4499
Ireland	2010	1.7	411	2.0090	0.9321	2.9411	826	383	1210	0.6831	0.2603	4.0250	1.3813
	2011	2.1	355	1.9828	0.9727	2.9556	705	346	1050	0.6709	0.2678	3.9526	1.4009
	2012	1.8	355	1.9676	0.9659	2.9335	698	342	1040	0.6707	0.2679	3.9111	1.3976
	2013	1.7	387	1.9884	0.9796	2.9680	769	379	1147	0.6700	0.2683	3.9680	1.4042
	2014	2.0	376	1.9863	0.9934	2.9796	746	373	1119	0.6666	0.2703	3.9621	1.4110
	2015	1.9	399	1.9994	1.0080	3.0075	797	402	1199	0.6648	0.2714	3.9984	1.4182
	2016	1.7	430	2.0063	1.0045	3.0107	862	431	1293	0.6664	0.2705	4.0174	1.4164
	2017	1.7	455	2.0182	1.0061	3.0243	918	458	1376	0.6673	0.2699	4.0506	1.4172
	2018	1.6	490	2.0257	0.9883	3.0140	993	484	1477	0.6721	0.2671	4.0720	1.4085
Greece	2010	2.7	805	2.1957	0.8841	3.0799	1768	712	2480	0.7129	0.2412	4.5811	1.3586
	2011	2.2	733	2.1958	0.8537	3.0494	1610	626	2236	0.7201	0.2365	4.5813	1.3443
	2012	1.9	703	2.1924	0.8034	2.9957	1542	565	2107	0.7318	0.2285	4.5706	1.3210
	2013	1.8	678	2.1945	0.8199	3.0144	1489	556	2045	0.7280	0.2311	4.5774	1.3286
	2014	1.4	678	2.1889	0.8231	3.0120	1485	558	2043	0.7267	0.2320	4.5595	1.3301
	2015	1.9	669	2.1949	0.8014	2.9962	1469	536	2006	0.7325	0.2280	4.5784	1.3201
	2016	2.3	653	2.2058	0.7540	2.9598	1441	493	1934	0.7453	0.2191	4.6134	1.2986
	2017	2.8	617	2.1628	0.8428	3.0056	1335	520	1856	0.7196	0.2368	4.4777	1.3392
	2018	3.3	611	2.1257	0.9301	3.0558	1300	569	1868	0.6956	0.2525	4.3642	1.3804
Spain	2010	10.4	2887	2.1413	0.9804	3.1217	6182	2830	9012	0.6859	0.2586	4.4116	1.4046
	2011	9.8	2597	2.1315	1.0122	3.1437	5536	2629	8164	0.6780	0.2635	4.3818	1.4202
	2012	9.8	2165	2.1137	1.0730	3.1867	4576	2323	6899	0.6633	0.2723	4.3281	1.4504
	2013	8.9	2062	2.1035	1.0864	3.1900	4337	2240	6578	0.6594	0.2746	4.2975	1.4572
	2014	7.7	2081	2.0910	1.0786	3.1696	4351	2245	6596	0.6597	0.2744	4.2603	1.4533
	2015	7.5	2167	2.0826	1.0631	3.1457	4513	2304	6817	0.6620	0.2730	4.2358	1.4455
	2016	8.2	2133	2.0752	1.0535	3.1286	4426	2247	6673	0.6633	0.2723	4.2139	1.4407
	2017	8.9	2241	2.0648	1.0483	3.1132	4627	2349	6977	0.6633	0.2723	4.1838	1.4381
	2018	9.6	2383	2.0679	1.0265	3.0944	4928	2446	7374	0.6683	0.2693	4.1929	1.4272
France	2010	17.5	4225	2.1849	1.1314	3.3163	9231	4780	14011	0.6588	0.2749	4.5470	1.4801
	2011	16.8	4371	2.1798	1.1171	3.2969	9528	4883	14411	0.6612	0.2736	4.5308	1.4728
	2012	16.9	4240	2.1787	1.1207	3.2993	9238	4752	13989	0.6603	0.2740	4.5274	1.4746

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Country	Year	CMR (%)	$T_{..}$ (million tonnes)	X (bits)	H_c (bits)	H (bits)	A (million tonnes • bits)	Φ (million tonnes • bits)	C (million tonnes • bits)	α (-)	R (-)	n (-)	c (-)
	2013	17.3	4242	2.1769	1.1173	3.2942	9234	4740	13974	0.6608	0.2738	4.5217	1.4729
	2014	17.8	4209	2.1748	1.1257	3.3005	9154	4738	13892	0.6589	0.2749	4.5154	1.4772
	2015	18.7	4085	2.1774	1.1466	3.3240	8895	4684	13578	0.6551	0.2771	4.5234	1.4879
	2016	19.4	4025	2.1816	1.1536	3.3352	8781	4643	13424	0.6541	0.2777	4.5366	1.4915
	2017	18.8	4276	2.1808	1.1353	3.3160	9325	4854	14179	0.6576	0.2756	4.5339	1.4821
	2018	19.6	4299	2.1855	1.1373	3.3228	9395	4889	14285	0.6577	0.2756	4.5487	1.4831
Croatia	2010	1.6	213	2.0163	0.7947	2.8109	430	169	599	0.7173	0.2383	4.0453	1.3171
	2011	2.4	214	2.0399	0.8180	2.8580	437	175	612	0.7138	0.2407	4.1123	1.3278
	2012	3.6	195	2.0451	0.8371	2.8822	399	163	563	0.7096	0.2435	4.1271	1.3366
	2013	3.7	205	2.0350	0.8159	2.8509	418	167	585	0.7138	0.2406	4.0984	1.3268
	2014	4.6	194	2.0454	0.8605	2.9059	397	167	564	0.7039	0.2472	4.1279	1.3475
	2015	4.3	206	2.0432	0.8579	2.9011	421	177	598	0.7043	0.2469	4.1216	1.3462
	2016	4.4	213	2.0411	0.8599	2.9010	435	183	618	0.7036	0.2474	4.1156	1.3472
	2017	5.0	212	2.0175	0.8909	2.9083	428	189	617	0.6937	0.2537	4.0487	1.3617
	2018	4.9	220	2.0343	0.8670	2.9012	448	191	639	0.7012	0.2489	4.0962	1.3505
Italy	2010	11.5	3332	2.1226	0.9455	3.0681	7072	3150	10223	0.6918	0.2549	4.3547	1.3878
	2011	11.6	3368	2.1219	0.9406	3.0625	7147	3168	10315	0.6929	0.2542	4.3527	1.3854
	2012	13.9	2992	2.1243	0.9827	3.1070	6356	2940	9296	0.6837	0.2600	4.3599	1.4058
	2013	16.1	2625	2.1288	1.0245	3.1532	5588	2689	8277	0.6751	0.2652	4.3734	1.4263
	2014	16.1	2588	2.1295	1.0206	3.1501	5511	2641	8153	0.6760	0.2647	4.3757	1.4244
	2015	17.3	2584	2.1292	1.0327	3.1618	5502	2668	8170	0.6734	0.2663	4.3746	1.4303
	2016	17.8	2616	2.1297	1.0334	3.1631	5571	2703	8275	0.6733	0.2663	4.3764	1.4307
	2017	18.4	2628	2.1313	1.0413	3.1726	5601	2736	8338	0.6718	0.2672	4.3812	1.4346
	2018	18.7	2661	2.1380	1.0373	3.1753	5689	2760	8450	0.6733	0.2663	4.4016	1.4326
Cyprus	2010	2.0	97	2.1094	0.6727	2.7821	205	65	270	0.7582	0.2099	4.3150	1.2626
	2011	1.9	96	2.1085	0.6508	2.7593	202	62	264	0.7641	0.2056	4.3124	1.2530
	2012	2.0	69	2.0898	0.6951	2.7849	145	48	193	0.7504	0.2155	4.2570	1.2724
	2013	2.4	69	2.0898	0.6951	2.7849	145	48	193	0.7504	0.2155	4.2570	1.2724
	2014	2.2	54	2.1116	0.8517	2.9634	113	46	159	0.7126	0.2415	4.3218	1.3434
	2015	2.4	57	2.1030	0.8906	2.9936	119	50	170	0.7025	0.2481	4.2960	1.3616
	2016	2.4	66	2.1343	0.9296	3.0638	141	61	203	0.6966	0.2518	4.3902	1.3801
	2017	2.4	76	2.1035	0.8445	2.9480	160	64	225	0.7135	0.2408	4.2976	1.3400
	2018	2.7	75	2.1058	0.8469	2.9527	158	64	222	0.7132	0.2411	4.3044	1.3411
Latvia	2010	1.2	125	1.9140	0.8278	2.7418	239	103	342	0.6981	0.2509	3.7685	1.3323
	2011	2.9	139	1.9437	0.8420	2.7857	271	117	388	0.6978	0.2511	3.8470	1.3388
	2012	1.3	145	1.9425	0.8555	2.7980	281	124	405	0.6943	0.2533	3.8438	1.3451
	2013	3.8	149	1.9553	0.8434	2.7986	292	126	418	0.6986	0.2505	3.8778	1.3395
	2014	5.3	143	1.9355	0.8431	2.7786	277	121	398	0.6966	0.2519	3.8250	1.3394
	2015	5.4	153	1.9542	0.8511	2.8053	298	130	428	0.6966	0.2518	3.8751	1.3431
	2016	6.5	144	1.9238	0.8690	2.7928	278	125	403	0.6888	0.2568	3.7942	1.3514
	2017	5.5	160	1.9241	0.8445	2.7686	308	135	443	0.6950	0.2529	3.7951	1.3400
	2018	4.8	171	1.9262	0.8442	2.7704	329	144	474	0.6953	0.2527	3.8005	1.3399
Lithuania	2010	3.9	211	2.0346	0.9131	2.9478	429	192	621	0.6902	0.2559	4.0972	1.3723
	2011	3.6	229	2.0237	0.8888	2.9125	464	204	667	0.6948	0.2530	4.0661	1.3608
	2012	3.8	219	2.0054	0.9105	2.9159	440	200	639	0.6877	0.2574	4.0151	1.3710
	2013	3.2	257	2.0160	0.8734	2.8895	517	224	741	0.6977	0.2511	4.0447	1.3535
	2014	3.8	245	2.0160	0.8881	2.9041	494	218	712	0.6942	0.2534	4.0445	1.3604
	2015	4.1	253	2.0077	0.8917	2.8994	508	226	734	0.6925	0.2545	4.0215	1.3621
	2016	4.6	258	2.0074	0.8894	2.8967	519	230	749	0.6930	0.2542	4.0205	1.3610
	2017	4.5	284	2.0088	0.8687	2.8775	570	247	817	0.6981	0.2509	4.0244	1.3513
	2018	4.3	275	2.0044	0.8815	2.8858	552	243	795	0.6946	0.2532	4.0122	1.3573
Luxembourg	2010	24.1	108	2.1784	0.9226	3.1010	235	100	335	0.7025	0.2481	4.5265	1.3768
	2011	20.7	98	2.1691	0.9929	3.1621	213	98	311	0.6860	0.2585	4.4975	1.4107
	2012	18.5	96	2.1795	1.0689	3.2483	209	103	312	0.6709	0.2677	4.5298	1.4484
	2013	15.3	92	2.1752	1.0590	3.2342	201	98	299	0.6726	0.2668	4.5166	1.4434
	2014	11.2	90	2.1546	1.0246	3.1792	194	92	286	0.6777	0.2637	4.4524	1.4263
	2015	9.7	99	2.1701	1.0315	3.2016	215	102	317	0.6778	0.2636	4.5006	1.4297
	2016	7.0	103	2.1842	1.0530	3.2372	226	109	335	0.6747	0.2655	4.5446	1.4404
	2017	10.6	111	2.1894	1.0402	3.2296	243	115	358	0.6779	0.2635	4.5611	1.4340
	2018	10.8	111	2.1958	1.0609	3.2567	243	118	361	0.6742	0.2658	4.5814	1.4444
Hungary	2010	5.3	473	2.0651	0.9347	2.9998	977	442	1420	0.6884	0.2570	4.1846	1.3826
	2011	5.4	476	2.0612	0.9320	2.9931	981	444	1425	0.6886	0.2569	4.1732	1.3813
	2012	6.1	433	2.0512	0.9708	3.0219	888	420	1308	0.6788	0.2630	4.1444	1.4000
	2013	6.2	488	2.0594	0.9412	3.0006	1006	460	1466	0.6863	0.2583	4.1681	1.3857
	2014	5.4	606	2.0637	0.8719	2.9356	1251	529	1780	0.7030	0.2477	4.1806	1.3528
	2015	5.8	605	2.0620	0.8806	2.9426	1247	532	1779	0.7008	0.2492	4.1758	1.3569
	2016	6.5	584	2.0625	0.9053	2.9678	1205	529	1735	0.6950	0.2529	4.1770	1.3685
	2017	6.9	669	2.0652	0.8914	2.9567	1382	596	1978	0.6985	0.2506	4.1850	1.3620
	2018	7.0	759	2.0824	0.8250	2.9074	1581	626	2207	0.7163	0.2390	4.2352	1.3310
Malta	2010	5.3	18	2.1340	0.9414	3.0754	38	17	55	0.6939	0.2536	4.3893	1.3858
	2011	4.5	22	2.1069	1.0246	3.1315	47	23	70	0.6728	0.2666	4.3077	1.4263
	2012	3.9	25	2.1012	0.9792	3.0804	53	25	77	0.6821	0.2609	4.2906	1.4041
	2013	6.3	22	2.1158	1.0268	3.1426	46	22	68	0.6733	0.2664	4.3342	1.4274
	2014	6.4	26	2.1301	0.9808	3.1109	54	25	80	0.6847	0.2593	4.3774	1.4048
	2015	4.6	30	2.1315	0.9111	3.0426	64	27	92	0.7005	0.2493	4.3817	1.3713

