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1 **Outsourcing of urban metabolisms and its consequences: a multiscale energy flow**  
2 **analysis of a French port-city**

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13

## 14 Abstract

15 Outsourcing of urban metabolisms is a phenomenon that has grown exponentially over the last century.  
16 It is a cause of vulnerability for cities for two main reasons. They are dependent on distant hinterlands  
17 and their consumption induces global environmental impact they do not fully control. This study aims  
18 to investigate these two effects of outsourcing through a single, multiscale approach to energy  
19 accounting. A spatially differentiated energy flow analysis (EFA) is developed, which includes  
20 indicators for dependency, embodied energy and energy losses. Applied to the case of the harbor-  
21 industrial area of Saint-Nazaire, France, the results show that the global scale dominates dependency  
22 and embodied energy indicators, whereas primary energy losses occur mainly at the domestic scale. The  
23 local scale accounts for less than 0.1% of the energy supply and about 6% of indirect flows. The spatial  
24 trajectories of some renewables (wood, biofuels, wind electricity) suggest that the energy transition  
25 could decrease global dependency, but with a transfer to the domestic level, and not necessarily to the  
26 local scale, without a radical change from the port's production system. Moreover, trade-offs could  
27 emerge between reducing the amount of embodied energy in foreign countries and using energy losses  
28 as a local secondary source, depending on the resource used to generate the losses. This study highlights  
29 thus the need to link local transition policies more closely to outsourcing issues in order to allow a  
30 comprehensive understanding of the possible transfers in terms of dependency and environmental  
31 burdens that may occur in a transition context.

32 Keywords : energy metabolism ; outsourcing ; dependency ; embodied energy ; energy losses ; energy  
33 transition

## 34 1. Introduction

35 One characteristic of current urban systems is their reliance on national and global hinterlands (Barles  
36 and Knoll, 2019). Cities are indeed open systems, which depend on outside territories for materials, food  
37 and energy supply as well as to process the resulting waste from urban activities (Krausmann, 2013).  
38 While this characteristic is inherent to cities from all size and shape, the extent of this outsourcing has  
39 exploded over the last century due to an ever-increasing demand of resources to sustain urban growth  
40 (Athanassiadis et al., 2016; Kennedy et al., 2007).

41 In particular, the massive globalization of energy markets poses several challenges for cities. Because  
42 they only have a partial control over the supply chains, their energy security may be threatened in case  
43 of global economic and ecological crises. For example, the explosion of the nuclear power plant in  
44 Fukushima in 2011 affected for months the worldwide availability and affordability of liquefied natural  
45 gas owing to Japan's increased demand (Hayashi and Hughes, 2013). This event demonstrated, if  
46 needed, how the interdependency of national energy supplies makes cities vulnerable to changes of  
47 consumption patterns occurring in foreign countries (Verrastro and Ladislaw, 2007). Moreover,  
48 outsourcing energy supply means leaving an external environmental rucksack in the form of indirect  
49 flows (carbon, water, energy etc.), that cannot be easily managed by local authorities wishing to reduce  
50 their environmental footprint (Chen and Zhu, 2019; Wiedmann et al., 2016).

51 The current energy transition undertaken by many countries worldwide aims to bring about potential  
52 solutions to these problems by encouraging energy efficiency policies and a secure supply from low-  
53 carbon energy sources (Rosales Carreón and Worrell, 2018). However, the geographical implications of  
54 this energy transition are not yet determined due to the multiplicity of the flows involved, the spatial  
55 distribution of these new resources and the heterogeneity of urban developments (Balta-Ozkan et al.,  
56 2015; Bridge et al., 2013). At the very least, these implications can be more complex than a mere  
57 reduction of the cities' energy dependence and environmental footprint. It is therefore essential to have  
58 a better understanding of the origins of current and potential future energy flows in order to formulate  
59 appropriate policy recommendations.

60 Because research on urban metabolism aims to provide a comprehensive understanding of urban flows'  
61 trajectories, it has been extensively used to address outsourcing-related issues. Different accounting  
62 approaches based on different definitions of the geographical systems boundaries have been developed  
63 to show various aspects of cities' outsourcing (Baynes and Wiedmann, 2012; Chavez and Ramaswami,  
64 2013; Minx et al., 2013; Zhang et al., 2018). Territory-based approaches are particularly useful to study  
65 the effects of consumption patterns and local planning on cities' spatial imprint, i.e. the extent of  
66 dependency on resources hinterlands (Barles and Knoll, 2019; Billen et al., 2009; Krausmann, 2013).  
67 However, these studies fall short in encompassing all relevant urban flows since they don't include  
68 indirect consumptions and emissions due to urban activities occurring outside the city's boundaries

69 (Galli et al., 2012; Ramaswami et al., 2011). Consumption-based and hybrid approaches integrate those  
70 flows at various levels to quantify their spatial spread (Lenzen and Peters, 2010; Wiedmann et al., 2016,  
71 2015), compare cities' performance and metabolic profiles (Chavez and Ramaswami, 2013; Chen et al.,  
72 2020; Hu et al., 2016; J. Lin et al., 2013) or unveil key drivers of indirect emissions in urban consumption  
73 (Chen and Zhu, 2019; Jones and Kammen, 2011; Larsen and Hertwich, 2010; T. Lin et al., 2013; Minx  
74 et al., 2013).

75 However, in the context of transition policies, both issues of cities' dependency on hinterlands and  
76 related indirect flows have not been adequately addressed. Since substitutions of resources flows are to  
77 be expected, unintended transfers of environmental burdens and dependency from a supply chain to  
78 another and/or from a spatial scale to another may occur. Yet, dependency and indirect emissions due  
79 to imports are often considered at an aggregate level (rest of the world) and multiscale analyses of these  
80 issues are scarce. Kim and Barles (2012) mapped the supply areas of Paris' energy consumption for  
81 different types of energy carriers, but the analysis did not consider related indirect emissions. Chen and  
82 Zhu (2019) distinguished local, domestic and foreign origins of Beijing's carbon footprint, but at  
83 aggregated sectoral levels, preventing thus from analyzing differences and possible trade-offs between  
84 energy supply chains. A finer decomposition of supply chains across scales by type of flows is therefore  
85 necessary to have a complete picture of the transition's consequences (Boyer and Ramaswami, 2017).

86 To this end, the objective of this paper is to perform a multiscale analysis of urban outsourcing and  
87 discuss its implications within the frame of transition policies. This study takes advantage of combining  
88 spatial imprint analysis with indirect flows estimations in order to provide a decomposition of flows'  
89 origins and impact across scales. The energy metabolism of a harbor-industrial area, the Saint-Nazaire  
90 agglomeration in France, is chosen as a case study. A previous work of the authors addressed the political  
91 perspective of urban outsourcing, by identifying the nature of the power relationships between Saint-  
92 Nazaire and its energy-supplying hinterlands (Bahers et al., 2020). Nevertheless, it used aggregated  
93 energy indicators, especially for indirect flows. Therefore, this work intends to broaden the quantitative  
94 part of the analysis by illustrating the need to use spatially-differentiated dependency and indirect flows  
95 indicators to better understand energy transition policies. At the end, the previous political framework  
96 and the quantitative approach to energy metabolisms presented in this work are complementary and  
97 should be used in parallel to allow a better contextualization of urban policies aiming at minimizing the  
98 negative effects of outsourcing.

99 The article is structured as follows. First, the method section will provide more information on the  
100 accounting approach, and its application in a multiscale context. The case study will be also briefly  
101 introduced. Then, the third section will present the quantitative results on external dependency and  
102 indirect energy flows associated with Saint-Nazaire's activities. The fourth section will discuss the

103 results in the light of energy transition policies. It will particularly stress insights brought by the  
104 multiscale analysis.

## 105 2. Methods

106 This section presents the extended territory-based approach applied in this study, which includes 1) a  
107 multiscale energy flow analysis (EFA) tracing flows trajectories back to their origins and 2) indirect  
108 energy flows estimations at the global, domestic and local scales. The Saint-Nazaire's case study is then  
109 detailed as wells as the data sources and main assumptions.

### 110 2.1. Methods for material and impact accounting at the city scale

111 Three main approaches exist to quantify urban metabolisms: territory-based, consumption-based and  
112 hybrid (trans-boundary) approaches (Athanasiadis et al., 2016; Chen et al., 2019). Territory-based  
113 approaches look into what comes in and out of the city, as well as what it produces and consumes (Huang  
114 et al., 2012). The most common method is material and energy flow analysis (MEFA), an accounting  
115 framework developed by a number of scientists and summarized by Eurostat (Eurostat, 2001). It uses  
116 local data, usually from different sources reporting direct emissions and resources consumption  
117 occurring within the city's boundaries. Consumption-based approaches rely most of the time on national  
118 or multi-region input-output (IO) tables, that approximate urban consumption as physical flows  
119 imported and exported at the global and/or domestic levels (Athanasiadis et al., 2016). Consumption-  
120 based modeling does not require collection of emissions data but assumes an emission intensity for  
121 imported products to estimate indirect emissions. While more comprehensive, this modeling using IO  
122 tables often lack in geographical resolution at the city scale (Baynes and Wiedmann, 2012). Expenditure  
123 data for all economic sectors are indeed not always publicly available at the level of metropolitan  
124 statistical areas (Ramaswami et al., 2008). Moreover, the imported products cannot be traced back to  
125 their origins (Chen et al., 2019), even though this particular issue has been solved at the national level  
126 by combining multi-region IO tables with ecological network analysis (Zheng et al., 2018).

