

Toward physical supply use tables of the French economy

Alexandre BORTHOMIEU

INRIA - STEEP Team

alexandre.borthomieu@inria.fr

Jean-Yves COURTONNE

INRIA - STEEP Team

jean-yves.courtonne@inria.fr

Vincent JOST

GSCOP - ROSP Team

vincent.jost@grenoble-inp.fr

Guillaume MANDIL

INRIA - STEEP Team

guillaume.mandil@inria.fr

Peter STURM

INRIA - STEEP Team

peter.sturm@inria.fr

February 18, 2021

Abstract

There are now several research works dealing with tables in physical flows. These works are crucial to try to answer questions about the possible trajectories of our societies and modes of consumption. In this paper, we wish to bridge the gap between these works and the analysis of material flows and to develop a methodology capable of providing physical flow tables in a unified formalism.

1 Introduction

Input-Output (IO) tables are an accounting framework for national economies popularized by Leontief (Leontief, 1970; Miller and Blair, 2009). This formalism makes it possible to provide a representation of the interactions between three components: (i) factors of production seen as exogenous to the system under study (such as labour or the environment as a supplier of resources or a recipient of emissions), (ii) economic sectors that transform factors of production to produce goods and services, and (iii) final consumption.

IO Analysis has gained popularity in the environmental assessment community (Suh, 2009) because

it allows, by tracing the interactions between economic sectors, to describe supply chains and allocate factors of production (in the broadest sense, including induced environmental pressures) to the final consumer. In this way, it is possible to perform environmental accounting from the consumer's point of view, including direct and indirect effects, in other words to calculate "footprints".

In practice, such tables are available today for most countries of the world in different formats (e.g. EXIOBASE, EORA, GTAP, WIOD, ...). The "model's core", i.e. the exchanges between sectors and towards final consumption are quantified in monetary units and the environmental extensions (e.g. carbon emissions) in physical units.

For several years now, research efforts has been aimed at moving towards tables expressed partially or totally in physical flows (Hubacek and Giljum, 2003; Suh, 2009; Teixeira et al., 2020; Nakamura et al., 2007; Bruckner et al., 2019), which have several advantages. The first is to arrive at an integrated energy/material description of a state of the economy whether past, present or scenarized (Teixeira et al., 2020). This is crucial to ensure the overall coherence of the evolutionary trajectories under debate: for example, do we have enough materials to implement the energy transition? What is the

climatic impact of this more material-intensive scenario (see also on this subject Vidal et al. (2018))? What are the trade-offs to be made in the allocation of resources between sectors according to the targeted criteria (e.g. level and mode of consumption, production mode, environmental pressures)? A second advantage is to provide a description of production chains that is closer to the reality on the ground, and therefore more likely to allow the identification of levers of change, thanks to a finer description of products and sectors (at least in some places) compared to monetary tables. For example, the notion of one euro spent or generated by the agricultural sector as a whole remains relatively abstract, whereas describing cereal supply chains is more concrete. Finally, the strong sustainability framework in which we place ourselves (Daly and Farley, 2011) naturally invites to describe the economy from the point of view of its material substrate, insofar as it is inscribed in a finite world involving biophysical constraints.

This paper proposes to bridge the gap between these past and current research efforts and the methodology of material flow analysis (MFA) of supply chains developed by Courtonne et al. (2015); Courtonne (2016) and in the ADEME AF-Filière project (www.flux-biomasse.fr). The path explored consists in using existing sectoral expertise, often very detailed, to transcribe them one by one into a common formalism (MFA of supply chains) before merging them to produce a single supply and use table for the economy, or rather, as we shall see, a table per relevant unit of account.

We first describe the method that we have developed to meet these objectives before presenting some initial use cases and discussing the prospective.