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Country	Year	CMR (%)	$T_{..}$ (million tonnes)	X (bits)	H_c (bits)	H (bits)	A (million tonnes • bits)	Φ (million tonnes • bits)	C (million tonnes • bits)	α (-)	R (-)	n (-)	c (-)
	2016	4.2	29	2.1454	0.9191	3.0644	63	27	90	0.7001	0.2496	4.4241	1.3751
	2017	6.5	32	2.1556	1.0395	3.1951	68	33	101	0.6747	0.2655	4.4554	1.4337
	2018	8.1	35	2.1812	0.9755	3.1567	75	34	109	0.6910	0.2554	4.5352	1.4023
The Netherlands	2010	25.3	1862	1.9925	0.9507	2.9433	3710	1770	5480	0.6770	0.2641	3.9793	1.3903
	2011	25.0	1872	1.9971	0.9490	2.9461	3739	1777	5515	0.6779	0.2636	3.9920	1.3894
	2012	26.5	1879	1.9891	0.9343	2.9234	3737	1756	5493	0.6804	0.2620	3.9698	1.3824
	2013	27.1	1877	1.9753	0.9212	2.8966	3708	1729	5437	0.6820	0.2610	3.9322	1.3761
	2014	26.6	1858	1.9828	0.9263	2.9091	3684	1721	5405	0.6816	0.2613	3.9525	1.3786
	2015	25.8	1874	1.9986	0.9310	2.9296	3745	1745	5490	0.6822	0.2609	3.9962	1.3808
	2016	28.5	1908	1.9801	0.9045	2.8846	3778	1726	5504	0.6864	0.2583	3.9451	1.3682
	2017	29.7	1885	1.9641	0.8837	2.8477	3702	1666	5368	0.6897	0.2562	3.9016	1.3583
	2018	29.0	1882	1.9710	0.8767	2.8476	3709	1650	5359	0.6921	0.2547	3.9203	1.3550
Austria	2010	6.6	811	2.0505	0.9875	3.0380	1663	801	2464	0.6750	0.2653	4.1426	1.4081
	2011	6.8	877	2.0777	1.0164	3.0942	1822	891	2714	0.6715	0.2674	4.2214	1.4223
	2012	7.6	881	2.0967	1.0531	3.1498	1847	928	2775	0.6657	0.2709	4.2773	1.4405
	2013	8.9	864	2.0956	1.0790	3.1746	1811	932	2743	0.6601	0.2742	4.2740	1.4535
	2014	9.9	878	2.1045	1.0752	3.1797	1848	944	2792	0.6619	0.2732	4.3005	1.4515
	2015	11.0	870	2.1030	1.0837	3.1867	1830	943	2772	0.6599	0.2743	4.2961	1.4558
	2016	11.4	907	2.1038	1.0555	3.1592	1908	957	2865	0.6659	0.2708	4.2983	1.4417
	2017	11.6	908	2.1022	1.0667	3.1689	1909	969	2877	0.6634	0.2723	4.2937	1.4473
	2018	11.4	929	2.1099	1.0606	3.1705	1960	985	2945	0.6655	0.2710	4.3165	1.4442
Poland	2010	10.8	3348	2.1516	0.9015	3.0531	7203	3018	10222	0.7047	0.2466	4.4431	1.3667
	2011	9.2	3662	2.1469	0.8643	3.0113	7862	3165	11027	0.7130	0.2412	4.4289	1.3493
	2012	10.6	3283	2.1585	0.9265	3.0850	7086	3042	10128	0.6997	0.2499	4.4644	1.3786
	2013	11.8	3196	2.1665	0.9625	3.1290	6924	3076	10000	0.6924	0.2545	4.4892	1.3960
	2014	12.5	3239	2.1720	0.9796	3.1515	7035	3173	10208	0.6892	0.2566	4.5063	1.4042
	2015	11.6	3203	2.1662	0.9769	3.1431	6938	3129	10067	0.6892	0.2565	4.4885	1.4029
	2016	10.2	3251	2.1590	0.9565	3.1156	7019	3110	10129	0.6930	0.2542	4.4662	1.3931
	2017	9.9	3384	2.1521	0.9401	3.0923	7283	3181	10464	0.6960	0.2523	4.4448	1.3852
	2018	9.7	3503	2.1496	0.9142	3.0638	7530	3202	10733	0.7016	0.2486	4.4372	1.3728
Portugal	2010	1.8	890	2.0543	0.6557	2.7100	1828	583	2411	0.7580	0.2100	4.1534	1.2551
	2011	1.7	837	2.0535	0.6797	2.7332	1718	569	2286	0.7513	0.2148	4.1512	1.2656
	2012	2.0	778	2.0542	0.6905	2.7447	1599	538	2136	0.7484	0.2169	4.1530	1.2704
	2013	2.5	696	2.0580	0.7675	2.8255	1431	534	1965	0.7284	0.2309	4.1641	1.3047
	2014	2.5	757	2.0567	0.7464	2.8031	1556	565	2121	0.7337	0.2272	4.1603	1.2952
	2015	2.1	760	2.0528	0.7670	2.8198	1560	583	2143	0.7280	0.2311	4.1492	1.3045
	2016	2.1	726	2.0484	0.7702	2.8186	1487	559	2046	0.7268	0.2320	4.1366	1.3059
	2017	2.0	788	2.0452	0.7514	2.7966	1612	592	2204	0.7313	0.2288	4.1273	1.2975
	2018	2.1	789	2.0524	0.7578	2.8102	1619	598	2217	0.7303	0.2295	4.1480	1.3003
Romania	2010	3.5	1350	2.2887	0.5701	2.8588	3090	770	3859	0.8006	0.1781	4.8862	1.2184
	2011	2.5	1776	2.2789	0.6172	2.8961	4047	1096	5143	0.7869	0.1886	4.8531	1.2385
	2012	2.6	1709	2.2930	0.5666	2.8595	3919	968	4887	0.8019	0.1771	4.9006	1.2170
	2013	2.5	1688	2.2784	0.6337	2.9121	3846	1070	4916	0.7824	0.1920	4.8513	1.2456
	2014	2.1	1710	2.2544	0.6820	2.9364	3855	1166	5022	0.7677	0.2029	4.7712	1.2666
	2015	1.7	1995	2.2429	0.6546	2.8975	4475	1306	5781	0.7741	0.1982	4.7334	1.2546
	2016	1.7	2020	2.2424	0.6574	2.8998	4531	1328	5859	0.7733	0.1988	4.7317	1.2559
	2017	1.7	1904	2.2557	0.6701	2.9257	4296	1276	5572	0.7710	0.2005	4.7756	1.2614
	2018	1.5	2055	2.2551	0.6568	2.9119	4634	1350	5984	0.7744	0.1980	4.7738	1.2556
Slovenia	2010	5.9	171	2.0745	0.9794	3.0540	354	167	522	0.6793	0.2627	4.2121	1.4042
	2011	7.6	164	2.0916	1.0303	3.1219	343	169	512	0.6700	0.2683	4.2623	1.4291
	2012	9.3	146	2.0835	1.0745	3.1580	305	157	462	0.6598	0.2744	4.2384	1.4512
	2013	9.2	148	2.0787	1.0736	3.1524	308	159	468	0.6594	0.2746	4.2244	1.4508
	2014	8.4	164	2.0852	1.0623	3.1476	342	174	516	0.6625	0.2728	4.2434	1.4451
	2015	8.4	169	2.0652	1.0477	3.1129	348	177	525	0.6634	0.2722	4.1849	1.4378
	2016	8.5	162	2.0569	1.0402	3.0971	333	169	502	0.6641	0.2718	4.1609	1.4341
	2017	9.7	176	2.0781	1.0884	3.1665	365	191	557	0.6563	0.2764	4.2224	1.4582
	2018	10.0	198	2.1192	1.0884	3.2076	420	216	635	0.6607	0.2738	4.3444	1.4582
Slovakia	2010	5.1	366	2.0510	0.9054	2.9565	750	331	1081	0.6937	0.2537	4.1440	1.3686
	2011	4.8	370	2.0405	0.8939	2.9344	755	331	1086	0.6954	0.2526	4.1138	1.3632
	2012	4.1	334	2.0342	0.9136	2.9478	680	305	985	0.6901	0.2560	4.0961	1.3725
	2013	4.6	335	2.0272	0.9228	2.9500	678	309	987	0.6872	0.2578	4.0761	1.3769
	2014	4.8	362	2.0240	0.9086	2.9326	733	329	1063	0.6902	0.2559	4.0672	1.3701
	2015	5.0	366	2.0321	0.9185	2.9506	743	336	1079	0.6887	0.2568	4.0900	1.3748
	2016	5.2	366	2.0320	0.9148	2.9469	744	335	1079	0.6896	0.2563	4.0898	1.3731
	2017	5.1	381	2.0469	0.9382	2.9851	779	357	1136	0.6857	0.2587	4.1322	1.3842
	2018	5.0	402	2.0522	0.9147	2.9669	824	367	1192	0.6917	0.2550	4.1473	1.3730
Finland	2010	13.5	1035	2.2794	0.9909	3.2703	2359	1026	3385	0.6970	0.2516	4.8547	1.4098
	2011	14.0	1048	2.2698	0.9702	3.2400	2379	1017	3396	0.7006	0.2493	4.8226	1.3997
	2012	15.3	1009	2.2726	0.9561	3.2286	2293	965	3257	0.7039	0.2472	4.8319	1.3928
	2013	10.1	1068	2.2461	0.8987	3.1448	2400	960	3360	0.7142	0.2404	4.7441	1.3654
	2014	7.3	895	2.2441	0.8994	3.1435	2007	805	2812	0.7139	0.2406	4.7373	1.3658
	2015	6.5	888	2.2699	0.8525	3.1224	2015	757	2772	0.7270	0.2318	4.8230	1.3437
	2016	5.3	930	2.2844	0.8156	3.1000	2125	759	2883	0.7369	0.2250	4.8716	1.3267
	2017	5.6	982	2.2760	0.8532	3.1293	2235	838	3073	0.7273	0.2316	4.8433	1.3441
	2018	5.9	1026	2.2703	0.8798	3.1501	2330	903	3233	0.7207	0.2360	4.8243	1.3565