127 In this study, a hybrid approach which combines the accuracy of local consumption, the level of details  
128 of a material flows analysis with the comprehensiveness of life cycle-based embodied assessment is  
129 used. In carbon accounting literature, which is the most prolific on this issue, this approach is referred  
130 to as trans-boundary infrastructure, community infrastructure-based or geographic-plus infrastructure  
131 footprint since it accounts for territorial emissions plus indirect emissions of key infrastructures and  
132 food provision (Chen et al., 2019). Trade balance of non-infrastructure emissions (e.g services) are not  
133 considered, which is the main difference with the consumption-based approach (Chavez and  
134 Ramaswami, 2013; Minx et al., 2013). In a more general context of material and impact footprint  
135 analysis, hybrid approaches can refer to any methodology based on a territorial MEFA combined with  
136 either multi-region IO tables, environmentally-extended or not depending on the indicator assessed (J.  
137 Lin et al., 2013; Lin et al., 2015; Liu and Müller, 2013) or life cycle indicators (e.g. emissions intensity

138 or impact factors) to account for upstream stages of the supply chains (Dittrich et al., 2012; Hillman and  
 139 Ramaswami, 2010; Kennedy et al., 2009; Mancini et al., 2015; Ramaswami et al., 2008).

140 Since hybrid is a rather generic term, extended territory-based approach will be used in the rest of the  
 141 document. Owing to the aggregated-related nature of IO tables, extended territory-based approaches  
 142 with life cycle indicators are particularly relevant when indirect flows associated with extraction and  
 143 transformation are diverse between different types of flows (Dittrich et al., 2012), which is the case for  
 144 energy carriers. However, limitations of the method are its labor-intensive process and the collection of  
 145 data from various sources that can compromise results' reliability (Chen et al., 2019). In this work, an  
 146 accounting method based on the use of life cycle indicators is performed and further detailed in the next  
 147 sub-section.

148 **2.2. Multiscale extended territory-based accounting method**

149 The extended territory-based accounting method used in this study presents two key characteristics: it  
 150 is adapted to fit a multiscale energy analysis and it accounts for two indirect energy flows related to  
 151 urban consumption, i.e. embodied energy consumption and energy losses. The first step consists in carry  
 152 out a multiscale energy flow analysis (EFA). EFA derives directly from the MEFA method, by  
 153 accounting only for technology energy (fossil fuels and renewable energy). Table 1 presents an overview  
 154 of common EFA indicators. Imports and exports indicators are divided into domestic and global  
 155 categories to highlight the proximity (or lack thereof) between the urban area and its hinterland. The  
 156 total final energy consumption (TFEC) indicator is linked with its related indirect energy flows, i.e.  
 157 embodied energy consumption and energy losses, that are generated at various spatial levels.

158 Table 1: Common Energy Flow Accounting (EFA) indicators and adaptation in case of a spatialization.  
 159 Adapted from (Kim and Barles, 2012).

Common EFA indicators	Definition	Multiscale EFA in this work
Domestic extraction to processing	Primary energy extracted within the geographical boundaries of the system and entering the economy to be processed inside the territory	-
Domestic extraction to exports	Primary energy extracted within the geographical boundaries of the system and entering the economy to be processed outside the territory	Global and domestic exports
Imports of processed energy	Final energy coming from another socioeconomic system	Global and domestic imports
Import of non-processed energy	Primary energy coming from another socioeconomic system	
Total final energy consumption (TFEC)	Energy delivered to final consumers	Global, domestic and local indirect energy flows
Exports of processed energy	Final energy that leaves the system to another economy	Global and domestic exports

Exports of non-processed energy	Primary energy that leaves the system to another economy	
---------------------------------	--	--

160

161 Primary and final energy are accounted separately. According to the International Energy Agency (IEA)  
 162 and the French statistics agency (INSEE) , final energy is the energy delivered to consumers in its final  
 163 form (e.g. motor gasoline) while primary energy is the energy available before any transformation occurs  
 164 (like crude oil, dry natural gas, solar energy etc.) (IEA, 2017; INSEE, 2020). But while primary energy  
 165 data in national statistics only account for primary energy imports and production, the EFA method  
 166 accounts also for primary energy embedded in final energy imports (Kim and Barles, 2012). Estimating  
 167 primary from final energy is performed with primary energy factors (PEF), which account for energy  
 168 losses due to inefficiencies in transformation and transportation processes (Wilby et al., 2014). The  
 169 factors used in this analysis are presented in Table A.1 in the appendices.

170 The second part of the analysis consists in estimating indirect energy flows related to the TFEC  
 171 indicator. Energy losses derive directly from the primary energy calculations, as explained by Eq. 1:

172 
$$L_i = \sum_n (EP_{ij} - EF_{ij}) = \sum_n (EF_{ij} * (PEF_{ij} - 1)) \quad (\text{Eq.1})$$

173 Where  $L_i$  are the energy losses (in Joules) associated to the energy carrier  $i$ ,  $EP_{ij}$  is the primary energy  
 174 consumption (in Joules) of energy carrier  $i$  coming from flow  $j$ ,  $EF_{ij}$  is the gross final energy consumption  
 175 (in Joules) of energy carrier  $i$  coming from flow  $j$  and  $PEF_{ij}$  the primary energy factor associated to the  
 176 transformation of flow  $j$  into flow  $i$ . These losses are traced back at the local, domestic and global scales  
 177 thanks to the information from the multiscale EFA.

178 Using Eq. 1, it is assumed that all the losses come from transformation processes (processing of raw  
 179 natural gas, conversion of gas or coal to electricity etc.) whereas losses occur also during transportation.  
 180 While this is clearly a limitation of the study, it is nuanced by the fact that energy transformation is  
 181 responsible for about 90% of the losses along the supply chains (Sims et al., 2007).

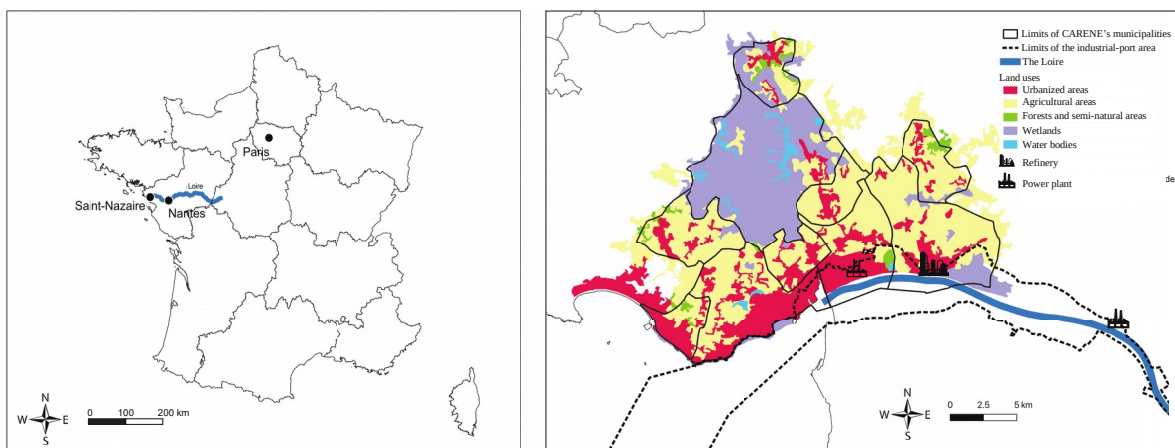
182 Indirect energy consumption refers to the energy used to produce the energy flows quantified in EFA  
 183 study. It is the energy consumed for crude oil processing, for example, or for the production of solar  
 184 panels. The embodied energy was obtained via the cumulative energy demand (CED) characterization  
 185 method developed by Frischknecht et al. (2015) and using the ecoinvent v.3.5 database. The database  
 186 contains more than 16000 interconnected processes of several economic sectors such as utilities,  
 187 construction, transportation, manufacturing, and mining, allowing thus to cover most processes of the  
 188 energy supply chains. The CED method differentiates between non-renewable (fossil and nuclear) and  
 189 renewable (biomass, solar, wind, geothermal, water) embodied energy. Only the non-renewable energy  
 190 factors were used. They are reported in Table A.1 in the appendices. It should be noted that data from



191 the ecoinvent database are considered generic, as most modelled supply chains (except electricity's) are  
192 not specific to the French case study, which induces uncertainties in the calculations.

### 193 2.3. Case study and data sources

194 The Saint-Nazaire metropolitan area, known as the Communauté d'Agglomération de la Région  
195 Nazairienne et de son Estuaire (CARENE), is composed of ten municipalities, located at the Loire  
196 river's mouth, on the French Atlantic coast. It is a heterogeneous territory in terms of land use and  
197 functionality. Figure 1 shows that the North and North-West are dominated by forests and semi-natural  
198 areas. The South and South-East, turned towards the ocean, are highly urbanized and industrialized.  
199 Saint-Nazaire is indeed an industrial-port area consisting in a complex network of highly energy-  
200 intensive industrial sites operating shipyards, steel, petrochemical and agri-fod activities (AXENNE,  
201 2016).



203 Figure 1 : Geographical location of the Saint-Nazaire metropolitan area in France (left side) and spatial  
204 distribution of its land uses (right side). The port zone is spreading across three municipalities, in the South-East  
205 of the territory. (single column)

206 Stretching over three municipalities (Saint-Nazaire, Montoir-de-Bretagne and Donges), the port zone is  
207 home to the 2<sup>nd</sup> largest crude oil refinery in France and to the largest methane terminal on the Atlantic  
208 coast (one of the three still operating in France) (DREAL, 2012). It provides about 12% of the France's  
209 petroleum products supply, 2% of its natural gas supply and, overall, 10% of the France's total energy  
210 supply (DROPEC, 2016). Therefore, this territory is a logistic hub for energy flows: in 2014, they  
211 represented about two third of the port's traffic, mainly petroleum products, natural gas and coal. This  
212 makes of the CARENE an interesting case for a multiscale energy metabolism study.

213 The EFA includes data from the residential, tertiary, industrial and transportation (road, rail and airline)  
214 sectors. They come from several local sources which are presented in Table 2 for each flow. In Table 2,  
215 most of data sources refer to how the quantities of flows were determined for the base year (2015),  
216 except for uranium, rapeseeds and wood imports for which the sources gave information on the origins

217 of the energy products. The total production of the refinery, estimated based on crude oil imports  
 218 provided by the Saint-Nazaire port authority as part of the OPTIMISME<sup>1</sup> research project, was divided  
 219 among the different petroleum products using an online public report from Total.