2 Methods for merging multi-unit data

2.1 Description of the formalism

To achieve this, we used a formalism (Courtonne et al., 2015) based on the Supply Use Tables (SUTs) that describes all the flows between the sectors and products of the economy. The SUTs combine two

tables, “Supply” and “Use” (see table 1) in which information about the flows is stored. Let us take as an example a simple flow graph (figure 1), we can then translate it into SUTs (and vice versa) by assuming that the nodes B, C, E, G are sectors and a, d, f, h are products.

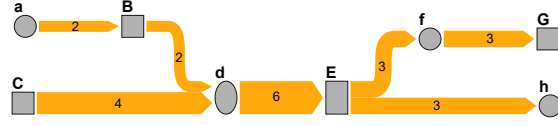


Figure 1: Simple flow graph

We thus obtain the following two tables: Use 1a and Supply 1b which describe our figure above.

| | B | C | E | G |
|---|---|---|---|---|
| a | | | | |
| d | 2 | 4 | | |
| f | | | 3 | |
| h | | | 3 | |

(a) Supply Table

| | B | C | E | G |
|---|---|---|---|---|
| a | 2 | | | |
| d | | | 6 | |
| f | | | | 3 |
| h | | | | |

(b) Use Table

Table 1: SUT - Supply Use Tables

To build a model of a given industry, we first need to model its structure and then gather large amounts of data to determine the value of the flows. In our formalism, this results in SUTs as before but which only reference potential flows (table 2). Thus, a “1” in the table indicates that a flow is possible between the two fields. Moreover, we have the possibility to give aggregation levels for each product and sector. These two options will allow us to propagate flows for which we have recorded data and deduct those we don’t have (missing flows).

Here we enter the heart of our method. Indeed, to compute these missing flow data, we have developed an algorithm that first assigns one of the following four types to each flow according to different crite-

| | B | C | E | G |
|---|---|---|---|---|
| a | | | | |
| d | 1 | 1 | | |
| f | | | 1 | |
| h | | | 1 | |

(a) Supply Table

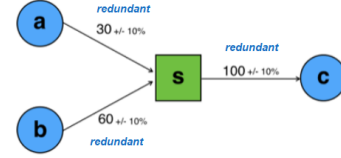
| | B | C | E | G |
|---|---|---|---|---|
| a | 1 | | | |
| d | | | 1 | |
| f | | | | 1 |
| h | | | | |

(b) Use Table

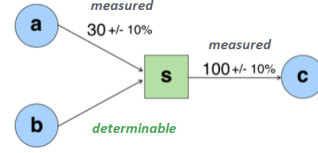
Table 2: Existing flows

ria (figure 2): “determined” (*DV*), “measured” (*MV*), “redundant” (*RV*) and “free” (*FV*). The data labeled as *MV* and *RV* are the inputs of our tool while *DV* and *FV* will be calculated. The *FV* are the most interesting variables because we cannot calculate them precisely. We are therefore forced to use intervals to describe them. To compute the *FV* as well as the *DV* we use a data reconciliation algorithm based on numerical optimization under constraints (some of which represent material balances): each node (product or sector) of our graph must have a balanced material balance. Therefore, each node will represent a set of constraints depending on the variable we want to compute. Thanks to this, we are able to determine all the variables identified as *DV* and to calculate the interval of the *FV* (the algorithm tries to reduce as much as possible the bounds of the starting intervals associated with each variable). Finally, our tool uses Monte-Carlo simulations to estimate and propagate the uncertainties of the calculated values (Courtonne et al., 2019).

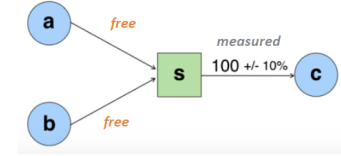
It is difficult to construct a complete representation of a large economic structure at once, in particular because of the too great quantity of flows to be known. However, it is possible to proceed in a piecewise manner. Based on this observation, we have developed a simple algorithm able to merge two supply chains without losing information on the underlying data structure (in our cqses, excel files obeying a spe-



(a) Redundant Variables



(b) Measured and Determined Variables



(c) Free Variables

Figure 2: Types of variables (Courtonne et al., 2019)

cific structure) of these supply chains. Thus the aggregation levels remain coherent and the flows linked to them also remain consistent. This algorithm works by concatenating the information on the sectors until it finds a product or a sector present in both chains, in which case it will simply merge the corresponding data avoiding duplicates.