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Country	Year	CMR (%)	$T_{..}$ (million tonnes)	X (bits)	H_c (bits)	H (bits)	A (million tonnes • bits)	Φ (million tonnes • bits)	C (million tonnes • bits)	α (-)	R (-)	n (-)	c (-)
Sweden	2010	7.2	1196	2.2302	0.9256	3.1558	2667	1107	3774	0.7067	0.2453	4.6918	1.3782
	2011	7.5	1268	2.2512	0.8983	3.1494	2854	1139	3993	0.7148	0.2400	4.7606	1.3652
	2012	8.2	1301	2.2654	0.8666	3.1320	2947	1127	4075	0.7233	0.2343	4.8079	1.3503
	2013	7.3	1316	2.2741	0.8566	3.1307	2993	1127	4120	0.7264	0.2322	4.8369	1.3457
	2014	6.5	1353	2.2752	0.8513	3.1264	3078	1152	4230	0.7277	0.2313	4.8406	1.3432
	2015	6.8	1337	2.2719	0.8931	3.1650	3038	1194	4232	0.7178	0.2380	4.8296	1.3628
	2016	7.0	1361	2.2578	0.9324	3.1903	3073	1269	4342	0.7077	0.2447	4.7827	1.3815
	2017	6.8	1414	2.2502	0.9140	3.1642	3182	1292	4474	0.7111	0.2424	4.7576	1.3727
	2018	6.7	1432	2.2480	0.9079	3.1559	3219	1300	4519	0.7123	0.2416	4.7502	1.3698

Appendix C.2

Ascendency analysis of the energy flow networks of EU27 countries between 2010 and 2018 where η_{tot} is the energy efficiency (calculated by values from Eurostat), $T_{..}$ is the total system throughput in TJ, X is the average mutual information in bits, H_c is the overhead in bits, H is the capacity for development in bits, A is the ascendency (X scaled by $T_{..}$) in TJ • bits, Φ is the overhead (H_c scaled by $T_{..}$) in TJ • bits, C is the capacity for development (H scaled by $T_{..}$) in TJ • bits, α is the degree of order (unitless), R is the theoretical robustness (unitless), n is the number of roles (unitless), c is the link density (unitless). The results are based on Eurostat data that have been obtained on the 21st of May 2021. According to Eurostat (personal communication), the values displayed on the Sankey diagrams at the website change every time that one of the following data set sources change: (env_ac_mfa), (env_wassd), (env_ac_sd) where the last two data sets integrate other sources, and therefore, the number of times that a value changes depends on the flow.

Country	Year	η_{tot} (%)	$T_{..}$ (TJ)	X (bits)	H_c (bits)	H (bits)	A (TJ • bits)	Φ (TJ • bits)	C (TJ • bits)	α (-)	R (-)	n (-)	c (-)
EU27	2010	81.1	324881081	2.0254	1.1861	3.2115	658022011	385325737	1043347748	0.6307	0.2907	4.0711	1.5084
	2011	80.9	318533095	2.0259	1.1930	3.2189	645323006	380016444	1025339449	0.6294	0.2914	4.0725	1.5121
	2012	81.5	320102936	2.0256	1.1932	3.2189	648414544	381950343	1030364887	0.6293	0.2915	4.0717	1.5122
	2013	80.9	319359819	2.0261	1.1907	3.2168	647058329	380265808	1027324137	0.6298	0.2912	4.0731	1.5108
	2014	82.0	311850607	2.0253	1.1910	3.2163	631599235	371419640	1003018875	0.6297	0.2912	4.0708	1.5110
	2015	82.5	321645239	2.0248	1.1929	3.2177	651266521	383706678	1034973199	0.6293	0.2915	4.0693	1.5120
	2016	82.9	322676201	2.0245	1.1902	3.2147	653248586	384061135	1037309721	0.6298	0.2912	4.0684	1.5106
	2017	82.9	328981020	2.0243	1.1791	3.2035	665968037	387911571	1053879608	0.6319	0.2900	4.0680	1.5048
	2018	83.0	321983747	2.0234	1.1819	3.2053	651515852	380538545	1032054397	0.6313	0.2904	4.0655	1.5062
Belgium	2010	84.7	15988251	2.0205	1.1591	3.1796	32304403	18532040	50836443	0.6355	0.2881	4.0573	1.4944
	2011	85.0	15295423	2.0223	1.1594	3.1817	30931459	17733512	48664971	0.6356	0.2880	4.0622	1.4945
	2012	87.5	14865424	2.0190	1.1388	3.1578	30013168	16928164	46941332	0.6394	0.2860	4.0530	1.4839
	2013	87.0	15252711	2.0221	1.1378	3.1599	30843133	17353797	48196929	0.6399	0.2857	4.0619	1.4834
	2014	88.2	14971297	2.0173	1.1129	3.1303	30202266	16662220	46864486	0.6445	0.2831	4.0484	1.4707
	2015	89.7	15113253	2.0165	1.1031	3.1196	30476461	16671327	47147788	0.6464	0.2820	4.0461	1.4657
	2016	87.0	15478072	2.0211	1.1376	3.1587	31282894	17607752	48890647	0.6399	0.2857	4.0590	1.4833
	2017	87.5	16257147	2.0207	1.1469	3.1676	32850358	18645010	51495367	0.6379	0.2868	4.0577	1.4881
	2018	90.1	16318018	2.0192	1.1231	3.1423	32949335	18327136	51276471	0.6426	0.2842	4.0536	1.4759
Bulgaria	2010	67.0	3518931	2.0135	1.1723	3.1858	7085515	4125172	11210687	0.6320	0.2900	4.0377	1.5012
	2011	65.6	3735938	2.0131	1.1340	3.1471	7520832	4236715	11757547	0.6397	0.2858	4.0365	1.4815
	2012	68.4	3722596	2.0154	1.1562	3.1715	7502343	4303881	11806224	0.6355	0.2881	4.0428	1.4929
	2013	70.4	3575134	2.0176	1.1710	3.1886	7213061	4186657	11399718	0.6327	0.2896	4.0490	1.5006
	2014	68.9	3647193	2.0180	1.1758	3.1938	7359943	4288481	11648424	0.6318	0.2901	4.0501	1.5031
	2015	70.4	3897432	2.0205	1.1736	3.1941	7874837	4573867	12448704	0.6326	0.2897	4.0573	1.5019
	2016	71.2	3793822	2.0194	1.1668	3.1862	7661292	4426666	12087958	0.6338	0.2890	4.0542	1.4984
	2017	70.8	3932724	2.0203	1.1750	3.1953	7945459	4620968	12566428	0.6323	0.2899	4.0568	1.5026
	2018	69.0	3738463	2.0222	1.1902	3.2123	7559754	4449378	12009132	0.6295	0.2914	4.0619	1.5106
Czech Republic	2010	71.5	8601148	2.0408	1.2196	3.2604	17553089	10490368	28043457	0.6259	0.2933	4.1147	1.5261
	2011	73.0	8632103	2.0454	1.2326	3.2780	17656129	10639709	28295838	0.6240	0.2943	4.1279	1.5329
	2012	73.0	8391354	2.0428	1.2104	3.2532	17141565	10156992	27298558	0.6279	0.2922	4.1203	1.5212
	2013	71.5	8216589	2.0441	1.2195	3.2636	16795258	10020014	26815272	0.6263	0.2930	4.1241	1.5260
	2014	72.6	8088822	2.0407	1.1984	3.2391	16507046	9693845	26200890	0.6300	0.2911	4.1145	1.5149
	2015	72.9	8025897	2.0423	1.1865	3.2287	16390976	9522547	25913523	0.6325	0.2897	4.1189	1.5086
	2016	72.7	7840437	2.0480	1.1970	3.2450	16056836	9385166	25442002	0.6311	0.2905	4.1352	1.5142
	2017	74.0	8166939	2.0395	1.1746	3.2141	16656398	9593281	26249679	0.6345	0.2886	4.1110	1.5025
	2018	72.8	8008661	2.0394	1.1624	3.2018	16333122	9309070	25642192	0.6370	0.2873	4.1108	1.4961
Denmark	2010	91.6	6474796	2.0200	1.2420	3.2620	13078962	8041626	21120588	0.6193	0.2968	4.0558	1.5379