220

Table 2: Data sources per energy carrier used in this study

	Energy carriers	Sources	Data year	Type of processing
<b>Imports</b>	Natural gas	(Saint-Nazaire port authority, 2016)	2015	None
	Crude oil			
	Coal			
	Uranium (for nuclear electricity)	(RTE, 2016)	2015	None
	Refined petroleum products (heavy fuel oil, gasoline, diesel, kerosene, LPG)	(Saint-Nazaire port authority, 2016)	2015	None
	Rape seeds (for biodiesel)	(CARGILL, 2018; Saint-Nazaire port authority, 2016)	2015	None
	Biodiesel	(Saint-Nazaire port authority, 2016)	2015	None
	Wood	(ATLANBOIS, 2016)	2015	None
<b>Domestic extraction and production</b>	Solar (thermal and photovoltaic)	(ENEDIS, 2015)	2015	None
	Geothermal	(AXENNE, 2016)	2012	None
	Biogas			None
	Electricity from natural gas (power plant)			None
	Refined petroleum products (refinery)	(TOTAL, 2013) Shares of products in the total production	2013	None
	Biodiesel from rape oil	(AXENNE, 2016)	2012	None
<b>Total final energy consumption</b>	Electricity (nuclear, wind, coal)	(ENEDIS, 2015)	2015	None
	Heat (natural gas)	(GRDF, 2015)	2015	None
	Heat (heavy fuel oil, coal, wood, steam)	(AXENNE, 2016)	2012	Estimate for wood based on the increase in number of dwellings between 2012 and 2015
	Transportation (fossil fuels, electricity)	(BASEMIS, 2015)	2014	Estimate based on the 2015 regional consumption of fossil fuels for transportation
<b>Exports</b>	Municipal solid waste (incineration)	(AXENNE, 2016)	2012	None
	Natural gas	(Saint-Nazaire port authority, 2016)	2015	None
	Refined petroleum products			
	Biofuels			

<sup>1</sup> The OPTIMISME research project (2016-2018) gathered CARENE's local authorities, professionals from the energy sector, industrials and researchers to develop appropriate tools to plan energy transition on the territory.

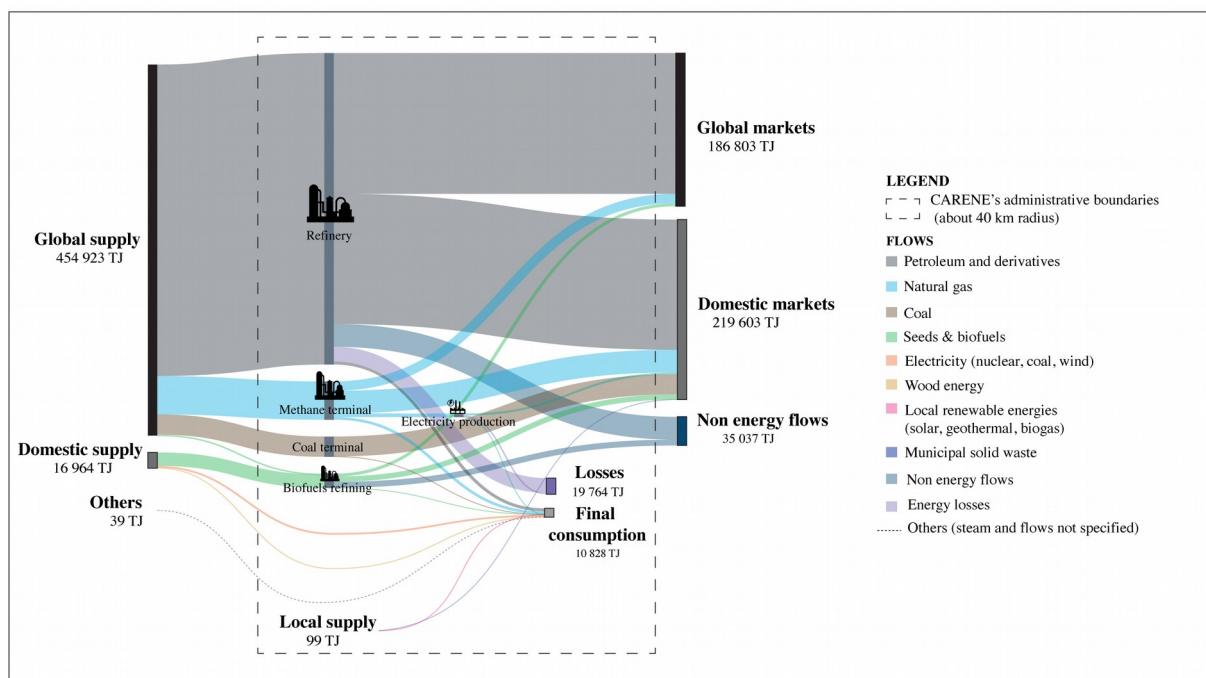
221 As shown in Table 2, some data are older than 2015, such as the power plant's and biodiesel productions  
222 (2012), the geothermal, biogas, wood, coal and fuel oil consumptions (2012) and the data from the  
223 BASEMIS® database (2014). As much as possible, assumptions were made to adjust these  
224 consumptions to the base year. For example, residential wood energy consumption was adjusted, taking  
225 as the adjustment variable the number of new dwellings built between 2012 and 2015. The consumption  
226 of petroleum products supplied by BASEMIS® was adapted to 2015 taking into account the 2014-2015  
227 evolution of regional consumption of petrol and diesel for cars, light- and heavy-duty trucks. However,  
228 the evolution of data related to industrial activities (energy production, coal and fuel oil consumptions)  
229 depends on external variables related to fluctuations in domestic and global economic markets.  
230 Therefore, it was not possible to derive a reliable approximate for 2015 and the values were not changed.  
231 From interviews with municipal stakeholders in the frame of the OPTIMISME project, geothermal and  
232 biogas consumptions did not evolve much between 2012 and 2015 and considering their low shares in  
233 the total territorial consumption, it was decided not to change them. Another important assumption is  
234 linked to the refinery's production. Indeed, it was impossible to determine with certainty what share of  
235 the petroleum products' consumption came from the refinery's production, and what share was imported.  
236 Therefore, it was assumed that the "domestic production/imports" breakdown for final consumption in  
237 the territory was the same as the one for direct energy inputs, which was considered reasonable given  
238 the black box nature of the refinery. Due to the lack of metadata for most sources, a calculation of  
239 uncertainties was not possible.

## 240 3. Results

241

### 242 3.1. External dependency of the CARENE's energy metabolism

243 Results obtained from the spatial analysis of the CARENE's energy metabolism are presented on Figure  
244 2. Figure 2 shows energy flows according to their type, their origin and destination markets. In particular,  
245 the global, domestic and local levels are distinguished. The figure includes also energy losses resulting  
246 from primary energy transformation and non-energy flows considered as co-products such as rapeseed  
247 cakes and petrochemicals from the refinery.



248

249 Figure 2: The CARENE's energy metabolism per type of energy flow in 2015. The dashed line represents the  
 250 territory's boundaries. (1.5 column)

251 The CARENE's energy metabolism is characterized by global transit flows, i.e. foreign imported flows  
 252 that go through the CARENE but whose final destinations are outside of its boundaries. Transit flows  
 253 are quite common for port areas, but the types of flows that transit depend on the specificity of each port  
 254 (Rosado et al., 2016; Voskamp et al., 2017). In the CARENE's case, fossil fuels dominate widely in the  
 255 form of petroleum and derivatives, natural gas and coal. It is worth noting that processing activities  
 256 related to fossil fuels generates energy losses in the same order of magnitude than the territory's own  
 257 energy consumption, reflecting thus the energy-intensive industrial activities of the area.

258 Two types of transit flows can be distinguished in Figure 2. Some are pure crossing flows and they are  
 259 sometimes also called throughput flows (Voskamp et al., 2017). They do not undergo any transformation  
 260 on the territory beside being transported. It is the case for imported petroleum products that transit  
 261 through the refinery to domestic markets (62.6 PJ), for natural gas either transhipped from the methane  
 262 terminal to other boats (11.5 PJ) or injected in the French distribution network (27.6 PJ), and for the  
 263 coal transferred directly to the coal power plant located 30 km away from the Port (24.3 PJ). The second  
 264 type of transit flows are processed on the territory to obtain different types of products or energy. Crude  
 265 oil processed in the refinery to supply the northern parts of France from the West to the East and abroad  
 266 is the main source of energy-related activities locally (269 PJ). Electricity obtained from the gas power  
 267 plant is also a significant flow (2.5 PJ) even though this activity is more seasonal, to meet national peak  
 268 energy demands during winter.

