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Metabolic relationships between cities and hinterland: a political-industrial ecology of energy metabolism of Saint-Nazaire metropolitan and port area (France)

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Highlights

- A "political-industrial ecology" of energy metabolism is implemented and discussed
- Article methods coupled quantitative and qualitative data to understand the politics of urban metabolism
- Metabolic relationships between cities and their hinterlands are based on synergies and cooperation
- Urban-rural metabolic relationships are also unbalanced power and conflicts.
- Power relationships and hidden flows are strong drivers of urban metabolism.
- Proximity and self-sufficiency are strong drivers of synergetic relationships.
- The Metabolic relationship framework helps understand interactive "hinterlands-city"

Abstract

Research on urban metabolism (UM) focuses on cities' material and energy systems by identifying paths and transformation processes of all kinds of flows in urban contexts. In particular, scientific studies aim to trace the origin and destination of materials, energy, water, emissions and waste flows in order to understand relationships between cities and other spatial areas (hinterlands) that lead to political, social and environment consequences. This research paper aims to analyze complex power relationships between cities and their hinterlands. In particular, the objective is to understand the

nature of these socio-material links. Are they based on synergies and cooperation, or, on the contrary, on unbalanced power and conflicts? We propose an approach which combines methodologies with the tools of Energy Flow Analysis (EFA) and semi-structured interviews, in order to develop a "political-industrial ecology" of energy metabolism (Breetz, 2017; Cousins and Newell, 2015). We have studied the Saint-Nazaire metropolitan area, which is constituted by an urban area and a port zone. This harbor consists in a complex network of highly energy-intensive industrial sites operating in the steel, petrochemical and agri-food industries. Based on an analysis of energy flows, institutional policies and professional practices, we have identified several situations of metabolic links that exist simultaneously. In conclusion, the metabolic relationships' framework is useful to understand how the "hinterlands-city" relationships shape and are shaped by the city's metabolism.

Key words: energy flows; urban metabolism; energy transition; political-industrial ecology; city-hinterland

1. Introduction

1.1 Urban metabolism, political-industrial ecology and the links between supply and consumption territories

UM refers to the set of socio-technical and socio-ecological processes by which flows of materials, energy, and water are consumed, transformed and rejected in different forms by cities (Newman, 1999; Barles, 2009; Ferrao and Fernández, 2013; Kennedy and Hoornweg, 2012). Due to the increase in urbanization and the urban population, the material and energy "weight" of cities is growing. This weight represents globally around 80% of energy consumption, 40 billion tons of materials and 65% of air emissions according to "UN Environment" and "International Resource Panel" (Swilling et al., 2018), which argues for a "circular metabolism" perspective at the city-area scale. It is therefore an important sustainability issue to accelerate the transitions of urban metabolisms (Bahers et al., n.d.; Dijst et al., 2018; Haberl et al., 2019; John et al., 2019).

Reviews show a recent revival of scientific interest for UM studies (Céspedes Restrepo and Morales-Pinzón, 2018; Cui, 2018; Dijst et al., 2018; John et al., 2019; Rosales Carreón and Worrell, 2018; Zhang et al., 2015a), with an acceleration since 2010 (Kennedy, 2016). Several cities have been analyzed (e.g. Amsterdam, Paris, Montreal, Brussels, Geneva, Glasgow, Rotterdam) with heterogeneous results. Metabolic processes shape a city by meeting the needs of its inhabitants, and, thus, impact its surrounding hinterland. It is this last point which is the focus of this research. Indeed, flows link urban societies to other territories, understood as geographic areas and subnational entities, which either receive waste or supply energy and biomass for food, but not only. Hinterlands provide cities also with materials, manufactured products, and wood for various industrial and service uses, which are conveyed by truck, freight and maritime transport via port infrastructure (Bahers et al., n.d.). These links of interdependence show that, sustainability, seen through the lens of urban self-sufficiency, cannot be considered at the city scale alone. The UM framework is thus very useful for the evaluation of urban developments, because it accounts for the relationships between the city and its supplying hinterlands (Kennedy et al., 2007; Currie and Musango, 2017).

However, few studies really focus on these metabolic relationships between cities and hinterlands and it represents a blind spot for research on UM. Urban environmental footprints (Billen et al., 2012), exosomatic social metabolism, i.e. the relationship between the metabolic subject and the external environment (Geng et al., 2011; Li et al., 2010; Ramos-Martin et al., 2007), ecological relationships (Zhang et al., 2017, 2016) or the city-countryside opposition (Wachsmuth, 2012) explored impacts or dynamics outside the city's boundaries. Other research focused on UM multiscale policies in order to study urban services linking networks of different flows that lead to territorial, material and social inequalities (Guibrunet, McFarlane 2013; Duro, Schaffartzik, et Krausmann 2018). However, the majority of these studies don't discuss what goes beyond urban boundaries, i.e. how the "hinterlands-city" relationships shape and are shaped by the city's metabolism. Without this UM's "territorialization", the city remains an unopened black box (Huang et al., 2018) (see Tanguy forthcoming) without real contextualization.

Moreover, we consider urban metabolism as a boundary object (Newell and Cousins, 2015). This is a powerful concept for conducting interdisciplinary research, as this work shows that resource consumption is structural and cannot be reduced only through more efficient waste and energy use. Therefore, new work calls for an extension of physical flow studies to the integration of social, institutional and cultural forces into metabolism research (Broto et al., 2012; Pincetl et al., 2012). The objective of this research is to go beyond the flows, to understand the practices of economic actors who have a role in a multiscale flow governance and to understand urban metabolism policies (Cousins, 2017; Guibrunet et al., 2016). These approaches are in line with the very recent work developed under the term "political-industrial ecology" (Breetz, 2017; Pincetl and Newell, 2017). According to Baka (Baka, 2017), politico-industrial ecology can help advance energy geographies in three key ways:

"(1) to bridge prescriptive and critical perspectives of energy studies, (2) to reveal the "hidden" discursive, material and livelihood flows (3) to assist in crafting more environmentally just and inclusive energy and environment policy pathways" (Baka, 2017)

It was shown that changes in socio-economic metabolisms (Fischer-Kowalski and Haberl, 2007; Haberl et al., 2019, 2016) could lead to power relations and conflicts (Baka and Bailis, 2014; John et al., 2019; Martinez-Alier et al., 2016) or "mend the metabolic rift" (Bahers and Giacchè, 2019; McClintock, 2010; Schneider and McMichael, 2010). This research aims to analyze complex power relationships between cities and their hinterlands. In particular, what are the nature of these socio-material links? Are they based on synergies and cooperation, or, on the contrary, on unbalanced power and conflicts? Indeed, we can make the hypothesis that flow governance patterns are very different and depend as much on the economic context as on the territory itself. For instance, the perception of urban waste areas varies according to the economic actors (Bahers et al., 2017), because urban discharges are sometimes treated in the city, but can also be eliminated very far from the production areas, or in the air or water. These socio-material relations are thus governed by mechanisms of control of raw materials and waste by the territories, but also by a social appropriation of city dwellers (Demaria and Schindler, 2016). Similarly, the strong presence of large-scale industrial sectors plays an important role in synergistic or conflictual situations. This approach also provides the opportunity to discuss the generalized urban theory - articulated by Neil Brenner (Brenner, 2014) and inspired by Henri Lefebvre's thinking - which states that all resources (including far flung resources) would be controlled by urban actors. According to this research, socio-metabolic

processes cause environmental injustices between people and places (Brenner, 2009) that underlie urban metabolism policies.

1.2. Port cities as nodes of distribution between supply and consumption territories

Being logistics hubs, port cities are keys to understand links between consumption and supply territories. Entry points of globalization, ports are transit areas for most of the exchanges of raw materials, steel products, energy, containers... All the economic actors of the final energy supply chain are present: importers, processors, consumers and distributors. The proximity of these stakeholders makes it possible to grasp power relationships at work to plan future industrial, economic and environmental changes. Port cities are thus areas of high stakes and studying them reveals the socio-technical processes that shape urban space. Port cities are also expected to be at the heart of energy transitions because their economic model depends very often on fossil fuels traffic and energy transformation or energy storage activities (Bosman et al., 2018; Carpenter et al., 2018; Hollen et al., 2015; Lenhart et al., 2015; Mat et al., 2016; Moon et al., 2018). As a result, the majority of employment assigned to these activities and energy transitions in these areas are prone to uncertainties, which sometimes lead to conflict with the workers' unions.

The port cities are also well-known cases studies in the field of industrial ecology (Baas, 2008; Cerceau et al., 2014; Chertow, 2007). Indeed, a current strategy is to build industrial synergies at the port-city interface, in a perspective of circular economy, such as in Marseille (France) or Rotterdam (the Netherlands). Moreover, several port cities, such as Gothenburg (Sweden), Rotterdam, or Hamburg (Germany), were case studies for material flows analyses (Hammer et al., 2003; Rosado et al., 2016; Voskamp et al., 2017a). This corpus makes it thus possible to have indicators to compare their dependence on fossil fuels, the importance of transit flows, and more generally their energy metabolism. This allows us to hypothesize that a port is particularly suitable to study metabolic links between cities and hinterlands, being the nodes of these exchanges.