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Country	Year	η_{tot} (%)	$T_{..}$ (TJ)	X (bits)	H_c (bits)	H (bits)	A (TJ • bits)	Φ (TJ • bits)	C (TJ • bits)	α (-)	R (-)	n (-)	c (-)
	2011	93.2	6251972	2.0179	1.2383	3.2562	12615720	7741653	20357373	0.6197	0.2965	4.0499	1.5360
	2012	93.4	5923884	2.0130	1.2356	3.2486	11924807	7319664	19244471	0.6196	0.2966	4.0362	1.5345
	2013	93.0	5991771	2.0131	1.2461	3.2591	12061857	7466078	19527935	0.6177	0.2976	4.0364	1.5401
	2014	93.7	5720279	2.0113	1.2586	3.2698	11504978	7199380	18704358	0.6151	0.2989	4.0313	1.5468
	2015	95.6	5975488	2.0080	1.2508	3.2589	11998967	7474287	19473254	0.6162	0.2984	4.0223	1.5427
	2016	94.9	5772253	2.0077	1.2439	3.2516	11589159	7179977	18769136	0.6175	0.2977	4.0215	1.5389
	2017	94.8	5476474	2.0062	1.2573	3.2635	10986948	6885379	17872326	0.6147	0.2991	4.0173	1.5461
	2018	94.3	5092404	2.0056	1.2377	3.2434	10213535	6302947	16516481	0.6184	0.2972	4.0157	1.5357
Germany	2010	77.8	61486168	2.0264	1.1369	3.1633	124595203	69901618	194496821	0.6406	0.2853	4.0739	1.4829
	2011	78.4	58687141	2.0252	1.1262	3.1513	118850415	66092411	184942826	0.6426	0.2842	4.0703	1.4774
	2012	78.7	59541688	2.0252	1.1415	3.1667	120584525	67968524	188553049	0.6395	0.2859	4.0705	1.4853
	2013	78.9	61068641	2.0271	1.1255	3.1526	123789418	68733457	192522875	0.6430	0.2840	4.0757	1.4771
	2014	79.1	59363401	2.0259	1.1340	3.1599	120262321	67319767	187582088	0.6411	0.2850	4.0724	1.4815
	2015	79.9	61346832	2.0267	1.1400	3.1667	124334063	69932928	194266991	0.6400	0.2856	4.0748	1.4845
	2016	80.5	60908361	2.0257	1.1538	3.1795	123379317	70277131	193656448	0.6371	0.2872	4.0718	1.4916
	2017	80.9	62220001	2.0260	1.1318	3.1578	126055642	70419584	196475226	0.6416	0.2847	4.0726	1.4803
	2018	80.0	56453687	2.0232	1.1223	3.1455	114219400	63355606	177575006	0.6432	0.2838	4.0650	1.4754
Estonia	2010	64.1	1049657	2.0495	1.1424	3.1919	2151222	1199128	3350350	0.6421	0.2845	4.1395	1.4858
	2011	63.5	1071913	2.0503	1.1535	3.2039	2197795	1236480	3434275	0.6400	0.2856	4.1421	1.4915
	2012	72.0	1304466	2.0694	1.2640	3.3334	2699456	1648867	4348323	0.6208	0.2960	4.1971	1.5497
	2013	65.6	1272392	2.0646	1.2267	3.2913	2627001	1560808	4187808	0.6273	0.2925	4.1832	1.5298
	2014	68.3	1288549	2.0671	1.1941	3.2612	2663515	1538696	4202211	0.6338	0.2890	4.1903	1.5126
	2015	72.5	1286143	2.0669	1.2297	3.2967	2658353	1581614	4239966	0.6270	0.2927	4.1899	1.5314
	2016	67.9	1317630	2.0635	1.3219	3.3854	2718931	1741833	4460765	0.6095	0.3018	4.1800	1.5811
	2017	70.5	1318170	2.0554	1.2252	3.2807	2709402	1615059	4324460	0.6265	0.2929	4.1567	1.5290
	2018	70.2	1480042	2.0630	1.2240	3.2870	3053274	1811554	4864827	0.6276	0.2924	4.1784	1.5284
Ireland	2010	84.9	2867225	2.0414	1.1146	3.1559	5853136	3195679	9048815	0.6468	0.2818	4.1164	1.4715
	2011	85.9	2660398	2.0386	1.0582	3.0968	5423384	2815227	8238611	0.6583	0.2752	4.1084	1.4430
	2012	83.2	2639011	2.0385	1.1125	3.1510	5379743	2935818	8315561	0.6469	0.2817	4.1083	1.4704
	2013	87.4	2697152	2.0385	1.1215	3.1600	5498124	3024781	8522905	0.6451	0.2828	4.1082	1.4750
	2014	85.7	2512092	2.0374	1.0626	3.0999	5118012	2669310	7787321	0.6572	0.2759	4.1049	1.4452
	2015	85.3	2717389	2.0323	1.0661	3.0985	5522673	2897056	8419728	0.6559	0.2766	4.0907	1.4470
	2016	91.8	2688544	2.0365	1.1146	3.1511	5475279	2996687	8471966	0.6463	0.2821	4.1026	1.4715
	2017	86.4	2831503	2.0336	1.1751	3.2087	5758057	3327272	9085329	0.6338	0.2890	4.0942	1.5027
	2018	88.4	2859074	2.0317	1.1507	3.1824	5808915	3289893	9098808	0.6384	0.2865	4.0890	1.4900
Greece	2010	84.1	6719089	2.0087	1.1249	3.1337	13496900	7558469	21055369	0.6410	0.2851	4.0243	1.4768
	2011	84.6	6660062	2.0145	1.2104	3.2250	13416977	8061476	21478452	0.6247	0.2939	4.0405	1.5212
	2012	82.4	6946502	2.0079	1.1132	3.1211	13948073	7732976	21681048	0.6433	0.2838	4.0220	1.4708
	2013	85.1	6717322	2.0056	1.0985	3.1041	13472213	7378958	20851171	0.6461	0.2822	4.0155	1.4633
	2014	86.1	6842933	2.0042	1.0328	3.0369	13714468	7067049	20781517	0.6599	0.2743	4.0116	1.4304
	2015	88.4	7134291	2.0047	1.0387	3.0433	14301873	7410120	21711993	0.6587	0.2750	4.0130	1.4333
	2016	90.1	7301081	2.0036	0.9935	2.9971	14628218	7253614	21881832	0.6685	0.2692	4.0099	1.4110
	2017	89.8	7600649	2.0034	0.9701	2.9735	15227230	7373600	22600829	0.6737	0.2661	4.0095	1.3996
	2018	89.9	7733755	2.0033	0.9783	2.9816	15493415	7565685	23059099	0.6719	0.2672	4.0093	1.4036
Spain	2010	81.8	25369726	2.0145	1.1239	3.1384	51106670	28512935	79619605	0.6419	0.2846	4.0403	1.4763
	2011	81.5	25151480	2.0146	1.1138	3.1284	50671045	28012574	78683619	0.6440	0.2834	4.0408	1.4711
	2012	80.7	26209235	2.0152	1.1529	3.1681	52815579	30217292	83032871	0.6361	0.2878	4.0422	1.4912
	2013	82.8	25632749	2.0164	1.1887	3.2051	51687067	30468599	82155666	0.6291	0.2915	4.0459	1.5098
	2014	83.5	26139461	2.0177	1.1978	3.2155	52741629	31309770	84051399	0.6275	0.2924	4.0494	1.5146
	2015	82.1	26261751	2.0153	1.1784	3.1937	52925765	30945740	83871504	0.6310	0.2905	4.0427	1.5044
	2016	83.3	26543584	2.0155	1.1843	3.1998	53497553	31435568	84933121	0.6299	0.2911	4.0431	1.5075
	2017	81.6	27490387	2.0166	1.1595	3.1761	55437698	31873892	87311590	0.6349	0.2884	4.0464	1.4946
	2018	83.1	27462343	2.0150	1.1559	3.1708	55335519	31742751	87078270	0.6355	0.2881	4.0417	1.4927
France	2010	69.0	47454727	2.0319	1.1714	3.2033	96421095	55588590	152009685	0.6343	0.2887	4.0893	1.5008
	2011	68.7	47695709	2.0321	1.1858	3.2179	96921698	56555991	153477689	0.6315	0.2903	4.0900	1.5083
	2012	69.2	46926942	2.0378	1.1715	3.2092	95626939	54972860	150599799	0.6350	0.2884	4.1061	1.5008
	2013	69.3	47086383	2.0396	1.1727	3.2124	96039606	55220330	151259936	0.6349	0.2884	4.1114	1.5015
	2014	68.5	45850914	2.0374	1.1699	3.2073	93418110	53640705	147058815	0.6352	0.2882	4.1051	1.5000
	2015	68.5	46301197	2.0361	1.1639	3.2001	94276033	53892026	148168059	0.6363	0.2877	4.1015	1.4969
	2016	69.8	45307951	2.0362	1.1668	3.2030	92255337	52864420	145119757	0.6357	0.2880	4.1016	1.4984
	2017	70.1	45603399	2.0362	1.1613	3.1975	92857882	52959586	145817469	0.6368	0.2874	4.1017	1.4955
	2018	69.6	45774938	2.0384	1.1744	3.2128	93305516	53758681	147064197	0.6345	0.2887	4.1078	1.5023
Croatia	2010	92.9	2120707	2.0125	1.1509	3.1634	4267881	2440821	6708703	0.6362	0.2877	4.0348	1.4902
	2011	92.5	1992400	2.0156	1.1731	3.1887	4015850	2337274	6353124	0.6321	0.2899	4.0434	1.5016
	2012	92.3	1881066	2.0143	1.1765	3.1908	3789118	2213032	6002150	0.6313	0.2904	4.0400	1.5034
	2013	92.7	1889086	2.0138	1.1579	3.1717	3804222	2187322	5991544	0.6349	0.2884	4.0384	1.4937
	2014	93.4	1820272	2.0135	1.1523	3.1658	3665045	2097497	5762542	0.6360	0.2878	4.0375	1.4909
	2015	93.5	1939397	2.0138	1.1480	3.1618	3905541	2226426	6131967	0.6369	0.2873	4.0384	1.4886
	2016	92.9	1991394	2.0141	1.1503	3.1644	4010860	2290723	6301583	0.6365	0.2876	4.0393	1.4898
	2017	93.5	2074055	2.0133	1.1431	3.1564	4175652	2370882	6546533	0.6378	0.2868	4.0370	1.4861
	2018	94.0	2047042	2.0110	1.1574	3.1684	4116607	2369197	6485804	0.6347	0.2885	4.0306	1.4935