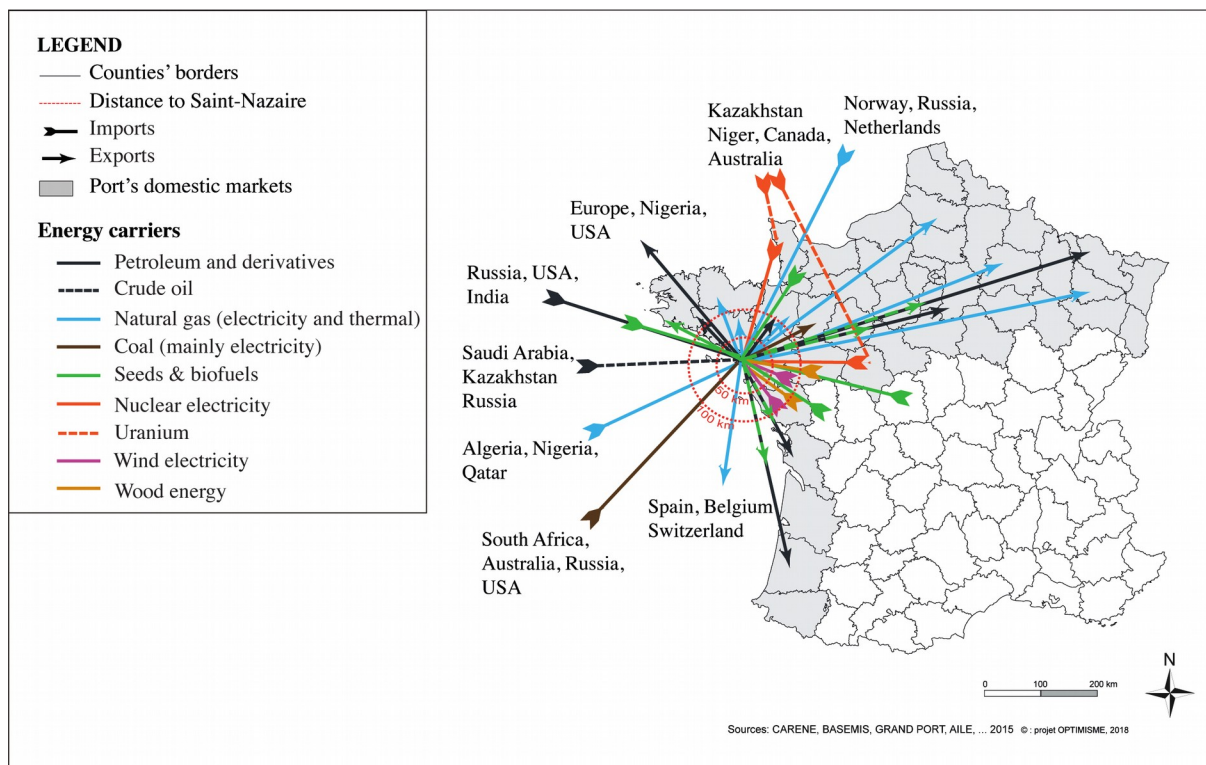
269 Excluding crossing flows, the extent of the metabolism's dependency on resource-supplying hinterlands  
 270 is reported in Table 3. Up to 96% of the total energy supply come from global sources, mainly due to  
 271 the refinery's activities. Local supply is almost inexistent and currently driven by the gas-fired power  
 272 plant's production. An interesting finding is the composition of the domestic supply, even though it  
 273 accounts for less than 5% of the total supply. Indeed, results show that most of the renewable energy  
 274 consumption is currently imported from neighbouring regions and not produced in the CARENE.

275 Table 3: External dependency rates for the CARENE's energy metabolism

	Global (without crossing flows)	Domestic	Local
CARENE's dependency	96%	4%	≈ 0.05%
Weight of energy carriers on the dependency in the respective scale			
Petroleum and derivatives	99.8%	-	-
Natural gas	< 0.01%	-	-
Coal	0.1%	-	-
Electricity (NR)	-	19%	83%
Seeds & biofuels	0.1%	78%	-
Wood energy	-	2%	-
Wind electricity	-	1%	-
Solar electricity	-	-	11%
Other renewables (geothermal, biogas)	-	-	6%

276

277 Figure 3 offers a more precise picture of supply distances at the domestic level. It shows that, on the  
 278 contrary of fossil fuels which come all from global trade, renewable energy carriers present a nuanced  
 279 picture. Biofuels' traffic tends to follow petroleum products, even though their hinterlands are mostly  
 280 domestic instead of foreign. Their production comes from rapeseeds (17.2 PJ), 82% of which are  
 281 imported from farms in western and central France (within a radius of about 400 km), the rest coming  
 282 from global sources. But this supply can be up to four times as distant as for other renewable energy  
 283 carriers, like wind (100 km) and wood (150 km). Only a neglectable fraction of renewable supply (solar,  
 284 geothermal, biogas) can be considered local (< 40 km).



285

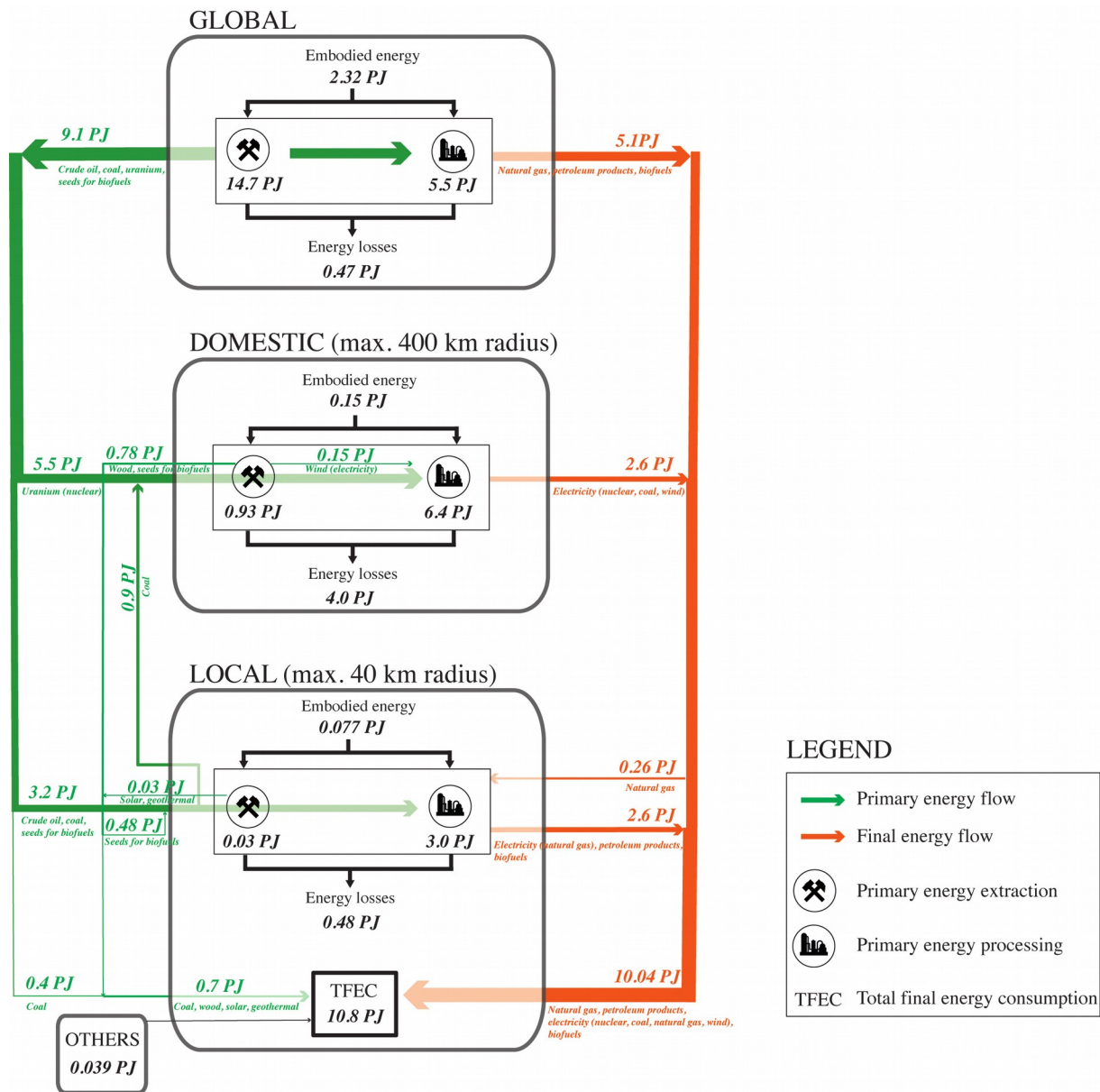
286 Figure 3: Energy supply areas and destinations markets by energy carrier (2015) (single column)

### 287 3.2. Indirect energy flows

288 Figure 4 presents the distribution across scales of indirect flows related to the CARENE's final energy  
 289 consumption. As shown on the Figure, the primary energy supply amounts to a total of 15.7 PJ to be  
 290 compared with the total final energy consumption (TFEC), which is 10.8 PJ. This means that 4.9 PJ of  
 291 energy (45% of the TFEC) are lost along the supply chains owing to processing and transformation  
 292 processes. While 94% of this primary energy come from foreign sources, reflecting the dependency  
 293 illustrated in the last section, these losses occur mostly within the reach of French public authorities.  
 294 This is explained by the structure of electricity production in France, which revolves around centralized  
 295 nuclear power plants, of great capacity but which are also highly inefficient.

296 On the contrary, extraction and processing activities related to thermal heat flows (petroleum products,  
 297 natural gas and coal) can be described as more energy efficient. Figure 3 shows that energy losses at the  
 298 global and local scales, where all extraction and processing occur, is neglectable in comparison with  
 299 electricity production. However, the amount of energy required to perform these activities, i.e. their  
 300 embodied energy, is higher (per PJ produced) and mostly external to France. Results indicate that  
 301 resources extraction, crude oil refining and natural gas processing occurring in foreign countries  
 302 represent 91% of the embodied energy due to CARENE's TFEC, which amounts to 2.55 PJ (24% of the  
 303 TFEC). From a different perspective, only 3% of the total amount of embodied energy is found at the  
 304 local scale and 6% is domestic. Therefore, on the contrary of energy losses, embodied energy of supply  
 305 chains is definitely a global challenge for cities, like it is for embodied carbon emissions (Chen and Zhu,

2019; Wiedmann et al., 2016) and embodied land use (Steen-Olsen et al., 2012) . This can only be resolved either through policies targeting footprint of upstream activities or with flows' substitution at the local level, through industrial symbiosis for example. This particular case will be discussed further in the section 4.2.