In a second section, we will show the methodology that combines the flows and economic actors approaches. The third section will present the results from the tools that will be discussed in a fourth section to answer the problem.

2. Method: complementarity of flow and economic actors approaches

2.1. Case study: the port city of Saint-Nazaire (France)

Saint-Nazaire is a French port city on the Atlantic coast, located just below the Brittany region and north of the Loire estuary. In the early nineteenth century, the city was still a small port, a stopover before arriving in Nantes, destination of most of the regional maritime trade. But with the intensification of trade and the increase in boats' size, the location of Saint-Nazaire became strategic. Therefore, the authorities decided to industrialize the area by installing the first shipyards, which will become the "Chantiers de l'Atlantique" shipyard in the mid-1950s, one of the largest in the world.

Today, the Saint-Nazaire's metropolitan area is composed of a highly urbanized space coupled with an industrial zone. In addition to shipyards, the Saint-Nazaire port area includes a complex network of energy-intensive industrial sites operating in the steel, petrochemical and agri-food sectors. In particular, the second largest crude oil refinery in France is located in the industrial-port area. In 2015, import / export traffic related to the refinery accounted for approximately 54% of total flows

(Saint-Nazaire port authority, 2016). Natural gas entering and leaving the methane terminal is the second contributor. It supplies 10 to 15% of the France's needs, with a slight decline in recent years (DREAL, 2012). This terminal is the largest terminal on the Atlantic coast and the seventh European terminal in terms of storage capacity (Saint-Nazaire port authority, 2016). The territory is also a final energy producer via the combined cycle gas plant at Montoir-de-Bretagne and the virgin oil refining activities for the biofuels market.

Finally, very close to the industrial-port area is the Cordemais coal power plant, whose coal fuel transit is mainly carried out by the port. The Cordemais plant, owned by the national electricity company "Electricité de France", is meant to be converted to renewable energy in the coming years abandoning coal (after closing the last fuel oil-based sections), as part of a French new energy transition policy. This heavy infrastructure, employing directly around 400 jobs, is obviously at the center of the economic stakes of the port territory.

2. 2 How to combine different methods? Mutual influence of flows and positioning of economic actors

We use the "Urban political ecology" perspectives and qualitative interviews to explore the social and environmental dimensions generally lost in quantitative approaches to urban metabolism (Bahers and Giacchè, 2019; Guibrinet et al., 2016). In this perspective, we followed the flows and interviewed actors who practice and intervene on their governance (see figure 1). This allows us to understand the economic and political context of metabolic links between territories, in order to consider both the resulting synergies and conflicts.

The objective is to reveal the challenges arising when actors discuss energy transition or circular economy through the prism of renewable and local energy production. The analysis includes territorial practices of local management of energy resources.

The following step consists in combining results of the EFA and structured interviews to reach a final conclusion. Triangulating data about energy flows, institutional policies and professional practices enables us to apprehend the two dimensions of metabolic links between territories: cooperation and power relationships. Data from interviews and flows analyses (see fig. 1) enabled linking energy flows with the practices and policies of metabolic relationships, and examining how they influence the flows circulation. Finally, we evaluated the impacts of energy flows on the political process and discourse of economic actors. The social and political impacts of energy flows are identified with reference to actors' interviews, and through observations. These metabolic links of inter-territorial cooperation and conflict are analyzed in this result section from the point of view of the actors' representations and flows' trajectories.

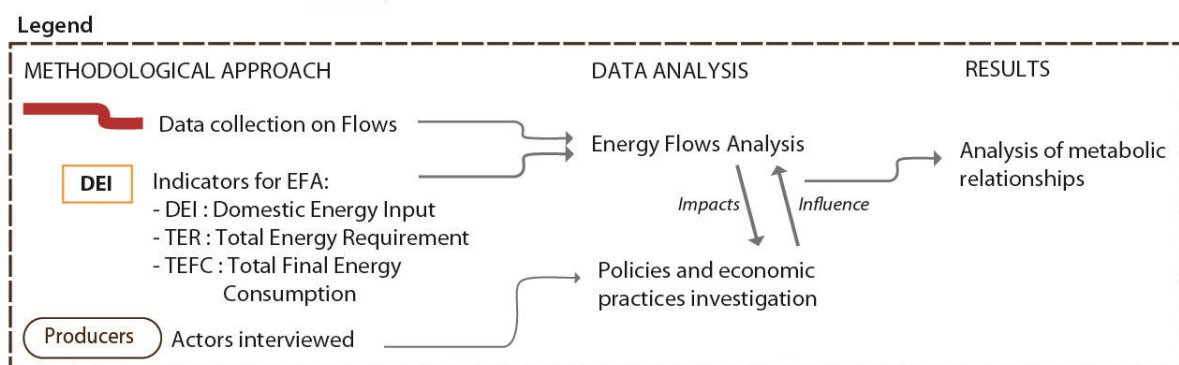
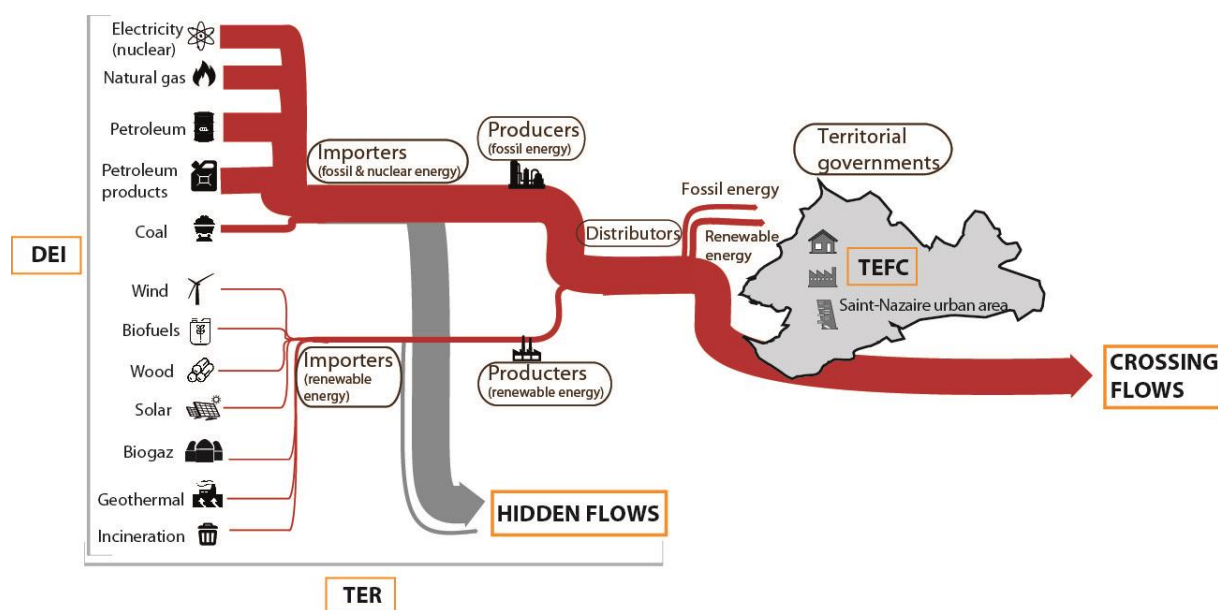


Fig. 1: Methodological figure to understand who are interviewed, what flows are collected and how the results are combined.

2. 3 Semi-structured interviews to understand the actors' strategies and the social representation of the metabolic links

Like other research in PIE (Cousins and Newell, 2015; Deutz et al., 2017), we have chosen to conduct semi-structured interviews to understand flow governance and the resulting political economy. Twenty-one (21) interviews were conducted with the six types of economic actors in 2018 (see Appendix 1), according to the flows we surveyed. That is why we have chosen (fossils/nuclear and renewable) energy importers, (fossils and renewable) energy producers, distributors and consumers (as territorial governments) as our informants. We met a lot of economic actors in order to obtain a wide panel. Nevertheless, one bias is that we did not get interviews with all of them, mainly because they refused (lack of time). Since the questions were of a strategic nature, managers or CEO were our primarily respondents.

We conducted the interviews in 2018, according to a semi-structured form consisting of main topics and sub-questions to revive the discussion. We developed a questionnaire that guided the interviews (cf. Appendix 2), with six main topics, sixteen broad questions and a range of optional questions. The questions addressed the economic actors' spatial perception of energy transition, conflicts related to

resources management and, more generally, energy challenges. We transcribed all interviews verbatim.

2. 4. The method of EFA to understand flow trajectories and material links

To quantify urban flows, we use the Energy Flow Analysis (EFA) method, which relies on the same principles than Material Flow Analysis (MFA) which is the most common method to quantify urban metabolisms (Kennedy et al., 2011). EFA focuses solely on energy flows and consists in estimating the input and output flows of a city, including the consequences of production and consumption activities. The EFA method was developed by several researchers and has been then applied to several cities, such as Paris (Kim and Barles, 2012), Vienna (Krausmann, 2013), Beijing (Zhang et al., 2014) and Brussels, Milan, Cap Town (Athanasiadis et al., 2017), just to name a few.