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Country	Year	η_{tot} (%)	$T_{..}$ (TJ)	X (bits)	H_c (bits)	H (bits)	A (TJ • bits)	Φ (TJ • bits)	C (TJ • bits)	α (-)	R (-)	n (-)	c (-)
Italy	2010	85.1	34531140	2.0151	1.0312	3.0463	69583874	35608930	105192804	0.6615	0.2734	4.0421	1.4296
	2011	84.7	33207822	2.0145	1.0575	3.0720	66897348	35117037	102014385	0.6558	0.2767	4.0404	1.4427
	2012	85.8	33466209	2.0229	1.0894	3.1124	67699651	36459432	104159083	0.6500	0.2800	4.0641	1.4587
	2013	85.4	30508512	2.0168	1.0770	3.0938	61529483	32857368	94386851	0.6519	0.2789	4.0468	1.4525
	2014	86.3	28681352	2.0165	1.0693	3.0858	57836172	30667684	88503857	0.6535	0.2780	4.0460	1.4486
	2015	86.0	30547726	2.0159	1.0525	3.0684	61582019	32151363	93733381	0.6570	0.2760	4.0444	1.4402
	2016	86.0	30535417	2.0166	1.0489	3.0655	61576283	32028935	93605218	0.6578	0.2755	4.0462	1.4384
	2017	86.3	31945641	2.0164	1.0740	3.0904	64415498	34308962	98724460	0.6525	0.2786	4.0458	1.4509
	2018	87.5	31407278	2.0165	1.0850	3.1016	63334195	34077113	97411308	0.6502	0.2799	4.0461	1.4565
Cyprus	2010	76.3	489742	2.1027	0.8591	2.9618	1029759	420747	1450506	0.7099	0.2432	4.2950	1.3468
	2011	75.9	465542	2.1064	0.8827	2.9891	980605	410955	1391559	0.7047	0.2466	4.3061	1.3579
	2012	74.2	437114	2.1063	0.8437	2.9500	920688	368798	1289486	0.7140	0.2405	4.3058	1.3396
	2013	78.1	394656	2.0968	0.8660	2.9628	827530	341759	1169289	0.7077	0.2447	4.2777	1.3500
	2014	76.6	394585	2.0982	0.8894	2.9877	827935	350951	1178886	0.7023	0.2482	4.2819	1.3610
	2015	77.8	420750	2.0981	0.8946	2.9927	882777	376420	1259197	0.7011	0.2490	4.2815	1.3635
	2016	77.3	446995	2.0992	0.8872	2.9864	938333	396572	1334905	0.7029	0.2478	4.2847	1.3600
	2017	77.4	455699	2.0974	0.8677	2.9651	955786	395415	1351201	0.7074	0.2449	4.2794	1.3508
	2018	77.2	464024	2.0976	0.8985	2.9961	973344	416923	1390266	0.7001	0.2496	4.2800	1.3653
Latvia	2010	94.2	999711	2.0176	1.1113	3.1289	2017022	1110983	3128005	0.6448	0.2829	4.0491	1.4698
	2011	94.7	1025042	2.0180	1.0262	3.0442	2068543	1051878	3120421	0.6629	0.2725	4.0502	1.4271
	2012	94.9	1090213	2.0170	1.0354	3.0525	2198977	1128852	3327829	0.6608	0.2738	4.0475	1.4317
	2013	93.7	1099333	2.0239	1.0560	3.0799	2224919	1160874	3385793	0.6571	0.2759	4.0668	1.4419
	2014	94.2	1097442	2.0219	1.0593	3.0812	2218907	1162504	3381411	0.6562	0.2764	4.0612	1.4436
	2015	94.3	1143874	2.0243	1.0056	3.0299	2315517	1150282	3465800	0.6681	0.2695	4.0679	1.4170
	2016	94.5	1163779	2.0215	1.0767	3.0981	2352563	1252989	3605551	0.6525	0.2786	4.0600	1.4523
	2017	94.7	1148651	2.0187	1.0570	3.0757	2318835	1214101	3532936	0.6563	0.2764	4.0523	1.4424
	2018	94.2	1216658	2.0240	1.0236	3.0476	2462568	1245370	3707938	0.6641	0.2718	4.0672	1.4258
Lithuania	2010	94.1	2543807	2.0040	0.9329	2.9369	5097721	2373081	7470802	0.6824	0.2608	4.0110	1.3817
	2011	95.4	2644609	2.0036	0.9427	2.9463	5298658	2493132	7791790	0.6800	0.2622	4.0099	1.3864
	2012	95.1	2627935	2.0038	0.9551	2.9589	5265751	2510052	7775803	0.6772	0.2640	4.0104	1.3924
	2013	95.2	2662761	2.0031	0.9373	2.9403	5333677	2495680	7829357	0.6812	0.2615	4.0085	1.3838
	2014	95.8	2432014	2.0039	0.9798	2.9836	4873444	2382770	7256215	0.6716	0.2673	4.0107	1.4043
	2015	96.4	2707595	2.0035	0.9728	2.9763	5424768	2633926	8058693	0.6732	0.2664	4.0098	1.4009
	2016	96.5	2787760	2.0028	0.9481	2.9509	5583420	2643086	8226506	0.6787	0.2630	4.0079	1.3890
	2017	97.0	2840316	2.0024	0.9652	2.9676	5687401	2741576	8428976	0.6747	0.2655	4.0066	1.3973
	2018	96.9	2744882	2.0023	0.9666	2.9689	5496084	2653307	8149391	0.6744	0.2657	4.0064	1.3980
Luxembourg	2010	94.3	815604	2.0408	0.5504	2.5912	1664507	448876	2113383	0.7876	0.1880	4.1148	1.2101
	2011	95.0	795503	2.0371	0.5024	2.5394	1620490	399627	2020118	0.8022	0.1768	4.1041	1.1902
	2012	94.8	780214	2.0386	0.5167	2.5553	1590576	403125	1993701	0.7978	0.1802	4.1086	1.1961
	2013	96.2	751815	2.0301	0.4723	2.5024	1526276	355051	1881327	0.8113	0.1697	4.0844	1.1778
	2014	95.9	733813	2.0320	0.4889	2.5209	1491129	358733	1849862	0.8061	0.1738	4.0898	1.1846
	2015	96.6	727219	2.0271	0.4913	2.5184	1474156	357261	1831417	0.8049	0.1747	4.0759	1.1856
	2016	97.5	726520	2.0205	0.4575	2.4780	1467953	332389	1800342	0.8154	0.1664	4.0573	1.1718
	2017	97.5	749254	2.0196	0.4698	2.4894	1513226	351970	1865196	0.8113	0.1697	4.0548	1.1768
	2018	97.6	775001	2.0189	0.4679	2.4868	1564673	362589	1927262	0.8119	0.1692	4.0528	1.1760
Hungary	2010	78.7	4888064	2.0306	1.1199	3.1504	9925629	5473900	15399529	0.6445	0.2831	4.0857	1.4742
	2011	79.3	4867524	2.0317	1.1661	3.1977	9889143	5675887	15565030	0.6353	0.2882	4.0887	1.4980
	2012	79.2	4722921	2.0325	1.1540	3.1865	9599344	5450220	15049564	0.6378	0.2868	4.0911	1.4917
	2013	82.6	4738122	2.0326	1.1709	3.2035	9630818	5547656	15178475	0.6345	0.2886	4.0915	1.5005
	2014	83.6	4935505	2.0328	1.1993	3.2322	10033124	5919288	15952413	0.6289	0.2917	4.0921	1.5154
	2015	82.6	4890850	2.0343	1.1898	3.2241	9949415	5818955	15768370	0.6310	0.2906	4.0962	1.5103
	2016	83.6	5042884	2.0346	1.1552	3.1899	10260355	5825731	16086086	0.6378	0.2868	4.0971	1.4924
	2017	85.1	5753237	2.0394	1.1533	3.1927	11733352	6635093	18368445	0.6388	0.2863	4.1108	1.4914
	2018	85.5	5852729	2.0378	1.1465	3.1843	11926605	6710334	18636938	0.6399	0.2857	4.1061	1.4879
Malta	2010	82.7	386354	2.1080	0.6449	2.7528	814419	249150	1063569	0.7657	0.2044	4.3108	1.2504
	2011	81.7	370060	2.1099	0.6652	2.7751	780806	246148	1026953	0.7603	0.2083	4.3167	1.2593
	2012	79.6	353544	2.1137	0.7247	2.8384	747287	256209	1003496	0.7447	0.2195	4.3280	1.2855
	2013	85.3	374674	2.0926	0.7611	2.8537	784031	285181	1069213	0.7333	0.2275	4.2651	1.3019
	2014	85.8	376418	2.0906	0.7679	2.8585	786934	289039	1075973	0.7314	0.2288	4.2592	1.3049
	2015	94.1	468452	2.0546	0.6464	2.7011	962501	302831	1265332	0.7607	0.2081	4.1544	1.2511
	2016	95.6	466325	2.0434	0.5643	2.6077	952882	263144	1216027	0.7836	0.1911	4.1221	1.2160
	2017	94.5	535888	2.0463	0.5822	2.6285	1096578	312004	1408583	0.7785	0.1949	4.1304	1.2236
	2018	95.4	572877	2.0400	0.6385	2.6785	1168681	365795	1534476	0.7616	0.2074	4.1125	1.2477
The Netherlands	2010	94.9	41010457	2.0163	1.1163	3.1326	82690276	45778576	128468852	0.6437	0.2836	4.0455	1.4724
	2011	95.2	39812285	2.0157	1.1219	3.1376	80251204	44663453	124914657	0.6424	0.2843	4.0439	1.4752
	2012	95.4	41146598	2.0156	1.0917	3.1073	82936300	44918235	127854535	0.6487	0.2808	4.0436	1.4599
	2013	95.7	41493986	2.0148	1.0832	3.0980	83600195	44947856	128548050	0.6503	0.2798	4.0411	1.4556
	2014	95.4	39936051	2.0148	1.1100	3.1249	80464461	44330632	124795093	0.6448	0.2830	4.0413	1.4692
	2015	95.4	41330519	2.0143	1.0754	3.0897	83250370	44447868	127698238	0.6519	0.2789	4.0397	1.4517
	2016	95.2	41865084	2.0139	1.0654	3.0793	84310776	44605151	128915927	0.6540	0.2777	4.0386	1.4467
	2017	95.3	41176330	2.0136	1.0687	3.0823	82912267	44004590	126916857	0.6533	0.2781	4.0379	1.4483
	2018	95.7	40576430	2.0111	1.0594	3.0705	81602569	42988170	124590739	0.6550	0.2772	4.0308	1.4436
Austria	2010	89.5	7079875	2.0248	1.1259	3.1507	14335604	7971247	22306851	0.6427	0.2841	4.0695	1.4773
	2011	89.7	7018450	2.0235	1.1527	3.1762	14201716	8090437	22292153	0.6371	0.2872	4.0656	1.4911
	2012	90.5	7279075	2.0219	1.1196	3.1415	14717582	8149640	22867222	0.6436	0.2836	4.0612	1.4741