310

311 Figure 4: Multiscale analysis of indirect energy flows along the supply chains of CARENE's final energy  
312 consumption (double column)

313

### 314 3.3. Comparison with previous studies

315 Material and energy flow analysis has been applied to many cities and metropolitan areas over the last  
316 two decades. Studies have been conducted on large cities, such as Paris (Barles, 2009; Kim and Barles,  
317 2012), Stockholm (Rosado et al., 2016) and Singapore (Schulz, 2007), intermediate cities like Rennes

318 and Le Mans in France (Bahers et al., 2018) and metropolitan areas like the Brussels Capital Region  
 319 (Athanassiadis et al., 2016) and Los Angeles county (Ngo and Pataki, 2008). The metabolic profiles of  
 320 several port-cities have also been analyzed including Amsterdam (Voskamp et al., 2017), Hamburg  
 321 (Hammer et al., 2003), Gothenburg (Rosado et al., 2016) and Lisbon (Rosado et al., 2014).

322 Table 4 summarizes the results of some of them according to indicators relevant to this study. Case  
 323 studies for the comparative analysis were selected based on data availability. In particular, the  
 324 comparison with the CARENE is performed on imports and domestic extraction related to fossil fuels  
 325 and renewable energies. Based on the aforementioned indicators, energy dependency to external  
 326 hinterlands is estimated for each city. Finally, indirect flows are reported when possible, even though  
 327 data on these indicators are scarce among MEFA studies. It should be noted that these results were  
 328 obtained using different methodologies, especially for the Brussels Capital Region for which embodied  
 329 energy of the area's energy use was estimated using a territory-based approach with IO tables  
 330 (Athanassiadis et al., 2016).

331 **Table 4: Indicators related to energy flows for different case studies**

	CARENE (2015)	Amsterdam (2012)	Gothenburg (2011)	Stockholm (2011)	Paris (2003)	Brussels Capital Region (2007)
Fossil fuels imports* (TJ/cap)	2.7	0.51	0.47	0.06	0.08	0.06
Renewable energy imports (TJ/cap)	0.15	0	Unknown	Unknown	Unknown	0.001
Industrial production (fossil fuels) (TJ/cap)	2.6	Unknown	0.33	0.07	0	0.003
Renewable energy production (TJ/cap)	0.0026	0.0043	Unknown	Unknown	Unknown	0.0028
Energy dependency	100%	99%	97%	85%	Unknown	95%
Losses (TJ/TJ TFEC)	0.46	Unknown	Unknown	Unknown	0.72	Unknown
Embodied energy (TJ/TJ TFEC)	0.24	Unknown	Unknown	Unknown	Unknown	2

332  
 333 The Saint-Nazaire port imports five to six times more fossil fuels per capita than Amsterdam and  
 334 Gothenburg, reflecting the energy-related nature of its industrial base, dominated by infrastructure  
 335 specialized in the processing of energy flows (refinery, methane terminal, power plant). This appears



336 also through the industrial production indicator, which is eight times higher than for Gothenburg.  
337 Renewable energy production on the other hand is far less developed than in the other case studies,  
338 including an industrial port-city like Amsterdam. Nevertheless, energy dependency to external  
339 hinterlands is similarly high between ports, which is expected due to their heavy reliance on fossil fuels  
340 for industrial activities. Stockholm and the Brussels Capital Region are slightly less energy dependent,  
341 even though the case of Brussels is close to Gothenburg's. The Brussels Capital Region imports indeed  
342 a significant part of its renewable energy consumption.

343 Finally, indirect energy flows could only be compared with Paris and Brussels due to a lack of accessible  
344 information. In particular, energy losses related to the Parisian energy use are 1.6 times higher than for  
345 the CARENE. This is quite consistent with the energy consumption profile of both areas presented in  
346 Table B.1 in the appendices, where Paris consumes more electricity coming from the national grid,  
347 hence more losses during transformation processes. Embodied energy related to energy use was found  
348 higher for the Brussels Capital Region. The comparison should be carried out carefully however due to  
349 different methodological choices mentioned previously. Embodied energy accounted in the Brussels'  
350 MEFA is more comprehensive because IO tables were used. The difference between the two values  
351 illustrates to some extent how embodied energy calculated in this work is probably underestimated.

## 352 4. Discussion

353 The current international energy context, which relies heavily on fossil fuels trade, favors dependency  
354 on remote hinterlands and high levels of embodied energy for industrialized cities like Saint-Nazaire. In  
355 a sense, the CARENE's energy metabolism is still a perfect representation of the past energy transition's  
356 outcome, that has led to the extension and centralization of the French national energy system (Kim and  
357 Barles, 2012). The current energy transition implies a spatial reorganization of this system, by proposing  
358 a diversification of primary energy sources. But the issues of dependency and indirect flows still remain.  
359 While alternative energy sources are not quite visible in the CARENE's metabolism yet, distinguishing  
360 different types of fossil and renewable energy flows helped to see the trends on how energy transition  
361 may spatially unfold for the territory. Some of the implications for dependency and indirect flows are  
362 discussed in this section.

### 363 4.1. Dependency of port-cities in a transition context

364 Port-cities are particularly threatened by the dependency to remote hinterlands since a significant part  
365 of their activities and revenues rely on foreign transit flows, whether they are just crossing the territory  
366 or processed and then exported. For example, a MFA study of Lisbon showed that crossing flows  
367 accounted for about 34% of all material and energy inputs (Rosado et al., 2014). In Amsterdam, they  
368 represented 37% of the inputs for the year 2012 in average, but with a high heterogeneity depending on  
369 the types of flows considered (Voskamp et al., 2017). In the case of fossil fuels, 77% of the imports

370 were just crossing while this share lowered to 30% for chemical products, suggesting that the  
371 Amsterdam's port is primarily an intermediary logistic hub for energy flows. In comparison, the  
372 CARENE's share of crossing flows is rather quite low (28% of the energy imports), while transit flows  
373 that are processed within the area such as crude oil and natural gas constitute 58% of the inputs. These  
374 results show that Saint-Nazaire's port is more than a logistic hub and that its dependency to foreign  
375 hinterlands is closely linked to its core productive system. In order to reduce this dependence, it will be  
376 necessary to radically modify the economic model, along the lines of the transition started by some ports  
377 in Europe and Asia (Cerceau et al., 2014; Mat et al., 2016). A key strategy of this endeavour, albeit not  
378 the only one, is substituting fossil fuels processing with renewable energy production (Mat et al., 2016).

379 This particular strategy appears fundamental to ensure the resilience of the CARENE area (both for the  
380 port and the urban part) since results show that only 8% of the current renewable energy consumption  
381 are locally produced. Nowadays, without any renewable production from the port, most of the renewable  
382 energy supply comes from neighbouring regions (77%), at the domestic level, suggesting that where  
383 renewable energy is concerned, dependency has not disappeared but has merely shifted scale. It will  
384 likely remain so as local energy autonomy is almost impossible to achieve for cities (Barles, 2019) and  
385 port areas have always been historically connected to their surrounding environment, even before their  
386 past transitions that led to globalization (Mat et al., 2016). Nevertheless, this relocation of energy supply  
387 and dependency does induce reinforced relationships between cities or regions that did not exist before  
388 and which must be identified. Some can lead to synergies and cooperation between a primary energy  
389 producer and a consumptive territory, e.g. wood supply from rural areas to cities. On the contrary, other  
390 cases can create conflictual power relations and competitions that may hamper the feasibility and  
391 sustainability of any energy transition plan (Bahers et al., 2020; Haberl et al., 2019). In the case of the  
392 CARENE, the conversion of the Cordemais' coal-fired power plant to a plant of a same size using  
393 combustion of green waste collected 200 km away is part of the national strategy to keep the  
394 infrastructure in place while finding alternative solutions. However, interviews with other energy  
395 producers, associations and local authorities highlighted that this decision threatens resources  
396 availability in the region, which may result in an actual decrease in the number of transition projects that  
397 could have been carried out by other stakeholders (Tanguy, 2019)

398 A multiscale analysis per type of energy flow helps to single out problematic energy carriers and the  
399 associated stakeholders by highlighting dependency issues. For example, in the CARENE's case, wood  
400 and biodiesel from rapeseed oil are to be watched closely. Wood is not indeed a resource that exists  
401 within the territory's boundaries, whereas it has a high substitution potential for residential natural gas  
402 use through district heating networks for example (AXENNE, 2016). Competitions for this resource  
403 may arise with other cities if such networks were to become more popular. This indicates that a regional  
404 coordination is required at the minimum for this resource. The biodiesel produced in Saint-Nazaire is  
405 already well integrated in the global and domestic markets, like its fossil counterparts. The risk to attract

406 important and distant agricultural resources that may compete with other needs, like food, is therefore  
407 high. A relevant complementary solution, which is already considered by the Saint-Nazaire's port  
408 authority and should be further investigated, is third-generation biofuels produced from microalgae  
409 (Ahmad et al., 2011).

#### 410 **4.2. Implications of a energy transition policy regarding indirect energy flows**

411 Results showed that accounting for indirect energy flows increased the CARENE's energy consumption  
412 by about 70% . This means that for every MJ consumed within the area, 0.7 MJ must be added in average  
413 to complete the quantitative energy balance. However, from a policy perspective, these additional 0.7  
414 MJ are not homogeneous in type and space. Embodied energy (0.24 MJ) contributes to the  
415 environmental rucksack of the city whereas energy losses (0.46 MJ) are energy waste, or excess heat,  
416 for the most part. It would be favorable if both were reduced but the second one can be recovered  
417 theoretically, through industrial or urban heating networks and thus be part of a local or national energy  
418 transition strategy. Therefore, managing indirect energy flows encompasses different types of policies  
419 and does not mean much if the flow type is not specified.

420 A noteworthy example of one policy that could potentially affect positively both types of indirect flows  
421 is the development of the aforementioned district/industrial heating networks. Such infrastructures are  
422 put at the forefront of energy transition in France by the law Transition Énergétique pour une Croissance  
423 Verte. This law sets the objective of a fivefold increase, by 2030, in the amount of heat from renewable  
424 and secondary sources distributed by heating networks (France Loi n°2015-992, 2015). A number of  
425 secondary sources are possible, including heat from incinerators, data centers and, which is of interest  
426 here, from industrial activities. Just taking the CARENE's example, a heating network is being  
427 investigated within the port zone to deliver heat generated from industrial processes, which is currently  
428 released to the atmosphere, to industries and residents for their heating needs (GPMSN, 2014). This  
429 solution addresses a priori the generation of both energy losses and embodied energy: it finds a use for  
430 the losses and allows displacing a roughly equivalent amount of natural gas (in the CARENE's case).