The EFA shows the trajectories of different types of energy flows involved in Saint-Nazaire's metabolism. In particular, we calculate 1) imports and domestic extraction, which make up for the direct energy input (DEI), 2) exports, 3) the total final energy consumption (TFEC), and 4) the indirect energy flows associated to imports. The total energy requirements (TER) can also be estimated by adding the indirect flows to the DEI. It should be noted that final and primary energies are accounted separately. In national statistics, final energy is indeed defined as the energy delivered to consumers whereas primary energy is the extracted energy in its original form, without transformation (like crude oil, raw natural gas, solar energy...). It thus equals to final energy plus energy losses occurring during transformation and transport processes (Kim and Barles, 2012).

All primary energy factors (PEF) used in this paper were taken from (Wilby et al., 2014), which used the PEF of the International Energy Agency (IEA) in 2009. In addition to primary energy itself, the energy used to extract primary energy and transform primary energy to final energy was also considered, in the Total Energy Requirement (TER) indicator (see figure 1) This indirect energy consumption, which is consumed for the most part outside the territory's boundaries, was obtained via cumulative energy demand factors used in life cycle assessment studies and developed by (Frischknecht et al., 2015).

Data sources for final energy consumption were primarily energy distributor database (natural gas, non-renewable and renewable electricity) (ENEDIS, 2015; GRDF, 2015), the BASEMIS regional database (petroleum products) (BASEMIS, 2015) and the results of a prospective study conducted for the CARENE on the potential of renewable energy production (AXENNE, 2016). The composition of the regional electricity mix, divided between nuclear, coal, gas and renewable sources, was taken from a report of the national electricity distributor (RTE, 2016). Finally, the Saint-Nazaire's port authority provided data of domestic imports and exports of primary and final energies (Saint-Nazaire port authority, 2016). The base year is 2015, for which the most recent data were available.

3. Results: EFA and typologies of metabolic relations

3. 1. What representations of relations between supply and consumption territories? Interface and scale typologies

The analysis of the semi-structured interviews reveals that economic actors have different representations of the metabolic relationships between supply and consumption territories. Indeed, five different types of interface/opposition typologies were distinguished, as regards to what we call “relationships between supply and consumption territories”. As mentioned in Table 1, there are rural - urban opposition, city - countryside, hinterland - port, industrial sectors - local actors and global markets - short circuits. The representativeness of these representations is given according to the number of economic actors who refer to these oppositions, in relation to the 21 interviews conducted. These ratios are quite balanced, although economic actors refer a little more to the rural-urban interface. These representations constitute oppositions and asymmetries between spaces. It should be noted that the notion of indirect supply (or flows) was not mentioned by the actors, although this concept is central in an EFA.

Interface / Opposition Typologies	Representativeness	Examples of quotes
Rural - urban	6/21	"We need tools specific to the rural and urban world" (Territorial engineer interviewee, 2018).
Hinterland - port	5/21	"The Port lives on fossil fuel revenues. We are much more in politics, but we must not forget the green economy, that of the hinterland with poultry farming." (Energy Producer Director interviewee, 2018)
City - countryside	4/21	"Competition between supply and consumption territory, the urban administration is starting to look at this because 50% of renewable energy has to be done with neighboring territories. But we're not there yet ... it is necessary to cooperate between cities and countryside" (Manager interviewee, 2018).
Industrial sectors - local actors	3/21	"The group is structured enough, we are not necessarily waiting for something from these local actors" (Energy Producer Director interviewee, 2018).
Global markets - short circuits	3/21	"We need to grow our renewable energy supply, to offer our customer opportunities. And we are looking for the production of energy in short circuit. (Manager of commercial development interviewee, 2018).

Table 1: Interface typology for metabolic links

In addition, we identified four types of geographic scales related to these interfaces whose representativeness is given in the Table 2. Indeed, these oppositions are not all conceptualized by the economic actors in the same spaces. Metabolic relationships are therefore represented at the metropolitan, regional, inter-regional or global scale and it is the regional scale that is most often cited in the interviews.

Typologies of interfaces scales	Representativeness	Examples of quotes
Metropolitan (urban area)	6/21	"The right scale is that of the metropolitan pole. The urban pole must draw resources from the rural territory; it is the alliance of territories that is possible. This creates a local taxation for the rural, and this is especially true in unattractive territories. The production of renewable energies allows the creation of activity, and makes it possible to fix the employment on the territory "(Manager of commercial development interviewee, 2018).
Regional (administrative area about 200 km in diameter)	8/21	"Regional control is essential to avoid the financial chasms. Regional steering is needed, but not only prescriptive. The risks of proximity to the installations must be regulated. " (Waste Manager interviewee, 2018)
Inter-regional	4/21	"The biomass stock is located in Aquitaine, Brittany, Normandy regions and we are far from taking all this flow" (Energy Producer Director interviewee, 2018).
Global	3/21	"The cost of materials and energy is not our subject. The energy cost is the global exchange! All it takes is a declaration in China to collapse "(Elected local authority Interview, 2018)

Table 2: Geographic scales of interfaces for metabolic links

Identifying these spatialized profiles of metabolic relationships helps to better understand the relationship of economic actors to the geography of energy. This typology points out thus different forms of involvement in the political economy of energy.

3. 2. Main indicators from the Energy Flow Analysis

Three main features characterize Saint-Nazaire's energy metabolism (cf. Table 3). Firstly, we can observe the harbor effect, or Rotterdam effect,, which is common to all port cities (Voskamp et al., 2017b). It is present when imports, exports and/or crossing flows exceed by orders of magnitude the domestic requirements of final energy (TFEC). In other words, they reflect the transit-related nature of the area. Table 3 shows that crossing flows, in form of natural gas and coal, account for 77% of energy imports and 36% of the system's total energy requirements (TER). The rest of the imports consists in mainly of crude oil and refined petroleum products, which are processed in the system's boundaries before being exported.

Indicator (Acronym)	Definition	Results in Petajoules
Imports	Primary and final energy flows coming from outside the system's boundaries	472
Domestic extraction	Primary energy extracted within the system's boundaries and entering the economy to be either processed or exported	0.07 (incinerated solid waste)
Exports	Primary and final energy flows that leave the system's boundaries	406
Hidden flows - external	Final energy consumed for the extraction and processing of imports	547
Hidden flows - domestic	Final energy consumed for the processing of domestic extraction	0 (included in the TFEC)
Crossing flows or throughput flows	Energy flows entering and leaving the system's boundaries without being processed	362 (natural gas and coal)
Total Final Energy Consumption (TFEC)	Energy delivered to consumers (excluding feedstock energy)	10.9
TFEC _{Fossil energy}	Part of fossil energy for TFEC	10.1
TFEC _{Renewable energy}	Part of renewable energy for TFEC	0.8
Direct Energy Input (DEI)	Domestic extraction + imports	472
Total Energy Requirement (TER)	DEI + domestic hidden flows + external hidden flows	1019

Table 3: Results of the EFA in PJ for 2015

The second main feature of Saint-Nazaire's metabolism is the large share of hidden energy flows in the metabolism. They represent around 54% of the total energy requirements (TER), and are mainly external. While this particular value is subject to uncertainties, it is consistent with 1) the large share

of imports in the TER and 2) the fossil nature of these imports (96% are petroleum products, natural gas and coal). Indeed, the energy yield of fossil energy over its production cycle is superior to one, meaning that more fossil energy is required in inputs than what is made available in the output. For example, this ratio was found at 1.4 for petroleum products and 1.09 for natural gas. The predominance of fossil energy is also found in domestic production, via the refinery and the power plants, as well as in the final energy consumption (TFEC), for which 66% consist in petroleum products, natural gas and coal.

Finally, at the other end of the spectrum, renewable energies are under-represented. Even though there is a diversity of sources, such as biofuels, wood, wind, solar, geothermal and biogas, they account for only 7.5% of Saint-Nazaire's TFEC, which is below the national average, estimated at 14.9% in 2015 (Ministry of ecological and solidarity transition, 2018). Moreover, it is worth noting that only 3.6% of this renewable energy consumption is domestic, the rest being imported either from neighboring regions (wood and wind energy) or from other countries (biofuels).

3.3. Synergetic metabolic links

3.3.1. Synergetic links to "proximity"

The combination of data on energy flows and the practices of the economic actors allows us to question the nature of these socio-material links. As a result, there are as many synergetic and cooperative relationships in the study area as conflicts. These metabolic links of inter-territorial cooperation are studied in this section from the point of view of the actors' representations and the spatial trajectory of flows.

Different types of synergies between consumption and supply territories are mentioned in the interviews. First, the broad concept of proximity (Camagni, 2017) is used as an influencing argument to organize synergetic metabolic links by 13 economic actors out of 21 interviewees. However, it is less the absence of intermediaries between producer and consumer that is referred to (in the sense of short energy circuits), than the geographical proximity between them. Some economic actors would like to build an economic model where energy production would be close to consumption sinks:

"The challenge is to show that there are economic models that stick to the physical flows [...] Five years ago, the president of our organization told us" the energy transition is a pet theme". Today he says to anyone we must consume less and produce locally" (Territorial engineer interviewee, 2018).