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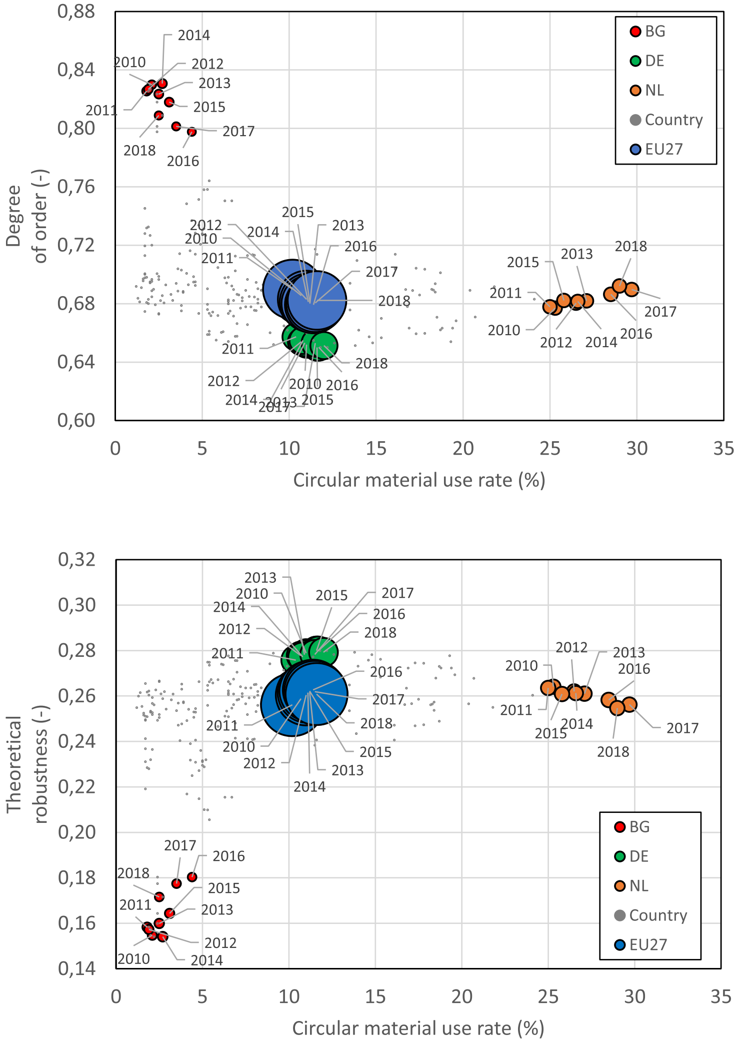
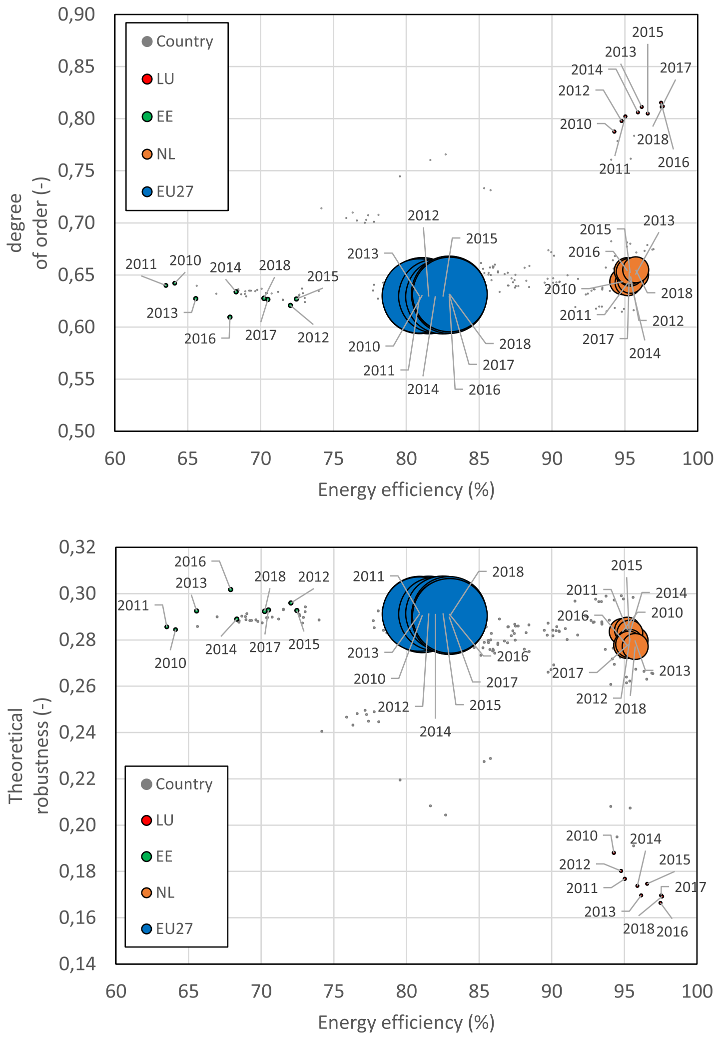
Country	Year	η_{tot} (%)	$T_{..}$ (TJ)	X (bits)	H_c (bits)	H (bits)	A (TJ • bits)	Φ (TJ • bits)	C (TJ • bits)	α (-)	R (-)	n (-)	c (-)
	2013	90.3	6881979	2.0212	1.1226	3.1438	13909663	7725584	21635247	0.6429	0.2840	4.0591	1.4756
	2014	90.5	6674692	2.0205	1.1210	3.1416	13486505	7482470	20968974	0.6432	0.2839	4.0574	1.4748
	2015	90.3	7183930	2.0224	1.1386	3.1610	14529003	8179525	22708528	0.6398	0.2857	4.0627	1.4838
	2016	90.9	7435029	2.0225	1.1311	3.1536	15037321	8409888	23447209	0.6413	0.2849	4.0629	1.4800
	2017	90.1	7378736	2.0237	1.1048	3.1285	14932162	8152235	23084397	0.6469	0.2818	4.0662	1.4665
	2018	91.1	7222918	2.0204	1.0892	3.1096	14593403	7867194	22460597	0.6497	0.2802	4.0570	1.4586
Poland	2010	79.0	19014221	2.0311	1.2046	3.2357	38619530	22904189	61523719	0.6277	0.2923	4.0871	1.5181
	2011	77.7	18955673	2.0305	1.1666	3.1971	38489030	22113845	60602875	0.6351	0.2883	4.0854	1.4983
	2012	80.7	19426484	2.0306	1.2054	3.2360	39447573	23416555	62864128	0.6275	0.2924	4.0858	1.5186
	2013	79.0	19058484	2.0303	1.1752	3.2055	38693958	22398168	61092126	0.6334	0.2893	4.0848	1.5028
	2014	79.9	18530639	2.0300	1.1588	3.1887	37616570	21472510	59089081	0.6366	0.2875	4.0840	1.4942
	2015	80.9	19109217	2.0284	1.1766	3.2050	38762050	22483027	61245077	0.6329	0.2895	4.0797	1.5035
	2016	81.1	19618392	2.0296	1.1863	3.2159	39817535	23273543	63091079	0.6311	0.2905	4.0829	1.5085
	2017	81.4	19965990	2.0303	1.1719	3.2023	40537191	23398941	63936132	0.6340	0.2889	4.0849	1.5010
	2018	80.9	20318592	2.0290	1.1784	3.2074	41226195	23943769	65169964	0.6326	0.2897	4.0812	1.5044
Portugal	2010	88.1	4615375	2.0121	1.0506	3.0628	9286811	4849056	14135867	0.6570	0.2760	4.0338	1.4392
	2011	87.0	4572287	2.0151	1.0748	3.0899	9213517	4914314	14127832	0.6522	0.2788	4.0420	1.4514
	2012	85.6	4460295	2.0138	1.0824	3.0962	8982350	4827653	13810003	0.6504	0.2798	4.0386	1.4552
	2013	87.7	4896096	2.0100	1.1340	3.1440	9841061	5552115	15393177	0.6393	0.2860	4.0278	1.4814
	2014	87.3	4766382	2.0111	1.1164	3.1275	9585753	5321140	14906893	0.6430	0.2839	4.0309	1.4724
	2015	86.7	5265357	2.0102	1.0784	3.0886	10584492	5678155	16262646	0.6508	0.2795	4.0284	1.4532
	2016	87.2	5301029	2.0095	1.0974	3.1069	10652588	5817436	16470024	0.6468	0.2818	4.0265	1.4628
	2017	85.6	5490103	2.0105	1.0729	3.0834	11037862	5890195	16928057	0.6520	0.2788	4.0292	1.4504
	2018	85.8	5164798	2.0113	1.1068	3.1181	10387890	5716405	16104295	0.6450	0.2828	4.0314	1.4675
Romania	2010	80.9	6442480	2.0224	1.1960	3.2184	13028995	7705259	20734254	0.6284	0.2920	4.0625	1.5136
	2011	80.7	6550064	2.0257	1.1825	3.2082	13268222	7745440	21013662	0.6314	0.2903	4.0718	1.5066
	2012	80.6	6439643	2.0298	1.1758	3.2056	13071272	7571582	20642854	0.6332	0.2893	4.0835	1.5030
	2013	83.9	5999528	2.0238	1.1550	3.1788	12141895	6929638	19071533	0.6367	0.2875	4.0666	1.4923
	2014	84.8	6240226	2.0202	1.1841	3.2043	12606647	7389152	19995799	0.6305	0.2908	4.0565	1.5074
	2015	82.8	6209452	2.0211	1.1606	3.1817	12549877	7206854	19756731	0.6352	0.2883	4.0589	1.4952
	2016	84.3	6254643	2.0191	1.1730	3.1921	12629052	7336546	19965597	0.6325	0.2897	4.0534	1.5016
	2017	83.2	6459826	2.0207	1.1744	3.1951	13053183	7586693	20639876	0.6324	0.2898	4.0577	1.5024
	2018	83.2	6487928	2.0204	1.1674	3.1878	13108448	7573975	20682423	0.6338	0.2890	4.0571	1.4987
Slovenia	2010	79.2	1421650	2.0796	1.0215	3.1012	2956499	1452262	4408761	0.6706	0.2680	4.2270	1.4248
	2011	77.7	1387246	2.0838	1.0173	3.1011	2890707	1411278	4301985	0.6719	0.2671	4.2391	1.4227
	2012	79.4	1390625	2.0803	1.0409	3.1213	2892978	1447520	4340498	0.6665	0.2704	4.2291	1.4344
	2013	79.8	1366735	2.0773	1.0422	3.1195	2839101	1424411	4263513	0.6659	0.2708	4.2201	1.4350
	2014	81.2	1426707	2.0744	1.0476	3.1221	2959596	1494681	4454277	0.6644	0.2716	4.2118	1.4378
	2015	83.2	1464963	2.0748	0.9985	3.0733	3039539	1462719	4502258	0.6751	0.2652	4.2129	1.4135
	2016	84.0	1576103	2.0719	1.0151	3.0870	3265592	1599831	4865423	0.6712	0.2676	4.2045	1.4216
	2017	83.4	1625886	2.0754	1.0147	3.0901	3374289	1649816	5024106	0.6716	0.2673	4.2145	1.4214
	2018	84.1	1620262	2.0712	1.0168	3.0880	3355924	1647471	5003395	0.6707	0.2679	4.2024	1.4225
Slovakia	2010	77.6	3514658	2.0260	1.1332	3.1592	7120551	3982909	11103459	0.6413	0.2849	4.0726	1.4810
	2011	78.3	3605681	2.0245	1.1346	3.1591	7299840	4090848	11390688	0.6409	0.2851	4.0686	1.4817
	2012	76.1	3413515	2.0269	1.1558	3.1827	6918714	3945412	10864127	0.6368	0.2874	4.0752	1.4927
	2013	77.4	3506335	2.0251	1.1350	3.1601	7100826	3979555	11080380	0.6408	0.2852	4.0703	1.4819
	2014	77.4	3339358	2.0285	1.1621	3.1906	6773910	3880572	10654482	0.6358	0.2879	4.0798	1.4959
	2015	77.4	3519818	2.0260	1.1605	3.1865	7131022	4084914	11215936	0..6358	0.2879	4.0726	1.4951
	2016	77.6	3449986	2.0263	1.1533	3.1795	6990547	3978718	10969264	0.6373	0.2871	4.0735	1.4914
	2017	78.5	3649838	2.0288	1.1545	3.1833	7404808	4213654	11618462	0.6373	0.2871	4.0807	1.4920
	2018	78.5	3459563	2.0278	1.1477	3.1755	7015417	3970447	10985863	0.6386	0.2864	4.0779	1.4885
Finland	2010	81.2	7349659	2.0144	1.2006	3.2150	14804870	8823925	23628795	0.6266	0.2929	4.0400	1.5160
	2011	81.2	7284363	2.0141	1.1961	3.2101	14671195	8712699	23383895	0.6274	0.2925	4.0392	1.5137
	2012	83.5	6980268	2.0129	1.1739	3.1868	14050350	8194299	22244649	0.6316	0.2902	4.0358	1.5021
	2013	85.6	7455076	2.0152	1.2100	3.2253	15023561	9020973	24044533	0.6248	0.2938	4.0424	1.5210
	2014	83.6	7278745	2.0158	1.1734	3.1892	14672689	8540579	23213268	0.6321	0.2900	4.0441	1.5018
	2015	84.9	6810727	2.0161	1.2065	3.2226	13730845	8217380	21948225	0.6256	0.2934	4.0448	1.5192
	2016	85.7	7212746	2.0143	1.1817	3.1959	14528375	8523162	23051537	0.6303	0.2909	4.0397	1.5061
	2017	86.2	7254630	2.0130	1.1783	3.1913	14603578	8548213	23151792	0.6308	0.2907	4.0362	1.5044
	2018	86.3	7422082	2.0138	1.1735	3.1873	14946817	8709864	23656681	0.6318	0.2901	4.0385	1.5019
Sweden	2010	79.7	10839130	2.0126	1.1905	3.2031	21814620	12903912	34718532	0.6283	0.2920	4.0350	1.5107
	2011	78.1	10691055	2.0152	1.1974	3.2126	21544747	12801751	34346498	0.6273	0.2925	4.0424	1.5144
	2012	79.4	11120394	2.0121	1.1675	3.1796	22375398	12982662	35358060	0.6328	0.2896	4.0337	1.4987
	2013	78.4	10414476	2.0153	1.2013	3.2166	20988560	12510500	33499059	0.6265	0.2929	4.0427	1.5164
	2014	79.2	10842866	2.0138	1.1766	3.1904	21835061	12758114	34593175	0.6312	0.2904	4.0384	1.5035
	2015	83.6	11361571	2.0128	1.1947	3.2075	22868363	13574120	36442482	0.6275	0.2924	4.0356	1.5130
	2016	82.9	11742335	2.0145	1.2002	3.2147	23654657	14093381	37748038	0.6266	0.2929	4.0403	1.5158
	2017	82.0	12055523	2.0149	1.2386	3.2535	24291189	14932009	39223198	0.6193	0.2967	4.0416	1.5361
	2018	79.4	11862427	2.0137	1.1967	3.2104	23887415	14196158	38083573	0.6272	0.2926	4.0382	1.5140