431 However, one could wonder on the consequences of this decision further up the supply chain. Indeed,  
432 excess heat (energy losses) comes from thermal industrial processes relying on natural gas to operate.  
433 Building a fraction of the city's energy supply from excess heat may thus reinforce at the same time the  
434 use of natural gas to operate processes delivering this energy, which will just partly decrease the  
435 dependency on this resource. In the specific case of natural gas, it could even hamper efforts in reducing  
436 a major part of embodied energy consumed in foreign countries. Figure C.1 in the appendices shows for  
437 example that embodied energy associated with natural gas use constitutes the main source of embodied  
438 energy at the global scale.

439 Future research involving comparison of different scenarios of excess heat integration in the territory's  
440 energy mix, with the calculations of related indirect flows, should be carried out to confirm this trend.  
441 While the conclusion drawn from this result should not discourage the implementation of excess heat  
442 recovery altogether, it certainly points out a limitation of this solution in the long-term objective of  
443 decreasing the territory's dependency and embodied energy. It is part of the debate between advocates  
444 of a "weak" and a "strong" energy transition (Duruiseau, 2014), the latter arguing, among other things,  
445 that punctual substitutions of fossil fuels, e.g. with excess heat, cannot be sufficient to allow the systems  
446 to remain and that only a major transformation of sociotechnical configurations is desirable (Raineau,  
447 2011). Results obtained on the CARENE's metabolism tend to confirm that a radical change is indeed  
448 needed, and that projects including primary renewable energies such as wood, third-generation biofuels  
449 and solar energy, should be primarily investigated.

450

## 451 5. Conclusions

452 The objective of this work is to comprehensively address outsourcing issues in order to enhance their  
453 integration in urban metabolism studies. It contributes to the growing efforts in urban metabolism  
454 research to develop spatial approaches for flows' accounting, with the ultimate goal of better  
455 contextualizing urban policies' consequences at different scales (Athanasiadis et al., 2015; Bahers et  
456 al., 2018; Guibrinet et al., 2016; Huang et al., 2018). In this paper, a multiscale extended territory-based  
457 approach was developed, looking at both the dependency on external hinterlands and the generation of  
458 external hidden flows (embodied consumption and energy losses) due the city's demand in resources.

459 This approach was applied to the energy metabolism of the CARENE, a harbor-industrial area in France.  
460 Local sources accounted for less than 0.1% of the territory's energy inputs, domestic and global scales  
461 representing 4% and 96% of the supply respectively. More than pure transit activities, local refining of  
462 crude oil was found to drive this dependency on foreign hinterlands, suggesting that substituting fossil  
463 fuels processing with renewable energy production is a key strategy to ensure the resilience of the area,  
464 both from the port's and the city's perspective. However, results highlight that an energy transition with  
465 more low-carbon energy sources (wood, wind electricity, biofuels) will not necessarily reduce external  
466 dependency, but merely changes its scale from foreign to domestic. On the contrary of fossil fuels,  
467 supply of domestic renewable energy sources tends to present a nuanced picture, with varying supply  
468 distances among energy carriers, that ultimately influence at which scale the transition should be planned  
469 for each resource.

470 Analyses of indirect energy flows drew attention on natural gas and electricity's consumptions, main  
471 drivers of the supply chains' embodied energy and energy losses respectively. They put into perspective  
472 one transition policy in particular, which is the industrial excess heat recovery to feed industrial or

473 district heating networks. Results suggest that, when the excess heat comes from natural gas, a trade-off  
 474 exists between reducing the amount of embodied energy in foreign countries and using this local  
 475 resource. While the conclusion drawn from this result should not discourage the implementation of  
 476 excess heat recovery altogether, it certainly points out a limitation of this solution in the long-term  
 477 objective of decreasing the territory's dependency and external embodied energy.

478 Future work is needed to go further into assessing the external consequences of energy policies across  
 479 scales. For example, the multiscale approach presented in this paper could be used to carry out detailed  
 480 scenario analyses of different energy transition policies in order to get a more comprehensive picture of  
 481 the trade-offs outlined in this study, similar to what was done for food systems by Boyer and Ramaswami  
 482 (2017). Recommendations for new policies should indeed consider the possible transfer of negative  
 483 effects across scales and supply chains in order to formulate truly sustainable actions.

## 484 6. Appendices

### 485 6.1. Appendice A

486  
 487 Table A.1 presents the primary energy factors cumulative energy demand (CED) factors for several  
 488 energy carriers. Following the IEA methodology on primary energy calculations (IEA, 2017), solar and  
 489 wind become energy products at the point of electricity generation, which means the efficiency of solar  
 490 and wind electricity production is not considered. CED factors for final energy carriers exclude CED  
 491 factors of the corresponding primary energy carriers indicated in Table A.1.

492 Table A.1: Primary energy factors and non-renewable cumulative demand energy (CED) factors for several energy carriers

Energy carrier	Primary energy factors (MJ primary energy/MJ final energy) (Sims et al., 2007; Wilby et al., 2014).	Non-renewable CED factors (MJ/MJ of energy carrier) (Frischknecht et al., 2015)
Primary energy		
Coal	-	0.013
Crude oil	-	0.044
Uranium	-	0.0077
Geothermal	-	0.28
Rapeseeds	-	0.39
Wood energy	-	0.02
Final energy		
Biodiesel	1.7	0.11
Electricity (coal/gas/nuclear)	3 / 1.7 / 3	0.002 / 0.01 / 0.0001
Natural gas (processed)	1.08	0.53

Petroleum products	1.06	0.014
Solar (photovoltaic)	1	0.28
Wind (electricity)	1	0.08

493

494 **6.2. Appendice B**

495 Table B.1 presents the part of each primary energy source in the total energy requirements of Paris and  
 496 the CARENE. The total energy requirements includes primary energy consumption and embodied  
 497 energy flows. Indirect flows encompasses here primary energy losses and embodied energy.

498 Table B.1: Share of primary energy sources in the total energy requirements of Paris and the CARENE

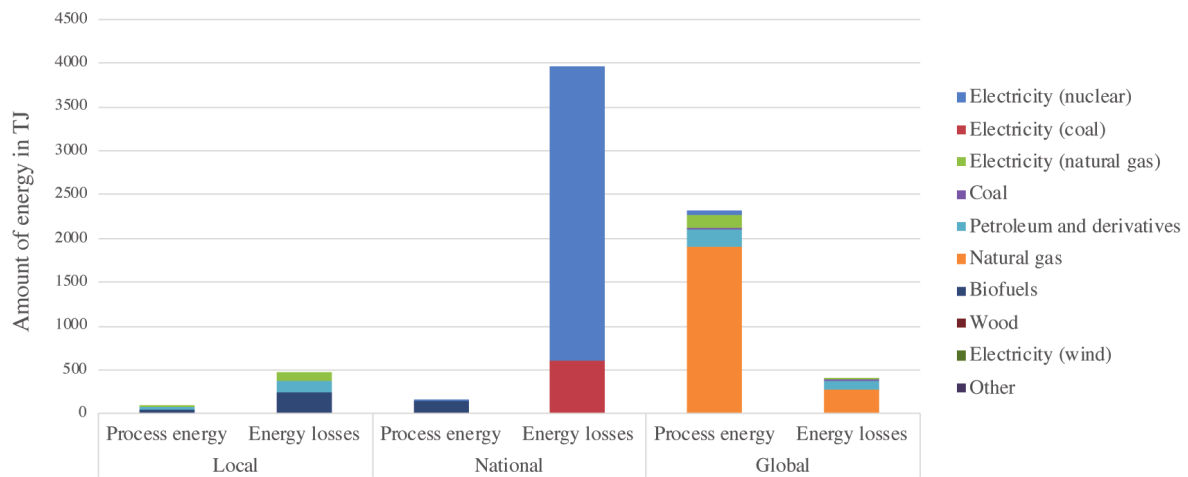
	Paris (2006) from Kim & Barles (2012)	CARENE (2015)
Primary energy sources	Shares in the total energy requirements (%)	
Nuclear	44	31
Petroleum	19	23
Natural gas	24	33
Coal	5	8
Biofuels	-	2
Wind	-	1
Wood	0	2
Other renewables	2 (hydraulic)	≈ 0 (solar, geothermal, biogas)
Others	6	1

499

500 **6.3. Appendice C**

501 Figure C.1 presents the distribution of indirect flows related to the CARENE's energy use across spatial  
 502 scales. Natural gas extraction and processing are the main sources of embodied energy, while the  
 503 conversion of nuclear energy to electricity causes the most energy losses.

504



505

506 Figure C.1 : Amount of embodied energy and energy losses related to final consumption per scale and energy  
 507 carrier

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## 513 8. References

514 Ahmad, A.L., Yasin, N.H.M., Derek, C.J.C., Lim, J.K., 2011. Microalgae as a sustainable energy  
 515 source for biodiesel production: A review. *Renew. Sustain. Energy Rev.* 15, 584–593.  
 516 <https://doi.org/https://doi.org/10.1016/j.rser.2010.09.018>

517 Athanassiadis, A., Christis, M., Bouillard, P., Vercauteren, A., Crawford, R.H., Khan, A.Z., 2016.  
 518 Comparing a territorial-based and a consumption-based approach to assess the local and global  
 519 environmental performance of cities. *J. Clean. Prod.* 173, 112–123.  
 520 <https://doi.org/10.1016/j.jclepro.2016.10.068>

521 Athanassiadis, A., Crawford, R.H., Bouillard, P., 2015. Overcoming the “black box” approach of  
 522 urban metabolism 547–556.