For some economic actors, proximity means to question the logic of energy market in order to distribute energy to consumers the closest and not to large networks:

"We must get out of capitalist logic: the energy we produce must be sold to a cooperative and not to the market. It is also necessary to invest in production units." (Manager of commercial development interviewee, 2018).

Some economic actors also mention the important role of territorial authorities to facilitate this proximity between companies. This "*proximity logic*" (Territorial engineer interviewee, 2018), under the city's impetus, brings some continuity to projects of synergies. Institutional involvement is also a governance factor for the success of symbiosis (Boons et al., 2011), as well as the role of local and regional authorities (Lenhart et al., 2015 resuming Chertow's studies, 2007). Thus, these synergetic metabolic links are created when local governments favor them and strongly encourage the economic actors to cooperate.

According to the EFA (see Figure 2), strong links between the industrial-port area and the city are suggested by intense metabolic relations. Indeed, 69% of the urban area's final energy needs come from the port industries. However, it should be noted that it is mainly fossil fuels that transit between port and city, as only 5% of the production is renewable energy. One can thus make the hypothesis that the city is playing the role of a commercial outlet for fossil energies - like any other – but which benefits from the port's geographical proximity.

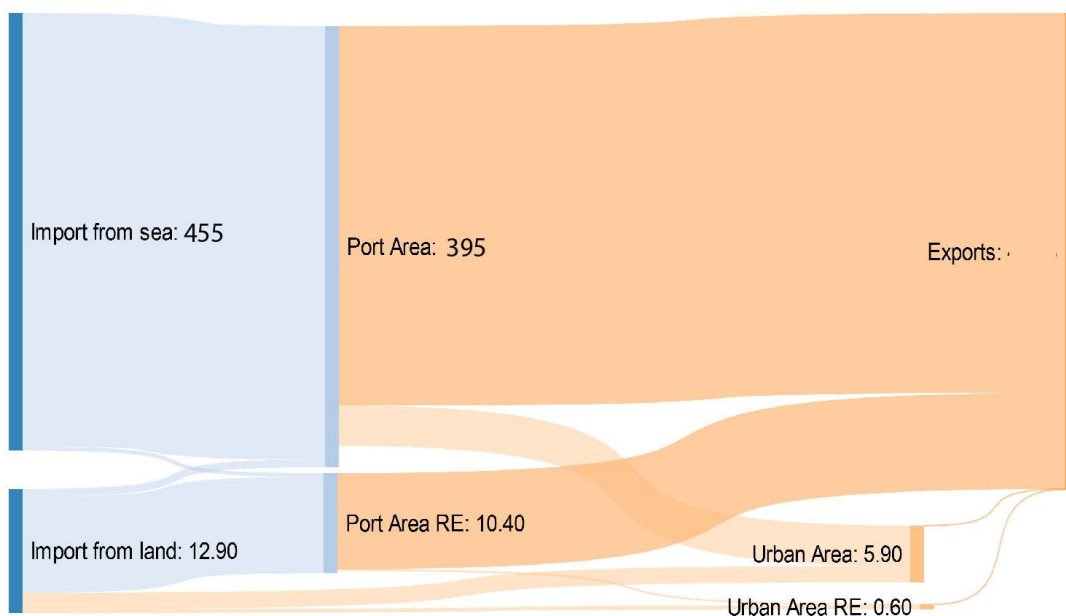


Figure 2: Sankey diagrams of energy flows between Saint-Nazaire's port area and urban area (Pj, 2015)

Finally, an "industrial symbiosis" approach is being undertaken jointly by the city (Saint-Nazaire agglomeration) and the port (through the organization "Grand Port Maritime of Nantes Saint-Nazaire" (GPMNSN) since 2014. An industrial heat network supplied by a "wood" boiler is being considered, which will produce 3,030 MWhth / year of heat. This network could be extended to a "excess heat" recovery network, like in other network examples of district heating (Heeres et al., 2004; Persson and Werner, 2012). This heat exchange conditioned by geographical proximity is seen by the economic actors as a lever of an "*energy synergy*" (Local government interviewee, 2018).

3.3.2. Synergies of cooperation between economic actors towards a territorial autonomy

Cooperation between economic actors is often put forward in interviews (19 out of 21 interviews). They reveal the stakes of collaborative relations between consumption and supply territories,

beyond market relations or competition. Several stakeholders thus mentioned the perspectives of *"building these interdependencies between territorial actors"* (Territorial engineer interviewee, 2018), which would not be undergone but called for. For this territorial engineer, these *"positive"* dependencies would have the effect of increasing territorial *"resilience"* in the economic sense of the term, i.e. an ability to be less dependent on the fluctuation of the energy market.

These interdependencies are also materialized through solidarity between territories of different functions. Thus, these interfaces between consumption and supply territories are defined by synergies between urban and rural:

"The urban territory has no resources; we will not set up a wind turbine in the middle of the city! Whereas the rural territory has space to put wind. It is a question of territorial solidarity. The urban territory finds answer in the rural territory" (Manager of commercial development interviewee, 2018).

According to some economic actors, the paradigm of metabolic relations would have changed and territories would communicate and cooperate *"because the financial stakes are very high and the administrative borders can be crossed"* (Waste management director interviewee, 2018).

These new cooperations are pushing stakeholders to discuss the issues of territorial autonomy, such as *"the ability of an energy system to function (or have the ability to function) fully, without the need of external support in the form of energy imports through its own local energy generation, storage and distribution systems"* (Rae and Bradley, 2012, p6499). This discourse is present among the economic actors: *"The autonomy, we think about it at the territorial scale, by integrating the resilience of the communities"* (Territorial engineer interviewee, 2018). In fact, this autonomy concept refers mainly to the capacity to produce locally for local needs, according to interviews. This term of autonomy is not shared by all actors, because it has a political connotation and some prefer the term *"self-sufficiency"* (Yalçın-Riollet et al., 2014).

Nevertheless, there is a real political issue behind energy self-sufficiency: *"autonomy yes, even if it is the opposite of national solidarity"* (Territorial engineer interviewee, 2018). Thus, energy autonomy questions the issue of local authorities' motivation and their contribution to national infrastructures (McKenna, 2018). Other economic actors also mentioned the decentralization of energy that *"adapts to existing local resources"* (Energy Producer Director interviewee, 2018).

3.4. Metabolic links of power relationship and conflict

3.4.1. Power conflicts at the international scale because of hidden flows

At the opposite of cooperation studied in the previous section, there are also links of power relationships and conflicts. This section presents their different types, from the point of view of the actors' representations and the spatial trajectory of flows.

Port cities have a strong logistical function, which gives them a role of a national and international hub. The metabolic consequences of this function are that the *"crossing flows"*, named as such in the EFA method, represent the largest share of ports' metabolisms (Hammer et al., 2003; Rosado et al.,

2016; Voskamp et al., 2017a). Similarly, in Saint-Nazaire agglomeration, most of the flows identified by the EFA transit through this port hub. These energy flows come mainly from foreign countries over-sea (see figure 3 where we have located supply areas in these foreign countries). When the supply is observed from a primary energy perspective (uranium, coal, natural gas, crude oil and renewable energies), 97% of Saint-Nazaire's energy consumption comes from foreign sources. This situation is far from a potential for territorial autonomy.