Appendix D.1



Top: Degree of order and *bottom:* theoretical robustness of the material flow networks of EU27 (as a whole), the Netherlands (NL), Germany (DE), and Bulgaria (BG) plotted against their circular material use rate between 2010 and 2018. Green and red colors represent countries with the highest and lowest robustness. The size of the bubbles represents the $T_{..}$ values in million tonnes.

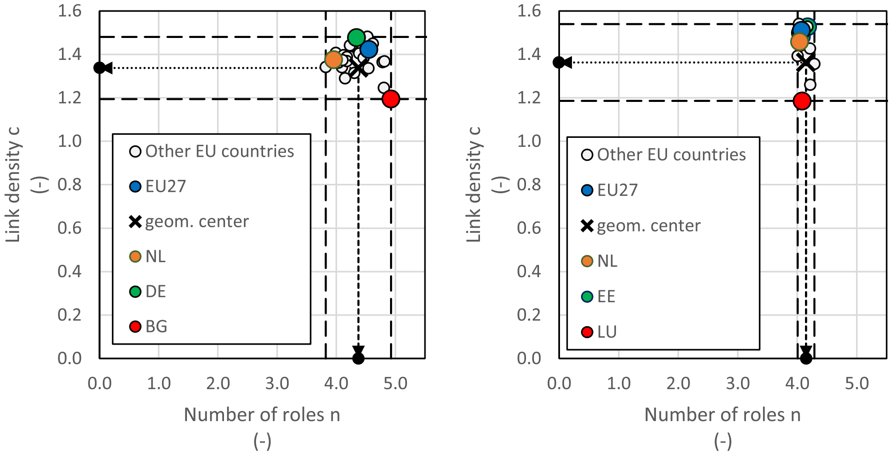
Appendix D.2



Top: Degree of order and *bottom:* theoretical robustness of the energy flow networks of EU27 (as a whole), the Netherlands (NL), Estonia (EE), and Luxembourg (LU) plotted against their energy efficiency between 2010 and 2018. Green and red colors represent countries with the highest and lowest robustness. The size of the bubbles represents the $T_{..}$ values in TJ.

Appendix E

The identification of the *"window of vitality"* of natural ecosystem communities has been described in the work of Zorach & Ulanowicz (2003) and the two relevant equations for calculating the node to node pathways and the links per node, were also mentioned in the work of Lietaer et al. (2010), and were used to calculate the values of the *"technological boundaries"* of the material and energy flow networks of the EU27 countries. The calculated minimum and maximum c and n values which were found to be relatively stable for all EU countries between 2010 and 2018. This stability was expected because both abstracted networks had a fixed number of nodes where the only fluctuating aspects were the values of their material and energy flows. The average values of c and n (per country for the years between 2010 and 2018) were then plotted against each other as shown in the figures below, and then were used to calculate the geometric means in both networks. These geometric means were $\mathrm{n_{center}} = 4.37$, and $\mathrm{c_{center}} = 1.33$ for the material flow networks, and $\mathrm{n_{center}} = 4.14$, and $\mathrm{c_{center}} = 1.36$ for the energy flow networks. Both geometric means were then used separately to find the new c and n values via extrapolation and to back-calculate the X and H_c values. Then, the adjusted degrees of order α_{adj} were calculated for both material and energy flow networks of the EU27 which are the degrees of order corresponding to the maximum theoretical robustness values that were calculated from the original data for all countries, for all years studied.



Average number of roles *n* (-) plotted against the average link density *c*. *Left: "Window of efficiency"* of the material flow networks of the EU countries between 2010 and 2018 where $n_{min} = 3.82$, $n_{max} = 4.92$, $c_{min} = 1.19$, $c_{max} = 1.48$, $n_{center} = 4.37$, and $c_{center} = 1.33$. *Right: "Window of efficiency"* of the energy flow networks of the EU countries between 2010 and 2018 where $n_{min} = 4.00$, $n_{max} = 4.28$, $c_{min} = 1.18$, $c_{max} = 1.54$, $n_{center} = 4.14$, and $c_{center} = 1.36$.

Appendix F

R code for the ascendency analysis of the material flows. The example of EU27 (as a whole) for 2010 is given with data (million tonnes) from Eurostat (Sankey diagrams) obtained on the 21st of May 2021.

```
#Add the data of the material flows (elements of the matrix) of the network's 12 nodes
node1 <- c(0,0,1589,0,0,0,0,0,0,0,0,0,0,0)
node2 <- c (0,0,5378,0,0,0,0,0,0,0,0,0,0,0)
node3 <- c(0,0,0,6967,0,0,0,0,0,0,0,0,0,0)
node4 <- c(0,0,0,0,604,222,2528,4527,0,0,0,0,0,0)
node5 <- c (0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node6 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node7 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node8 <- c (0,0,0,0,0,0,0,0,1792,2735,0,0,0,0)
node9 <- c(0,0,0,0,0,0,0,0,0,0,103,783,710,195)
node10 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node11 <- c (0,0,0,0,0,0,103,0,0,0,0,0,0,0)
node12 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node13 <- c(0,0,0,710,0,0,0,0,0,0,0,0,0,0)
node14 <- c (0,0,0,195,0,0,0,0,0,0,0,0,0,0)" … etc etc.
#Give names to each node and bind the nodes to construct a matrix
CASE_EU27_2010 <- rbind(node1, node2, node3, node4, node5, node6, node7,node8,node9,node10,node11,node12,node13,node14) colnames (CASE_EU27_2010) <- c("Imports", "Natural resources extracted", "Direct material inputs", "Processed material", "exports", "Dissipative flows", "Total emissions", "Material use", "Waste treatment", "Material accumulation", "Incineration", "Waste landfilled", "Recycling", "Backfilling")
rownames(CASE_EU27_2010) <- c("Imports", "Natural resources extracted", "Direct material inputs", "Processed material", "exports", "Dissipative flows", "Total emissions", "Material use", "Waste treatment", "Material accumulation", "Incineration", "Waste landfilled", "Recycling", "Backfilling")
#Calculate the total system throughput (TST) of the network
Sigma_Ti_CASE_EU27_2010 <- rowSums(CASE_EU27_2010)
Sigma_Tj_CASE_EU27_2010 <- colSums(CASE_EU27_2010)
TST_CASE_EU27_2010 <- sum(CASE_EU27_2010)
#Calculate the network's capacity for development C
Capacity_function_CASE_EU27_2010 <- apply(CASE_EU27_2010, 1:2, function(x) {ifelse(any(x == 0), NaN, -x*log2(x/TST_CASE_EU27_2010))})
Capacity_function_CASE_EU27_2010[is.nan(Capacity_function_CASE_EU27_2010)] <- 0
Capacity_CASE_EU27_2010 <- sum(Capacity_function_CASE_EU27_2010)
#Calculate the ascendency A of the network
Ascendency_function_1_CASE_EU27_2010 <- apply(CASE_EU27_2010, 1:2, FUN=function(x) {ifelse(any(x == 0), NaN, x*TST_CASE_EU27_2010)})
Ascendency_function_1_CASE_EU27_2010[is.nan(Ascendency_function_1_CASE_EU27_2010)] <- 0
Ascendency_function_2_CASE_EU27_2010 <- sweep(Ascendency_function_1_CASE_EU27_2010, MARGIN=1, FUN="/", STATS=rowSums (CASE_EU27_2010))
Ascendency_function_2_CASE_EU27_2010[is.nan(Ascendency_function_2_CASE_EU27_2010)] <- 0
Ascendency_function_3_CASE_EU27_2010 <- sweep(Ascendency_function_2_CASE_EU27_2010, MARGIN=2, FUN="*", STATS=1/colSums (CASE_EU27_2010))
```

```
Ascendency_function_3_CASE_EU27_2010[is.nan(Ascendency_function_3_CASE_EU27_2010)] <- 0
Ascendency_function_4_CASE_EU27_2010 <- apply(Ascendency_function_3_CASE_EU27_2010, 1:2, function(x) {ifelse(any(x == 0), NaN, log2(x))})
Ascendency_function_4_CASE_EU27_2010[is.nan(Ascendency_function_4_CASE_EU27_2010)] <- 0
Ascendency_function_5_CASE_EU27_2010 <- Ascendency_function_4_CASE_EU27_2010 * CASE_EU27_2010
Ascendency_function_5_CASE_EU27_2010[is.nan(Ascendency_function_5_CASE_EU27_2010)] <-0
Ascendency_CASE_EU27_2010 <- sum(Ascendency_function_5_CASE_EU27_2010)
#Calculate the overhead (or reserve) Φ of the network
Reserve_function_1_CASE_EU27_2010 <- apply(CASE_EU27_2010, 1:2, function(x) {ifelse(any(x ==0), NaN, x^2)})
Reserve_function_1_CASE_EU27_2010[is.nan(Reserve_function_1_CASE_EU27_2010)] <- 0
Reserve_function_2_CASE_EU27_2010 <- sweep(Reserve_function_1_CASE_EU27_2010, MARGIN=1, FUN="/", STATS=rowSums(CASE_EU27_2010))
Reserve_function_2_CASE_EU27_2010[is.nan(Reserve_function_2_CASE_EU27_2010)] <-0
Reserve_function_3_CASE_EU27_2010 <- sweep(Reserve_function_2_CASE_EU27_2010, MARGIN=2, FUN="/", STATS=colSums(CASE_EU27_2010))
Reserve_function_3_CASE_EU27_2010[is.nan(Reserve_function_3_CASE_EU27_2010)] <-0
Reserve_function_4_CASE_EU27_2010 <- apply(Reserve_function_3_CASE_EU27_2010, 1:2, function(x) {ifelse(any(x == 0), NaN, log2(x))})
Reserve_function_4_CASE_EU27_2010[is.nan(Reserve_function_4_CASE_EU27_2010)] <- 0
Reserve_function_5_CASE_EU27_2010 <- -Reserve_function_4_CASE_EU27_2010 * CASE_EU27_2010
Reserve_function_5_CASE_EU27_2010[is.nan(Reserve_function_5_CASE_EU27_2010)] <-0
Reserve_CASE_EU27_2010 <- sum(Reserve_function_5_CASE_EU27_2010)
#Calculate the degree of order α of the network
Degree_of_order_CASE_EU27_2010 = Ascendency_CASE_EU27_2010 / Capacity_CASE_EU27_2010
#Calculate the theoretical robustness R of the network
Theoretical_robustness_CASE_EU27_2010 = -Degree_of_order_CASE_EU27_2010* (log(Degree_of_order_CASE_EU27_2010))
#create the robustness curve
a <- seq(0,1,0.001)
plot(a, -a*log(a), ylab="Theoretical robustness", xlab="Degree of order", type="l", col="orange")
points(Degree_of_order_CASE_EU27_2010,Theoretical_robustness_CASE_EU27_2010, type="o", cex=1.5, pch=19, col="black")
text(Degree_of_order_CASE_EU27_2010, Theoretical_robustness_CASE_EU27_2010, labels=round(Theoretical_robustness_CASE_EU27_2010, digits=4), cex=1, pos=4, font=10, col="black")
grid(nx = NULL, 10, col = "lightgray", lty = "dotted", lwd = par("lwd"), equilogs = TRUE)
################## #################
```