523 ATLANBOIS, 2016. Principales données de la filière bois en Pays de la Loire.

524 AXENNE, 2016. Stratégie de développement des énergies renouvelables sur le territoire de la  
 525 CARENE (Strategy for the development of renewable energies on Saint-Nazaire metropolitan  
 526 area).

527 Bahers, J.-B., Barles, S., Durand, M., 2018. Urban Metabolism of Intermediate Cities: The Material  
 528 Flow Analysis, Hinterlands and the Logistics-Hub Function of Rennes and Le Mans (France). *J.*  
 529 *Ind. Ecol.* 0. <https://doi.org/10.1111/jiec.12778>

530 Bahers, J.-B., Tanguy, A., Pincetl, S., 2020. Metabolic relationships between cities and hinterland: a  
 531 political-industrial ecology of energy metabolism of Saint-Nazaire metropolitan and port area  
 532 (France). *Ecol. Econ.* 167, 106447.  
 533 <https://doi.org/https://doi.org/10.1016/j.ecolecon.2019.106447>

- 534 Balta-Ozkan, N., Watson, T., Mocca, E., 2015. Spatially uneven development and low carbon  
535 transitions: Insights from urban and regional planning. *Energy Policy* 85, 500–510.  
536 <https://doi.org/https://doi.org/10.1016/j.enpol.2015.05.013>
- 537 Barles, S., 2019. L'autonomie métabolique urbaine, un oxymore, une gageure?, in: Lopez, F.,  
538 Pellegrino, M., Coutard, O. (Eds.), *Les Territoires de l'autonomie Énergétique: Espaces, Échelles*  
539 *et Politiques*. ISTE Editions Ltd, London.
- 540 Barles, S., 2009. Urban metabolism of Paris and its region. *J. Ind. Ecol.* 13, 898–913.  
541 <https://doi.org/10.1111/j.1530-9290.2009.00169.x>
- 542 Barles, S., Knoll, M., 2019. Long-term transitions, urban imprint and the construction of hinterlands,  
543 in: Soens, T., Schott, D., Toyka-Seid, M., De Munck, B. (Eds.), *Urbanizing Nature: Actors and*  
544 *Agencies (Dis)Connecting Cities and Nature since 1500*. Routledge, New York.
- 545 BASEMIS, 2015. Regional database of energy consumption and greenhouse gas emissions from Air  
546 Pays de la Loire.
- 547 Baynes, T.M., Wiedmann, T., 2012. General approaches for assessing urban environmental  
548 sustainability. *Curr. Opin. Environ. Sustain.* 4, 458–464.  
549 <https://doi.org/https://doi.org/10.1016/j.cosust.2012.09.003>
- 550 Billen, G., Barles, S., Garnier, J., Rouillard, J., Benoit, P., 2009. The food-print of Paris: long-term  
551 reconstruction of the nitrogen flows imported into the city from its rural hinterland. *Reg.*  
552 *Environ. Chang.* 9, 13–24. <https://doi.org/10.1007/s10113-008-0051-y>
- 553 Boyer, D., Ramaswami, A., 2017. What Is the Contribution of City-Scale Actions to the Overall Food  
554 System's Environmental Impacts?: Assessing Water, Greenhouse Gas, and Land Impacts of  
555 Future Urban Food Scenarios. *Environ. Sci. Technol.* 51, 12035–12045.  
556 <https://doi.org/10.1021/acs.est.7b03176>
- 557 Bridge, G., Bouzarovski, S., Bradshaw, M., Eyre, N., 2013. Geographies of energy transition: Space,  
558 place and the low-carbon economy. *Energy Policy* 53, 331–340.  
559 <https://doi.org/10.1016/J.ENPOL.2012.10.066>
- 560 CARGILL, 2018. Montoir-de-Bretagne [WWW Document]. URL [https://www.cargill.fr/fr/montoir-](https://www.cargill.fr/fr/montoir-de-bretagne)  
561 [de-bretagne](https://www.cargill.fr/fr/montoir-de-bretagne) (accessed 4.11.18).
- 562 Cerceau, J., Mat, N., Junqua, G., Lin, L., Laforest, V., Gonzalez, C., 2014. Implementing industrial  
563 ecology in port cities: International overview of case studies and cross-case analysis. *J. Clean.*  
564 *Prod.* 74, 1–16. <https://doi.org/10.1016/j.jclepro.2014.03.050>
- 565 Chavez, A., Ramaswami, A., 2013. Articulating a trans-boundary infrastructure supply chain  
566 greenhouse gas emission footprint for cities: Mathematical relationships and policy relevance.  
567 *Energy Policy* 54, 376–384. <https://doi.org/https://doi.org/10.1016/j.enpol.2012.10.037>
- 568 Chen, G., Shan, Y., Hu, Y., Tong, K., Wiedmann, T., Ramaswami, A., Guan, D., Shi, L., Wang, Y.,  
569 2019. Review on City-Level Carbon Accounting. *Environ. Sci. Technol.* 53, 5545–5558.  
570 <https://doi.org/10.1021/acs.est.8b07071>
- 571 Chen, S., Long, H., Chen, B., Feng, K., Hubacek, K., 2020. Urban carbon footprints across scale:  
572 Important considerations for choosing system boundaries. *Appl. Energy* 259.  
573 <https://doi.org/10.1016/j.apenergy.2019.114201>
- 574 Chen, S., Zhu, F., 2019. Unveiling key drivers of urban embodied and controlled carbon footprints.  
575 *Appl. Energy* 235, 835–845. <https://doi.org/https://doi.org/10.1016/j.apenergy.2018.11.018>
- 576 Dittrich, M., Bringezu, S., Schütz, H., 2012. The physical dimension of international trade, part 2:



577 Indirect global resource flows between 1962 and 2005. *Ecol. Econ.* 79, 32–43.  
578 <https://doi.org/https://doi.org/10.1016/j.ecolecon.2012.04.014>

579 DREAL, 2012. La situation des transports en Pays de la Loire (Transportation sector in the Pays de la  
580 Loire region).

581 DROPEC, 2016. Le profil énergie climat régional (energy and carbon regional profile) [WWW  
582 Document].

583 Duruisseau, K., 2014. L'émergence du concept de transition énergétique. Quels apports de la  
584 géographie ? *Bull. la Société géographique Liège* 63, 21–34.

585 ENEDIS, 2015. Open database from the national electricity distributor (ENEDIS).

586 Eurostat, 2001. Economy-wide material flow accounts and derived indicators. A methodological  
587 guide. Luxembourg.

588 France Loi n°2015-992, 2015. Loi n°2015-992 du 17 août 2015 relative à la transition énergétique  
589 pour une croissance verte (in French).

590 Frischknecht, R., Wyss, F., Büsler Knöpfel, S., Balouktsi, M., 2015. Cumulative energy demand in  
591 LCA: the energy harvested approach. *Int. J. Life Cycle Assess.* 7, 957–960.

592 Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2012. Integrating  
593 Ecological, Carbon and Water footprint into a “Footprint Family” of indicators: Definition and  
594 role in tracking human pressure on the planet. *Ecol. Indic.* 16, 100–112.  
595 <https://doi.org/10.1016/J.ECOLIND.2011.06.017>

596 GPMSN, 2014. Démarche d'écologie industrielle (industrial ecology initiative).

597 GRDF, 2015. Open database from the national natural gas distributor (GRDF).

598 Guibrunet, L., Sanzana Calvet, M., Castán Broto, V., 2016. Flows, system boundaries and the politics  
599 of urban metabolism: Waste management in Mexico City and Santiago de Chile. *Geoforum* 85,  
600 353–367. <https://doi.org/10.1016/j.geoforum.2016.10.011>

601 Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019.  
602 Contributions of sociometabolic research to sustainability science. *Nat. Sustain.* 2, 173–184.  
603 <https://doi.org/10.1038/s41893-019-0225-2>

604 Hammer, M., Giljum, S., Hinterberger, F., 2003. Material Flow Analysis of the City of Hamburg.

605 Hayashi, M., Hughes, L., 2013. The Fukushima nuclear accident and its effect on global energy  
606 security. *Energy Policy* 59, 102–111. <https://doi.org/https://doi.org/10.1016/j.enpol.2012.11.046>

607 Hillman, T., Ramaswami, A., 2010. Greenhouse Gas Emission Footprints and Energy Use  
608 Benchmarks for Eight U.S. Cities. *Environ. Sci. Technol.* 44, 1902–1910.  
609 <https://doi.org/10.1021/es9024194>

610 Hu, Y., Lin, J., Cui, S., Khanna, N.Z., 2016. Measuring Urban Carbon Footprint from Carbon Flows in  
611 the Global Supply Chain. *Environ. Sci. Technol.* 50, 6154–6163.  
612 <https://doi.org/10.1021/acs.est.6b00985>

613 Huang, C.-L., Vause, J., Ma, H.-W., Yu, C.-P., 2012. Using material/substance flow analysis to  
614 support sustainable development assessment: A literature review and outlook. *Resour. Conserv.  
615 Recycl.* 68, 104–116. <https://doi.org/https://doi.org/10.1016/j.resconrec.2012.08.012>

616 Huang, Q., Zheng, X., Liu, F., Hu, Y., Zuo, Y., 2018. Dynamic analysis method to open the “black  
617 box” of urban metabolism. *Resour. Conserv. Recycl.* 139, 377–386.