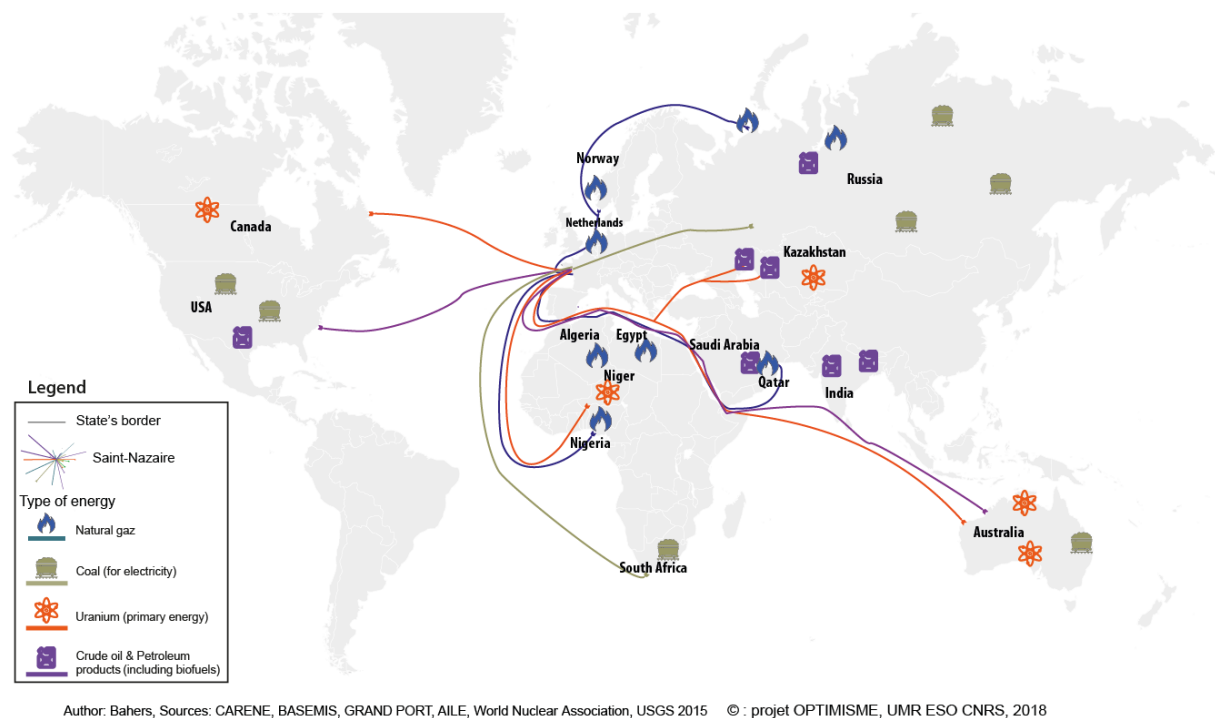


Figure 3: Supply areas for Saint-Nazaire's energy consumption

Moreover, the EFA methodology allows us to calculate hidden flows. They generally consist of secondary energy consumption, such as electricity consumed in processing natural gas or diesel to transport wood or coal (Baka and Bailis, 2014). These hidden (or indirect) flows are not produced within the system of studies, but are dependent on the consumption of the city, which makes it possible to calculate the total energy requirements (TER). In the EFA method, hidden flows are associated with direct energy imports. In the Saint-Nazaire port area, hidden energy flows account for most of the territory's metabolism. They amount to 547 PJ (petajoules), 1.2 times the total imports of the city (DEI) and constitute the majority of the TER. However, about 85% of these hidden energy flows can be attributed to crossing flows (petroleum products, natural gas and coal), which are distributed to other French, European and other international regions.

3.4.2. Power conflicts at the regional scale around local resources

8 economics actors mention conflicts regarding local resources. The conflicting links between supply and consumption territories even exist for renewable energy resources, such as wood or biomass, particularly because of power relations between governments at different geographical scales (local, regional and state). However, the EFA shows that 40% of renewable energy consumption comes from local and regional areas. This multi-level energy governance, which is essential for low-carbon urban strategies (Bulkeley et al., 2014; Emelianoff, 2014), stumbles in our case study to be consistent and effective. As this economic actor explains, the various public authorities (local, regional and national) are not coordinated and are fighting for their legitimacy: *"to make coherence and to downscale on the territory, the idea is beautiful and comprehensive ... but the road is not operational and there is no financial means! In addition, the work culture is very top-down!"* (Territorial engineer interviewee, 2018). Thus, the local approach of energy transition is very top-down and technocratic, which does not allow a sharing and a coherence in the metabolic relations between territories. This *"lack of common political cohesion"* between public authorities is a major obstacle for six operational actors during interviews, because *"everyone has his vision and no collective projects"* (Port manager interviewee, 2018).

There are also relationships of cities dominating supply areas, a consequence of the metropolisation of cities (Brenner, 2014), whose metabolism is increasingly globalized (Boudreau et al., 2006). In our case study, this can be seen in the control of rural resources by urban infrastructures: *"As regards to the urban biomass thermal plant, people are tired of supplying urban "bobos" (Bourgeois Bohemian) with their environmental friendly thermal plant of which they are so proud of. If there were not (rural) territories like us, there would be no biomass. Moreover, it's starting to be a serious concern because all the wood resources are depleting!"* (Energy producer director interviewee, 2018). In the same way, these new 'politics of scale' (Brenner, 2014) are expressed by the spatial divisions of the cities' supplying functions. Some industrial activities are also pushed back into the *ad hoc* areas of cities, which the economic actors also mentioned: *"It is true that this synergy between city and port is a bit like the industrial port dealing with what smell bad (i.e. waste)"* (Waste managers interviewee, 2018). This effect results in a very large gap between the Domestic Energy Input (DEI) and the Domestic Energy Consumption (DEC), which is three times smaller.

3.4.2. Power conflicts at the local scale: the example of Cordemais thermal power plant

The Cordemais thermal power plant illustrates very well what a new political ecology of energy can produce in a critical perspective. Since 2016, it is expected to convert in the coming years to abandon the coal. This very heavy infrastructure (about 400 direct jobs) is at the center of the region's economic challenges for a majority of the economics actors interviewed (13 mention it). But whereas the coal came from very distant sources, the new resources, such as green waste, could be more local and more sustainable, which led to the idea of calling them in 2017 the "green coal" by the plant's CEO. This name no longer seems appropriate in 2018, especially because green waste has been abandoned (for the moment anyway). It is the local authority that has alerted the public company "Electricité de France" (EDF), because the local supply stream seemed too weak. It would have been necessary to collect green waste in trucks from more than a 200 km region. As a result, a mixed of solid waste and (untreated or treated) wood waste have become the potential stream to supply the thermal power plant.

The first step was to identify the availability of these resources, in relation to existing technologies, and their adaptability to the industrial infrastructure. The particular question of the territorial scale of their availability is debated between the economic actors. Some of them consider that waste is available on 100-150 km for Cordemais. Others think that regional administrative boundaries should not be crossed. For the promoters of this model, the resource is present at a territorial scale that will not hinder its implementation and its transportation. Although borders have a regulatory meaning for waste and for an industrial plant, this issue does not seem to cause difficulties. However, if we listen to other economic actors, the consequences would be significant in terms of regional economic structuring:

"Regarding wood waste, there is pressure on the secondary resource. For example, if Cordemais turns into a wood waste thermal plant, within a radius of 600 km it will hurt! The plant could absorb all waste and tilt the market. These are wastes that tomorrow could become scarce"(Waste manager interviewee, 2018).

Moreover, some economic actors see the threat of opposition between a large infrastructure, which must continue to live despite an old model, and energy-short circuits that emerge gradually. Some say that these centralized networks cannot coexist with short supply chains. Finally, the entire port energy sector is at stake, which has the effect of crystallizing all the tensions between jobs and the energy transition.

"The problem is that energy brings a lot of money to the port. This is a sensitive point because we must not let it be thought that we want to give up on energy. For example, we lose the coal at Cordemais, but we have the marine renewable energy. Except that it does not make as many jobs of handling and crane operators, dockers ... it is about 200-300 jobs less. The local trade union is absolutely against threatened jobs, that's why they have protested against the sea wind turbine because jobs on fuel are threatened. They do not want this transition."(Port manager interviewee, 2018).

This urban infrastructure in transition makes it possible to explore symptomatic conflicts in the metabolic relationships between supply and consumption territories. It is at the heart of the new challenges faced by centralized networks, about their sustainability and their questioning (Coutard et al., 2004).

4. Discussion: Interrogating the drivers of metabolic relationships

Our research showed that by combining EFA and policies and economic practices investigation, we can reveal several drivers of metabolic relationships. The proximity issue is one of them because it facilitates synergetic links. This issue is also tackled in several studies. They hypothesize that localizations close to firms would favor and facilitate economic cooperation between actors, particularly through industrial synergies, for example within port territories (Schiller et al., 2014), a national program of waste and resource exchange in the UK (Jensen et al., 2011) or at the urban symbiosis scale (Lenhart et al., 2015; Van Berkel et al., 2009). Proximity is therefore a real asset in the implementation of synergies between territories, even if the geographical distance can vary extremely depending on the type of flows.

A second driver in favor of synergetic links is the stakes of energy self-sufficiency. Most of interviews mention it as an issue of new cooperation. There is also a trend in the literature that energy self-sufficiency comes from local actors willing to be more independent of private utilities (Engelken et al., 2016). Moreover, energy self-sufficiency is closely linked to the deployment of new renewable energy technologies (Rae and Bradley, 2012). From an EFA perspective, there is a link between spatial proximity and geography of renewable energies. While renewable energy consumption remains low in the agglomeration, 3.6% of this energy is produced locally and 40% comes from neighboring territories. Urban energy autonomy is thus not feasible, but autonomy at an inter-territorial scale between city and region could be a perspective for public policy.

Moreover, as shown in the Cordemais example, it is not enough for an infrastructure to claim renewable energy-based operations to avoid metabolic conflicts (Martinez-Alier et al., 2016). They remain because of the threats on jobs and disagreements on transition strategies. The transformation of this large infrastructure in France illustrates the challenges of geography in political energies faced by the countries that based their development on fossil energy imports. The difficulty of unraveling path dependencies is obvious from this example, and modernity has been built on cheap and abundant fossil energy. This energy has, in multiple ways, alienated urban areas from their hinterlands, as they have relied on imported high energy fuels and coal. Jobs and flows are deeply intertwined with these flows. The energy transition, which is seen as reconnecting city and countryside, has implications for land use and energy capacity. We can question the hypothesis that energy resources available in surrounding countryside would be sufficient to satisfy current levels of energy use, including industrial manufacturing, transportation, food processing and basic heating requirements. For cities and their peripheries to reduce their urban metabolism, it seems also be necessary to profoundly reduce energy consumption (Smil, 2015).