R code for the ascendency analysis of the energy flows. The example of EU27 (as a whole) for 2010 is given with data (TJ) from Eurostat (Sankey diagrams) obtained on the 21st of May 2021.

```
#Add the data of the energy flows (elements of the matrix) of the network's 17 nodes
node1 <- c(0,0,0,0,54793330,0,0,0,0,0,0,0,0,0,0,0,0)
node2 <- c(0,0,0,0,29208591,0,0,0,0,0,0,0,0,0,0,0,0)
node3 <- c(0,0,0,0,727004,0,0,0,0,0,0,0,0,0,0,0,0)
node4 <- c(0,0,0,0,209826,0,0,0,0,0,0,0,0,0,0,0,0)
node5 <- c(0,0,0,0,0,28262989,56675765,0,0,0,0,0,0,0,0,0,0)
node6 <- c(0,0,0,0,0,0,0,28262989,0,0,0,0,0,0,0,0,0)
node7 <- c(0,0,0,0,0,0,0,14872929,41802837,0,0,0,0,0,0,0,0)
node8 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node9 <-c(0,0,0,0,0,0,0,0,0,44845434,3086044,300650,1051079,1344800,1955370,176114,17305330)
node10 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node11 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node12 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node13 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node14 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node15 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node16 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
node17 <- c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
#Give names to each node and bind the nodes to construct a matrix
CASE_EU27_2010 <- rbind(node1, node2, node3, node4, node5, node6, node7, node8, node9, node10, node11, node12, node13, node14, node15, node16, node17) colnames(CASE_EU27_2010) <- c("Imports", "Production", "Stock draw", "Stat. dif. inflow", "Available from all sources", "Direct carry-over", "Transformation", "Transformation losses", "Available after transformation", "Final consumption", "Consumption of the energy branch", "Stat. dif. outflow", "Distribution and transmission losses", "International aviation", "Marine bunkers", "Stock build", "Exports")
rownames(CASE_EU27_2010) <- c("Imports", "Production", "Stock draw", "Stat. dif. inflow", "Available from all sources", "Direct carry-over", "Transformation", "Transformation losses", "Available after transformation", "Final consumption", "Consumption of the energy branch", "Stat. dif. outflow", "Distribution and transmission losses", "International aviation", "Marine bunkers", "Stock build", "Exports")
#Calculate the total system throughput (TST) of the network
Sigma_Ti_CASE_EU27_2010 <- rowSums(CASE_EU27_2010)
Sigma_Tj_CASE_EU27_2010 <- colSums(CASE_EU27_2010)
TST_CASE_EU27_2010 <- sum(CASE_EU27_2010)
#Calculate the network's capacity for development C
```

```
Capacity_function_CASE_EU27_2010 <- apply(CASE_EU27_2010, 1:2, function(x) {ifelse(any(x == 0), NaN, -x*log2(x/TST_CASE_EU27_2010))})
Capacity_function_CASE_EU27_2010[is.nan(Capacity_function_CASE_EU27_2010)] <- 0
Capacity_CASE_EU27_2010 <- sum(Capacity_function_CASE_EU27_2010)
#Calculate the ascendency A of the network
Ascendency_function_1_CASE_EU27_2010 <- apply(CASE_EU27_2010, 1:2, FUN=function(x) {ifelse(any(x == 0), NaN, x*TST_CASE_EU27_2010)})
Ascendency_function_1_CASE_EU27_2010[is.nan(Ascendency_function_1_CASE_EU27_2010)] <- 0
Ascendency_function_2_CASE_EU27_2010 <- sweep(Ascendency_function_1_CASE_EU27_2010, MARGIN=1, FUN="/", STATS=rowSums(CASE_EU27_2010))
Ascendency_function_2_CASE_EU27_2010[is.nan(Ascendency_function_2_CASE_EU27_2010)] <- 0
Ascendency_function_3_CASE_EU27_2010 <- sweep(Ascendency_function_2_CASE_EU27_2010, MARGIN=2, FUN="*", STATS=1/colSums(CASE_EU27_2010))
Ascendency_function_3_CASE_EU27_2010[is.nan(Ascendency_function_3_CASE_EU27_2010)] <- 0
Ascendency_function_4_CASE_EU27_2010 <- apply(Ascendency_function_3_CASE_EU27_2010, 1:2, function(x) {ifelse(any(x == 0), NaN, log2(x))})
Ascendency_function_4_CASE_EU27_2010[is.nan(Ascendency_function_4_CASE_EU27_2010)] <- 0
Ascendency_function_5_CASE_EU27_2010 <- Ascendency_function_4_CASE_EU27_2010 * CASE_EU27_2010
Ascendency_function_5_CASE_EU27_2010[is.nan(Ascendency_function_5_CASE_EU27_2010)] <-0
Ascendency_CASE_EU27_2010 <- sum(Ascendency_function_5_CASE_EU27_2010)
#Calculate the overhead (or reserve) Φ of the network
Reserve_function_1_CASE_EU27_2010 <- apply(CASE_EU27_2010, 1:2, function(x) {ifelse(any(x ==0), NaN, x^2)})
Reserve_function_1_CASE_EU27_2010[is.nan(Reserve_function_1_CASE_EU27_2010)] <- 0
Reserve_function_2_CASE_EU27_2010 <- sweep(Reserve_function_1_CASE_EU27_2010, MARGIN=1, FUN="/", STATS=rowSums(CASE_EU27_2010))
Reserve_function_2_CASE_EU27_2010[is.nan(Reserve_function_2_CASE_EU27_2010)] <-0
Reserve_function_3_CASE_EU27_2010 <- sweep(Reserve_function_2_CASE_EU27_2010, MARGIN=2, FUN="/", STATS=colSums(CASE_EU27_2010))
Reserve_function_3_CASE_EU27_2010[is.nan(Reserve_function_3_CASE_EU27_2010)] <-0
Reserve_function_4_CASE_EU27_2010 <- apply(Reserve_function_3_CASE_EU27_2010, 1:2, function(x) {ifelse(any(x == 0), NaN, log2(x))})
Reserve_function_4_CASE_EU27_2010[is.nan(Reserve_function_4_CASE_EU27_2010)] <- 0
Reserve_function_5_CASE_EU27_2010 <- -Reserve_function_4_CASE_EU27_2010 * CASE_EU27_2010
Reserve_function_5_CASE_EU27_2010[is.nan(Reserve_function_5_CASE_EU27_2010)] <-0
Reserve_CASE_EU27_2010 <- sum(Reserve_function_5_CASE_EU27_2010)
#Calculate the degree of order α of the network
Degree_of_order_CASE_EU27_2010 = Ascendency_CASE_EU27_2010 / Capacity_CASE_EU27_2010
#Calculate the theoretical robustness R of the network
Theoretical_robustness_CASE_EU27_2010 = -Degree_of_order_CASE_EU27_2010*(log (Degree_of_order_CASE_EU27_2010))
#create the robustness curve a <- seq(0,1,0.001) plot(a, -a*log(a), ylab="Theoretical robustness", xlab="Degree of order", type="l", col="orange") points(Degree_of_order_CASE_EU27_2010,Theoretical_robustness_CASE_EU27_2010, type="o", cex=1.5, pch=19, col="black") text(Degree_of_order_CASE_EU27_2010, Theoretical_robustness_CASE_EU27_2010, labels=round(Theoretical_robustness_CASE_EU27_2010, digits=4), cex=1, pos=4, font=10, col="black") grid(nx = NULL, 10, col = "lightgray", lty = "dotted", lwd = par("lwd"), equilogs = TRUE)
####### ###########################
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