- 618 <https://doi.org/https://doi.org/10.1016/j.resconrec.2018.09.010>
- 619 IEA, 2017. Understanding and using the Energy Balance [WWW Document]. URL  
620 <https://www.iea.org/commentaries/understanding-and-using-the-energy-balance> (accessed  
621 3.20.20).
- 622 INSEE, 2020. Primary energy [WWW Document]. Defin. methods Qual.
- 623 Jones, C.M., Kammen, D.M., 2011. Quantifying Carbon Footprint Reduction Opportunities for U.S.  
624 Households and Communities. *Environ. Sci. Technol.* 45, 4088–4095.  
625 <https://doi.org/10.1021/es102221h>
- 626 Kennedy, C., Cuddihy, J., Engel-yan, J., 2007. Metabolism of Cities. *J. Ind. Technol.* 11, 43–59.
- 627 Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havránek, M., Pataki, D.,  
628 Phdungsilp, A., Ramaswami, A., Mendez, G.V., 2009. Greenhouse Gas Emissions from Global  
629 Cities. *Environ. Sci. Technol.* 43, 7297–7302. <https://doi.org/10.1021/es900213p>
- 630 Kim, E., Barles, S., 2012. The energy consumption of Paris and its supply areas from the eighteenth  
631 century to the present. *Reg. Environ. Chang.* 12, 295–310. [https://doi.org/10.1007/s10113-011-](https://doi.org/10.1007/s10113-011-0275-0)  
632 [0275-0](https://doi.org/10.1007/s10113-011-0275-0)
- 633 Krausmann, F., 2013. A city and its hinterland: Vienna’s energy metabolism 1800-2006, in: Singh,  
634 S.J., Haberl, H., Chertow, M., Mirtl, M., Schmid, M. (Eds.), *Long Term Socio-Ecological*  
635 *Research: Studies in Society-Nature Interactions Across Spatial and Temporal Scales*. Springer  
636 Science, pp. 1–588. <https://doi.org/10.1007/978-94-007-1177-8>
- 637 Larsen, H.N., Hertwich, E.G., 2010. Identifying important characteristics of municipal carbon  
638 footprints. *Ecol. Econ.* 70, 60–66. <https://doi.org/https://doi.org/10.1016/j.ecolecon.2010.05.001>
- 639 Lenzen, M., Peters, G.M., 2010. How City Dwellers Affect Their Resource Hinterland. *J. Ind. Ecol.*  
640 14, 73–90. <https://doi.org/10.1111/j.1530-9290.2009.00190.x>
- 641 Lin, J., Hu, Y., Cui, S., Kang, J., Ramaswami, A., 2015. Tracking urban carbon footprints from  
642 production and consumption perspectives. *Environ. Res. Lett.* 10. [https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/10/5/054001)  
643 [9326/10/5/054001](https://doi.org/10.1088/1748-9326/10/5/054001)
- 644 Lin, J., Liu, Y., Meng, F., Cui, S., Xu, L., 2013. Using hybrid method to evaluate carbon footprint of  
645 Xiamen City, China. *Energy Policy* 58, 220–227.  
646 <https://doi.org/https://doi.org/10.1016/j.enpol.2013.03.007>
- 647 Lin, T., Yu, Y., Bai, X., Feng, L., Wang, J., 2013. Greenhouse Gas Emissions Accounting of Urban  
648 Residential Consumption: A Household Survey Based Approach. *PLoS One* 8.  
649 <https://doi.org/10.1371/journal.pone.0055642>
- 650 Liu, G., Müller, D.B., 2013. Mapping the Global Journey of Anthropogenic Aluminum: A Trade-  
651 Linked Multilevel Material Flow Analysis. *Environ. Sci. Technol.* 47, 11873–11881.  
652 <https://doi.org/10.1021/es4024404>
- 653 Mancini, L., Benini, L., Sala, S., 2015. Resource footprint of Europe: Complementarity of material  
654 flow analysis and life cycle assessment for policy support. *Environ. Sci. Policy* 54, 367–376.  
655 <https://doi.org/https://doi.org/10.1016/j.envsci.2015.07.025>
- 656 Mat, N., Cerceau, J., Shi, L., Park, H.S., Junqua, G., Lopez-Ferber, M., 2016. Socio-ecological  
657 transitions toward low-carbon port cities: Trends, changes and adaptation processes in Asia and  
658 Europe. *J. Clean. Prod.* 114, 362–375. <https://doi.org/10.1016/j.jclepro.2015.04.058>
- 659 Minx, J., Baiocchi, G., Wiedmann, T., Barrett, J., Creutzig, F., Feng, K., Förster, M., Pichler, P.P.,

- 660 Weisz, H., Hubacek, K., 2013. Carbon footprints of cities and other human settlements in the  
661 UK. *Environ. Res. Lett.* 8. <https://doi.org/10.1088/1748-9326/8/3/035039>
- 662 Ngo, N.S., Pataki, D.E., 2008. The energy and mass balance of Los Angeles County. *Urban Ecosyst.*  
663 11, 121–139. <https://doi.org/10.1007/s11252-008-0051-1>
- 664 Raineau, L., 2011. Vers une transition énergétique? *Natures Sci. Sociétés* 19, 133–143.
- 665 Ramaswami, A., Chavez, A., Ewing-Thiel, J., Reeve, K.E., 2011. Two Approaches to Greenhouse Gas  
666 Emissions Foot-Printing at the City Scale. *Environ. Sci. Technol.* 45, 4205–4206.  
667 <https://doi.org/10.1021/es201166n>
- 668 Ramaswami, A., Hillman, T., Janson, B., Reiner, M., Thomas, G., 2008. A Demand-Centered, Hybrid  
669 Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories. *Environ. Sci. Technol.* 42,  
670 6455–6461. <https://doi.org/10.1021/es702992q>
- 671 Rosado, L., Kalmykova, Y., Patrício, J., 2016. Urban metabolism profiles. An empirical analysis of  
672 the material flow characteristics of three metropolitan areas in Sweden. *J. Clean. Prod.* 126, 206–  
673 217. <https://doi.org/https://doi.org/10.1016/j.jclepro.2016.02.139>
- 674 Rosado, L., Niza, S., Ferrão, P., 2014. A Material Flow Accounting Case Study of the Lisbon  
675 Metropolitan Area using the Urban Metabolism Analyst Model. *J. Ind. Ecol.* 18, 84–101.  
676 <https://doi.org/10.1111/jiec.12083>
- 677 Rosales Carreón, J., Worrell, E., 2018. Urban energy systems within the transition to sustainable  
678 development. A research agenda for urban metabolism. *Resour. Conserv. Recycl.* 132, 258–266.  
679 <https://doi.org/10.1016/J.RESCONREC.2017.08.004>
- 680 RTE, 2016. Bilans électriques et perspectives - Pays de la Loire (Electricity assessment and  
681 perspectives - Pays de la Loire region).
- 682 Saint-Nazaire port authority, 2016. Suivi des vracs solides et liquides importés et exportés (Account  
683 on solids and liquids products imported and exported) - Base year 2015.
- 684 Schulz, N.B., 2007. The Direct Material Inputs into Singapore 's Development. *J. Ind. Ecol.* 11, 117–  
685 131. <https://doi.org/10.1162/jie.2007.1200>
- 686 Sims, R.E., Schock, R.N., Adegbululgbé, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W.,  
687 Nimir, H., Schlamadinger, B., Torres-Martinez, J., Turner, C., Uchiyama, Y., Vuori, S.J.,  
688 Wamukonya, N., Zhang, X., 2007. Energy Supply, in: Metz, B., Davidson, O.R., Bosch, P.R.,  
689 Dave, R., Meyer, L.A. (Eds.), *Climate Change 2007: Mitigation. Contribution of Working Group  
690 III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*  
691 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 692 Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A.E., Hertwich, E.G., 2012. Carbon, Land, and  
693 Water Footprint Accounts for the European Union: Consumption, Production, and Displacements  
694 through International Trade. *Environ. Sci. Technol.* 46, 10883–10891.  
695 <https://doi.org/10.1021/es301949t>
- 696 Tanguy, A., 2019. Le rôle des compétitions territoriales dans la transition énergétique. *Flux* 116–117,  
697 176–191. <https://doi.org/10.3917/flux1.116.0176>
- 698 TOTAL, 2013. La plateforme de Donges - Un site industriel majeur de l'estuaire de la Loire (The  
699 Donges platform - A major industrial site of the Loire's estuary) [WWW Document]. URL  
700 <http://www.ufip.fr/uploads/img/A0.pdf>
- 701 Verrastro, F., Ladislaw, S., 2007. Providing energy security in an interdependent world. *Wash. Q.* 30,  
702 95–104. <https://doi.org/10.1162/wash.2007.30.4.95>

- 703 Voskamp, I.M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J.P., Rijnaarts, H.H.M., 2017.  
704 Enhanced Performance of the Eurostat Method for Comprehensive Assessment of Urban  
705 Metabolism: A Material Flow Analysis of Amsterdam. *J. Ind. Ecol.* 21, 887–902.  
706 <https://doi.org/10.1111/jiec.12461>
- 707 Wiedmann, T.O., Chen, G., Barrett, J., 2016. The Concept of City Carbon Maps: A Case Study of  
708 Melbourne, Australia. *J. Ind. Ecol.* 20, 676–691. <https://doi.org/10.1111/jiec.12346>
- 709 Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The  
710 material footprint of nations. *Proc. Natl. Acad. Sci. U. S. A.* 112, 6271–6276.  
711 <https://doi.org/10.1073/pnas.1220362110>
- 712 Wilby, M.R., Rodríguez González, A.B., Vinagre Díaz, J.J., 2014. Empirical and dynamic primary  
713 energy factors. *Energy* 73, 771–779. <https://doi.org/https://doi.org/10.1016/j.energy.2014.06.083>
- 714 Zhang, C., Chen, W.-Q., Ruth, M., 2018. Measuring material efficiency: A review of the historical  
715 evolution of indicators, methodologies and findings. *Resour. Conserv. Recycl.* 132, 79–92.  
716 <https://doi.org/https://doi.org/10.1016/j.resconrec.2018.01.028>
- 717 Zheng, H., Wang, X., Li, M., Zhang, Y., Fan, Y., 2018. Interregional trade among regions of urban  
718 energy metabolism: A case study between Beijing-Tianjin-Hebei and others in China. *Resour.*  
719 *Conserv. Recycl.* 132, 339–351. <https://doi.org/https://doi.org/10.1016/j.resconrec.2017.05.010>
- 720
- 721