The situation of power relationships between cities and their hinterlands remains very important. The energy sector is highly globalized and characterized by an intensification of maritime transport. This generates a highly externalized metabolism, with open urban socio-energy relations and their hinterlands. Moreover, fossil fuels are predominant in Saint-Nazaire port, since they represent 96% of the DEI (if we consider biofuels are renewable energies, which is debatable (Harjanne and Korhonen, 2019). It is thus a "fossil" metabolism, which contributes to discussion of the "*fossil capitalism*" theory by Andreas Malm (Malm, 2016). These fossil sectors thus generate "*uneven power relations*" (Huber, 2009), which are not insignificant in the case of our port case study. According to the interviews, this is illustrated by the low price of fossil fuels, such as natural gas, which hampers the development of renewable biomass thermal plants. The externalization of energy metabolism is therefore a strong driver of power relationships.

A second important driver revealed by our study concerns the hidden flows. These are a very strong illustrator of the power relations, specific to urban metabolism (John et al., 2019), as shown in other cases, like the water cycle (Linton and Budds, 2014), the Hebei's iron and steel industry (Dai, 2015) and the energy biomass savings (Baka and Bailis, 2014). In our case study, this concerns energy consumption and atmospheric emissions from supply territories, which are disconnected from consumption activities. This issue of hidden flows remains an overlooked public policy, while they are strongly responsible for a large part of the territory's energy requirements.

5. Conclusion: From Energy flows analysis to Metabolic relationships framework

From an Energy Flow Analysis, this study challenges conceptions of urban metabolism thanks to the understanding of the practices of economic actors who have a role in the flow governance. We manage to go beyond the quantification of flows to understand urban metabolism policies (Cousins, 2017; Guibrunet et al., 2016). It is thus necessary to study at which scales the energy supply come from. This allowed us to investigate inside and outside the city, when some metabolism studies are concentrated at the municipal boundaries without opening up the urban "black box". Our approach contributes to the emerging field of "political-industrial ecology" (Breetz, 2017; Pincetl and Newell, 2017), whose objective is to combine prescriptive and critical results in energy studies (Baka, 2017).

These arguments were developed through a political-industrial ecology analysis of Saint-Nazaire agglomeration. The issue of supply, linked to both the logistics role of the port and the regional hinterland, highlights the need to combine the results of the EFA and semi-structured interviews. The results show that the metabolic relationships between cities and their hinterlands are based on both synergies and cooperation, and unbalanced power and conflicts. The recognition of these power relationships is essential for a vision towards a sustainable urban metabolism (John et al., 2019). The proposal of the metabolic relationships' framework is useful in this sense to understand how the "hinterlands-city" relationships shape and are shaped by the city's metabolism.

Appendix

Appendix 1: List of economic actors interviewed

Type of actors interviewed (linked to figure 1)	List of organizations	List of interviewees
Importers (fossil & nuclear energy) (n=3)	Methane terminal	Environmental Quality Manager
	Logistic company	Chief executive officer (CEO)
	Logistic company	CEO
Producers (fossil & nuclear energy) (n=2)	Coal-fired power plant	Environmental Quality Manager
	Gaz power plan	Project manager
Importers (renewable energy) (n=1)	Renewable electricity distributor	Project manager
Producers (renewable energy) Environmental organizations (NGO) for renewable energy (n=11)	Energy from algae	CEO
	Methanization plants	Project engineer
	Excess heat energy recovery	Project manager
	Excess heat energy recovery	CEO
	Biomass boilers from wood waste	President
	Boilers from wood, plastic and cardboards waste	Project manager
	Boilers from wood, plastic and cardboards waste	Project manager
	Promotion of wind energy	Manager
	Promotion of solar energy	President

	Promotion of wood energy	Project manager
	Promotion of renewable energy	Project engineer
Distributors (<i>n=1</i>)	Nuclear and renewable electricity distributor	Project engineer
Local/regional governments (<i>n=3</i>)	Urban/local government	Manager
	Industrial-port zone	Project engineer
	Regional government	Elected person

Appendix 2: List of questions for the semi-structured interviews

Thematics	Questions and relaunching the discussion
<i>Role of the structure</i>	What is the role of your structure in the energy transition and the circular economy? You, personally, what is your mission in the structure? What is your personal trajectory?
<i>Relationships with other economic actors</i>	Who are the economic actors with whom you work on these topics? In what context, in what form? urban planning, private partnerships? What is the impact of local energy policies? What are there oppositions between actors? Divergences of interests?
<i>Challenges and opportunities involved in energy resources management</i>	What are the main obstacles? - Economic, environmental, political, and spatial? What are the main opportunities? - Economic, environmental, political, and spatial?
<i>Territorialisation of energy policies</i>	How is the local territory organized in relation to these issues? What is the relationship between the economic actors and the city in relation to these issues? Are there conflicts, oppositions of positions? Why ? Since when ?
<i>Spatial perception of energy transition</i>	Are there competitions between sectors, between resources? How is the arbitration between technical choices organized? (large infrastructures, short circuits) How important is the geographic supply radius in transition choices?
<i>Perspective on the potential for operationalization of energy synergies.</i>	What are the important issues for energy synergies that will appear? economic, environmental, political and spatial.

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Bibliography

- Athanassiadis, A., Fernandez, G., Meirelles, J., Meinherz, F., Hoekman, P., Cari, Y.B., 2017. Exploring the energy use drivers of 10 cities at microscale level. *Energy Procedia*, CISBAT 2017 International Conference Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale 122, 709–714. <https://doi.org/10.1016/j.egypro.2017.07.374>
- AXENNE, 2016. Stratégie de développement des énergies renouvelables sur le territoire de la CARENE (Strategy for the development of renewable energies on Saint-Nazaire metropolitan area).
- Baas, L., 2008. Industrial symbiosis in the Rotterdam Harbour and Industry Complex: reflections on the interconnection of the techno-sphere with the social system. *Business Strategy and the Environment* 17, 330–340. <https://doi.org/10.1002/bse.624>
- Bahers, J.-B., Barles, S., Durand, M., n.d. Urban Metabolism of Intermediate Cities: The Material Flow Analysis, Hinterlands and the Logistics-Hub Function of Rennes and Le Mans (France). *Journal of Industrial Ecology* 0. <https://doi.org/10.1111/jiec.12778>
- Bahers, J.-B., Durand, M., Beraud, H., 2017. Quelle territorialité pour l'économie circulaire ? Interprétation des typologies de proximité dans la gestion des déchets. *Flux* 129–141. <https://doi.org/10.3917/flux1.109.0129>
- Bahers, J.-B., Giacchè, G., 2019. Towards a metabolic rift analysis: The case of urban agriculture and organic waste management in Rennes (France). *Geoforum* 98, 97–107. <https://doi.org/10.1016/j.geoforum.2018.10.017>
- Baka, J., Bailis, R., 2014. Wasteland energy-scapes: A comparative energy flow analysis of India's biofuel and biomass economies. *Ecological Economics* 108, 8–17. <https://doi.org/10.1016/j.ecolecon.2014.09.022>
- Baka, J.E., 2017. Political-industrial ecologies of energy, in: *Handbook on the Geographies of Energy*.
- Barles, S., 2009. Urban metabolism of Paris and its region. *Journal of Industrial Ecology* 13, 898–913. <https://doi.org/10.1111/j.1530-9290.2009.00169.x>
- BASEMIS, 2015. Regional database of energy consumption and greenhouse gas emissions from Air Pays de la Loire.
- Billen, G., Garnier, J., Barles, S., 2012. History of the urban environmental imprint: introduction to a multidisciplinary approach to the long-term relationships between Western cities and their hinterland. *Reg Environ Change* 12, 249–253. <https://doi.org/10.1007/s10113-012-0298-1>
- Boons, F., Spekkink, W., Mouzakis, Y., 2011. The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. *Journal of Cleaner Production* 19, 905–911. <https://doi.org/10.1016/j.jclepro.2011.01.003>
- Bosman, R., Loorbach, D., Rotmans, J., Van Raak, R., 2018. Carbon Lock-Out: Leading the Fossil Port of Rotterdam into Transition. *Sustainability* 10, 2558. <https://doi.org/10.3390/su10072558>
- Boudreau, J.-A., Hamel, P., Jouve, B., Keil, R., 2006. Comparing metropolitan governance: The cases of Montreal and Toronto. *Progress in Planning*, Comparing metropolitan governance: The cases of Montreal and Toronto 66, 7–59. <https://doi.org/10.1016/j.progress.2006.07.005>
- Breetz, H.L., 2017. Political-industrial ecology: Integrative, complementary, and critical approaches. *Geoforum* 85, 392–395. <https://doi.org/10.1016/j.geoforum.2016.11.011>
- Brenner, N., 2014. *Implosions/Explosions: Towards a Study of Planetary Urbanization*. JOVIS Verlag.
- Brenner, N., 2009. What is critical urban theory? *City* 13, 198–207. <https://doi.org/10.1080/13604810902996466>
- Broto, V.C., Allen, A., Rapoport, E., 2012. Interdisciplinary perspectives on urban metabolism. *Journal of Industrial Ecology* 16, 851–861.
- Bulkeley, H., Castán Broto, V., Maassen, A., 2014. Low-carbon Transitions and the Reconfiguration of Urban Infrastructure. *Urban Studies* 51, 1471–1486. <https://doi.org/10.1177/0042098013500089>

- Camagni, R., 2017. Regional Competitiveness: Towards a Concept of Territorial Capital, in: Capello, R. (Ed.), *Seminal Studies in Regional and Urban Economics: Contributions from an Impressive Mind*. Springer International Publishing, Cham, pp. 115–131. https://doi.org/10.1007/978-3-319-57807-1_6
- Carpenter, A., Lozano, R., Sammalisto, K., Astner, L., 2018. Securing a port's future through Circular Economy: Experiences from the Port of Gävle in contributing to sustainability. *Marine Pollution Bulletin* 128, 539–547. <https://doi.org/10.1016/j.marpolbul.2018.01.065>
- Cerceau, J., Mat, N., Junqua, G., Lin, L., Laforest, V., Gonzalez, C., 2014. Implementing industrial ecology in port cities: international overview of case studies and cross-case analysis. *Journal of Cleaner Production* 74, 1–16. <https://doi.org/10.1016/j.jclepro.2014.03.050>
- Céspedes Restrepo, J.D., Morales-Pinzón, T., 2018. Urban metabolism and sustainability: Precedents, genesis and research perspectives. *Resources, Conservation and Recycling* 131, 216–224. <https://doi.org/10.1016/j.resconrec.2017.12.023>
- Chertow, M.R., 2007. "Uncovering" Industrial Symbiosis. *Journal of Industrial Ecology* 11, 11–30. <https://doi.org/10.1162/jiec.2007.1110>
- Cousins, J.J., 2017. Volume control: Stormwater and the politics of urban metabolism. *Geoforum* 85, 368–380. <https://doi.org/10.1016/j.geoforum.2016.09.020>
- Cousins, J.J., Newell, J.P., 2015. A political–industrial ecology of water supply infrastructure for Los Angeles. *Geoforum* 58, 38–50. <https://doi.org/10.1016/j.geoforum.2014.10.011>
- Coutard, O., Hanley, R., Zimmerman, R., 2004. *Sustaining Urban Networks: The Social Diffusion of Large Technical Systems*, 1st ed. Routledge.
- Cui, X., 2018. How can cities support sustainability: A bibliometric analysis of urban metabolism. *Ecological Indicators* 93, 704–717. <https://doi.org/10.1016/j.ecolind.2018.05.056>
- Currie, P.K., Musango, J.K., 2017. African Urbanization: Assimilating Urban Metabolism into Sustainability Discourse and Practice. *Journal of Industrial Ecology* 21, 1262–1276. <https://doi.org/10.1111/jiec.12517>
- Dai, T., 2015. A study on material metabolism in Hebei iron and steel industry analysis. *Resources, Conservation and Recycling* 95, 183–192. <https://doi.org/10.1016/j.resconrec.2015.01.002>
- Demaria, F., Schindler, S., 2016. Contesting Urban Metabolism: Struggles Over Waste-to-Energy in Delhi, India. *Antipode* 48, 293–313. <https://doi.org/10.1111/anti.12191>
- Deutz, P., Baxter, H., Gibbs, D., Mayes, W.M., Gomes, H.I., 2017. Resource recovery and remediation of highly alkaline residues: A political-industrial ecology approach to building a circular economy. *Geoforum* 85, 336–344. <https://doi.org/10.1016/j.geoforum.2017.03.021>
- Dijst, M., Worrell, E., Böcker, L., Brunner, P., Davoudi, S., Geertman, S., Harmsen, R., Helbich, M., Holtslag, A.A.M., Kwan, M.-P., Lenz, B., Lyons, G., Mokhtarian, P.L., Newman, P., Perrels, A., Ribeiro, A.P., Rosales Carreón, J., Thomson, G., Urge-Vorsatz, D., Zeyringer, M., 2018. Exploring urban metabolism—Towards an interdisciplinary perspective. *Resources, Conservation and Recycling* 132, 190–203. <https://doi.org/10.1016/j.resconrec.2017.09.014>
- Emelianoff, C., 2014. Local Energy Transition and Multilevel Climate Governance: The Contrasted Experiences of Two Pioneer Cities (Hanover, Germany, and Vaxjo, Sweden). *Urban Studies* 51, 1378–1393. <https://doi.org/10.1177/0042098013500087>
- ENEDIS, 2015. Open database from the national electricity distributor (ENEDIS).
- Engelken, M., Römer, B., Drescher, M., Welp, I., 2016. Transforming the energy system: Why municipalities strive for energy self-sufficiency. *Energy Policy* 98, 365–377. <https://doi.org/10.1016/j.enpol.2016.07.049>
- Ferrao, P., Fernández, J.E., 2013. *Sustainable Urban Metabolism*, 1st ed. MIT Press, Cambridge, Massachusetts.
- Fischer-Kowalski, M., Haberl, H., 2007. *Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use*. Edward Elgar Publishing.
- Frischknecht, R., Wyss, F., Büsser Knöpfel, S., Balouktsi, M., 2015. Cumulative energy demand in LCA: the energy harvested approach. *The International Journal of Life Cycle Assessment* 7, 957–960.

- Geng, Y., Liu, Y., Liu, D., Zhao, H., Xue, B., 2011. Regional societal and ecosystem metabolism analysis in China: A multi-scale integrated analysis of societal metabolism(MSIASM) approach. *Energy*, PRES 2010 36, 4799–4808. <https://doi.org/10.1016/j.energy.2011.05.014>
- GRDF, 2015. Open database from the national natural gas distributor (GRDF).
- Guibrunet, L., Sanzana Calvet, M., Castán Broto, V., 2016. Flows, system boundaries and the politics of urban metabolism: Waste management in Mexico City and Santiago de Chile. *Geoforum*. <https://doi.org/10.1016/j.geoforum.2016.10.011>
- Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V. (Eds.), 2016. *Social Ecology*. Springer International Publishing, Cham.
- Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. *Nature Sustainability* 2, 173. <https://doi.org/10.1038/s41893-019-0225-2>
- Hammer, M., Giljum, S., Hinterberger, F., 2003. Material flow analysis of the City of Hamburg. Sustainable Europe Research Institute (SERI), Vienne.
- Harjanne, A., Korhonen, J.M., 2019. Abandoning the concept of renewable energy. *Energy Policy* 127, 330–340. <https://doi.org/10.1016/j.enpol.2018.12.029>
- Heeres, R.R., Vermeulen, W.J.V., de Walle, F.B., 2004. Eco-industrial park initiatives in the USA and the Netherlands: first lessons. *Journal of Cleaner Production, Applications of Industrial Ecology* 12, 985–995. <https://doi.org/10.1016/j.jclepro.2004.02.014>
- Hollen, R.M.A., van den Bosch, F.A.J., Volberda, H.W., 2015. Strategic levers of port authorities for industrial ecosystem development. *Marit Econ Logist* 17, 79–96. <https://doi.org/10.1057/mel.2014.28>
- Huang, Q., Zheng, X., Liu, F., Hu, Y., Zuo, Y., 2018. Dynamic analysis method to open the “black box” of urban metabolism. *Resources, Conservation and Recycling* 139, 377–386. <https://doi.org/10.1016/j.resconrec.2018.09.010>
- Huber, M.T., 2009. Energizing historical materialism: Fossil fuels, space and the capitalist mode of production. *Geoforum, Themed Issue: Postcoloniality, Responsibility and Care* 40, 105–115. <https://doi.org/10.1016/j.geoforum.2008.08.004>
- Jensen, P.D., Basson, L., Hellowell, E.E., Bailey, M.R., Leach, M., 2011. Quantifying ‘geographic proximity’: experiences from the United Kingdom’s national industrial symbiosis programme. *Resources, Conservation and Recycling* 55, 703–712.
- John, B., Luederitz, C., Lang, D.J., von Wehrden, H., 2019. Toward Sustainable Urban Metabolisms. From System Understanding to System Transformation. *Ecological Economics* 157, 402–414. <https://doi.org/10.1016/j.ecolecon.2018.12.007>
- Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The Changing Metabolism of Cities. *Journal of Industrial Ecology* 11, 43–59. <https://doi.org/10.1162/jie.2007.1107>
- Kennedy, C., Hoornweg, D., 2012. Mainstreaming Urban Metabolism. *Journal of Industrial Ecology* 16, 780–782. <https://doi.org/10.1111/j.1530-9290.2012.00548.x>
- Kennedy, C., Pincetl, S., Bunje, P., 2011. The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution, Selected papers from the conference Urban Environmental Pollution: Overcoming Obstacles to Sustainability and Quality of Life (UEP2010), 20-23 June 2010, Boston, USA* 159, 1965–1973. <https://doi.org/10.1016/j.envpol.2010.10.022>
- Kennedy, C.A., 2016. Industrial Ecology and Cities, in: Clift, R., Druckman, A. (Eds.), *Taking Stock of Industrial Ecology*. Springer International Publishing, Cham, pp. 69–86. https://doi.org/10.1007/978-3-319-20571-7_4
- Kim, E., Barles, S., 2012. The energy consumption of Paris and its supply areas from the eighteenth century to the present. *Regional Environmental Change* 12, 295–310. <https://doi.org/10.1007/s10113-011-0275-0>
- Krausmann, F., 2013. A City and Its Hinterland: Vienna’s Energy Metabolism 1800–2006, in: Long Term Socio-Ecological Research, Human-Environment Interactions. Springer, Dordrecht, pp. 247–268. https://doi.org/10.1007/978-94-007-1177-8_11

- Lenhart, J., van Vliet, B., Mol, A.P.J., 2015. New roles for local authorities in a time of climate change: the Rotterdam Energy Approach and Planning as a case of urban symbiosis. *Journal of Cleaner Production* 107, 593–601. <https://doi.org/10.1016/j.jclepro.2015.05.026>
- Li, Y., Zhang, Y., Yang, N., 2010. Ecological network model analysis of China's endosomatic and exosomatic societal metabolism. *Procedia Environmental Sciences, International Conference on Ecological Informatics and Ecosystem Conservation (ISEIS 2010)* 2, 1400–1406. <https://doi.org/10.1016/j.proenv.2010.10.152>
- Linton, J., Budds, J., 2014. The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. *Geoforum* 57, 170–180. <https://doi.org/10.1016/j.geoforum.2013.10.008>
- Malm, A., 2016. *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*. Verso, London ; New York.
- Martinez-Alier, J., Temper, L., Demaria, F., 2016. Social Metabolism and Environmental Conflicts in India, in: Ghosh, N., Mukhopadhyay, P., Shah, A., Panda, M. (Eds.), *Nature, Economy and Society: Understanding the Linkages*. Springer India, New Delhi, pp. 19–49. https://doi.org/10.1007/978-81-322-2404-4_3
- Mat, N., Cerceau, J., Shi, L., Park, H.-S., Junqua, G., Lopez-Ferber, M., 2016. Socio-ecological transitions toward low-carbon port cities: trends, changes and adaptation processes in Asia and Europe. *Journal of Cleaner Production, Towards Post Fossil Carbon Societies: Regenerative and Preventative Eco-Industrial Development* 114, 362–375. <https://doi.org/10.1016/j.jclepro.2015.04.058>
- McClintock, N., 2010. Why farm the city? Theorizing urban agriculture through a lens of metabolic rift. *Cambridge J Regions Econ Soc* 3, 191–207. <https://doi.org/10.1093/cjres/rsq005>
- McKenna, R., 2018. The double-edged sword of decentralized energy autonomy. *Energy Policy* 113, 747–750. <https://doi.org/10.1016/j.enpol.2017.11.033>
- Ministry of ecological and solidarity transition, 2018. *Chiffre clés des énergies renouvelables - Edition 2018 (Key figures of renewable energies - 2018 edition)*.
- Moon, D.S.H., Woo, J.K., Kim, T.G., 2018. Green Ports and Economic Opportunities, in: Froholdt, L.L. (Ed.), *Corporate Social Responsibility in the Maritime Industry, WMU Studies in Maritime Affairs*. Springer International Publishing, Cham, pp. 167–184. https://doi.org/10.1007/978-3-319-69143-5_10
- Newell, J.P., Cousins, J.J., 2015. The boundaries of urban metabolism: Towards a political–industrial ecology. *Progress in Human Geography* 39, 702–728. <https://doi.org/10.1177/0309132514558442>
- Newman, P.W.G., 1999. Sustainability and cities: extending the metabolism model. *Landscape and Urban Planning* 44, 219–226. [https://doi.org/10.1016/S0169-2046\(99\)00009-2](https://doi.org/10.1016/S0169-2046(99)00009-2)
- Persson, U., Werner, S., 2012. District heating in sequential energy supply. *Applied Energy* 95, 123–131. <https://doi.org/10.1016/j.apenergy.2012.02.021>
- Pincetl, S., Bunje, P., Holmes, T., 2012. An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. *Landscape and Urban Planning* 107, 193–202. <https://doi.org/10.1016/j.landurbplan.2012.06.006>
- Pincetl, S., Newell, J.P., 2017. Why data for a political-industrial ecology of cities? *Geoforum*. <https://doi.org/10.1016/j.geoforum.2017.03.002>
- Rae, C., Bradley, F., 2012. Energy autonomy in sustainable communities—A review of key issues. *Renewable and Sustainable Energy Reviews* 16, 6497–6506. <https://doi.org/10.1016/j.rser.2012.08.002>
- Ramos-Martin, J., Giampietro, M., Mayumi, K., 2007. On China's exosomatic energy metabolism: An application of multi-scale integrated analysis of societal metabolism (MSIASM). *Ecological Economics* 63, 174–191. <https://doi.org/10.1016/j.ecolecon.2006.10.020>
- Rosado, L., Kalmykova, Y., Patrício, J., 2016. Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden. *Journal of Cleaner Production* 126, 206–217. <https://doi.org/10.1016/j.jclepro.2016.02.139>

- Rosales Carreón, J., Worrell, E., 2018. Urban energy systems within the transition to sustainable development. A research agenda for urban metabolism. *Resources, Conservation and Recycling* 132, 258–266. <https://doi.org/10.1016/j.resconrec.2017.08.004>
- RTE, 2016. Bilans électriques et perspectives - Pays de la Loire (Electricity assessment and perspectives - Pays de la Loire region).
- Saint-Nazaire port authority, 2016. Suivi des vracs solides et liquides importés et exportés (Account on solids and liquids products imported and exported) - Base year 2015.
- Schiller, F., Penn, A., Druckman, A., Basson, L., Royston, K., 2014. Exploring Space, Exploiting Opportunities. *Journal of Industrial Ecology* 18, 792–798. <https://doi.org/10.1111/jiec.12140>
- Schneider, M., McMichael, P., 2010. Deepening, and repairing, the metabolic rift. *The Journal of Peasant Studies* 37, 461–484. <https://doi.org/10.1080/03066150.2010.494371>
- Smil, V., 2015. *Power Density: A Key to Understanding Energy Sources and Uses*. MIT Press.
- Swilling, M., Hajer, M., Baynes, T., Bergesen, J., Labbé, F., Kaviti Musango, J., Ramaswami, A., Robinson, B., Salat, S., Suh, S., 2018. The weight of cities—Resource requirements of future urbanisation. Paris: UN Environment/International Resource Panel (IRP).
- Van Berkel, R., Fujita, T., Hashimoto, S., Geng, Y., 2009. Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. *Journal of Environmental Management* 90, 1544–1556. <https://doi.org/10.1016/j.jenvman.2008.11.010>
- Voskamp, I.M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J.P., Rijnaarts, H.H.M., 2017a. Enhanced Performance of the Eurostat Method for Comprehensive Assessment of Urban Metabolism: A Material Flow Analysis of Amsterdam. *Journal of Industrial Ecology* 21, 887–902. <https://doi.org/10.1111/jiec.12461>
- Voskamp, I.M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J.P., Rijnaarts, H.H.M., 2017b. Enhanced Performance of the Eurostat Method for Comprehensive Assessment of Urban Metabolism: A Material Flow Analysis of Amsterdam. *Journal of Industrial Ecology* 21, 887–902. <https://doi.org/10.1111/jiec.12461>
- Wachsmuth, D., 2012. Three Ecologies: Urban Metabolism and the Society-Nature Opposition: Three Ecologies. *The Sociological Quarterly* 53, 506–523. <https://doi.org/10.1111/j.1533-8525.2012.01247.x>
- Wilby, M.R., Rodríguez González, A.B., Vinagre Díaz, J.J., 2014. Empirical and dynamic primary energy factors. *Energy* 73, 771–779. <https://doi.org/10.1016/j.energy.2014.06.083>
- Yalçın-Riollet, M., Garabuau-Moussaoui, I., Szuba, M., 2014. Energy autonomy in Le Mené: A French case of grassroots innovation. *Energy Policy* 69, 347–355. <https://doi.org/10.1016/j.enpol.2014.02.016>
- Zhang, Y., Li, Y., Zheng, H., 2017. Ecological network analysis of energy metabolism in the Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration. *Ecological Modelling* 351, 51–62. <https://doi.org/10.1016/j.ecolmodel.2017.02.015>
- Zhang, Y., Xia, L., Fath, B.D., Yang, Z., Yin, X., Su, M., Liu, G., Li, Y., 2016. Development of a spatially explicit network model of urban metabolism and analysis of the distribution of ecological relationships: case study of Beijing, China. *Journal of Cleaner Production* 112, 4304–4317. <https://doi.org/10.1016/j.jclepro.2015.06.052>
- Zhang, Y., Yang, Z., Yu, X., 2015. Urban Metabolism: A Review of Current Knowledge and Directions for Future Study. *Environ. Sci. Technol.* 49, 11247–11263. <https://doi.org/10.1021/acs.est.5b03060>
- Zhang, Y., Zheng, H., Fath, B.D., 2014. Analysis of the energy metabolism of urban socioeconomic sectors and the associated carbon footprints: Model development and a case study for Beijing. *Energy Policy* 73, 540–551. <https://doi.org/10.1016/j.enpol.2014.04.029>