2.2 Handling multiple units

When working on a merging system subject to material balance constraints, the units are an important aspect: the principle of material balance works with a reference unit which is of course most of the time grams or tons. However, not all physical flows intrinsic to each product can be described with mass units. Indeed, the data collected will have other types of units such as cubic meters, liters or even Watt-hours. We can then say that there are two main types of balances: material and energy. But how then can we merge and reconcile two supply chains if the units of several flows are different?

Three specific cases related to this question can be described. The first one is quite basic, it is only

about conversion factors. Many units have a logical link for the same balance between them such as ton, liter, etc. for the material balance and Watt-hour, Joules, etc. for the energy balance. These units can change our interpretation of the flow but it is possible to switch from one to the other within the same balance with a simple calculation. This case can be easily taken into account: all we need to do is to convert all the needed flows into the same “reference” unit and then reconcile them as described above. In this way, the balance constraints can be respected and the variables calculated.

The second case is a little more delicate. Indeed, we sometimes wish to take into account both types of balances, material and energy. The more we add products in the modeling of the chains, the more likely we are to end up with several different units, but especially related to the different types of balances. Let us take an example of a simple chain representing a node in our flow chart. Suppose this node models a coal-fired power plant. This power plant will obviously use tons of coal as input and produce energy such as heat or electricity. However, if we follow the combustion so that it respects the material balance, we see only coal, then CO_2 , H_2O , ashes. It is only when we decide to observe the energy balance that the power plant’s electricity production appears. Thus, this combustion can be described according to both balances. The material balance: there is a certain tonnage of coal that enters the plant and coupled with oxygen we obtain a certain quantity of CO_2 with other co-products. The energy balance: the plant will produce a certain amount of electricity that can only be measured in “energy” units such as Watt-hour. The energy input, however, is not a truly visible flow. Indeed, this energy comes from the energy contained in the coal. We will therefore add a flow that will correspond to the HHV or LHV (Higher or Lower Heating Value) of the coal. In this way, the energy balance can also be respected.

The following graphs represent this simple example. Figure 3 shows the input data. The missing flows can be clearly seen in order to make a precise analysis of the “supply chain”.

With this input data, the reconciliation gives us fig-

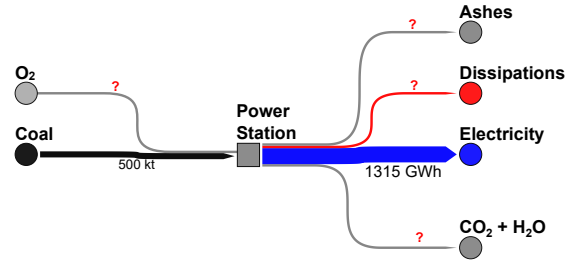


Figure 3: Input data graph

ure 4 which makes no physical sense.

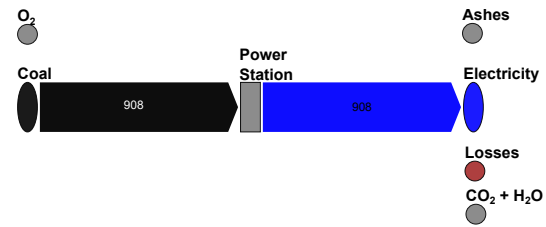


Figure 4: Sankey diagram of the reconciliation result without prior data processing

Figure 5, after processing the data according to both, mass/energy aspects, is probably closer to reality and the material and energy balances are respected.

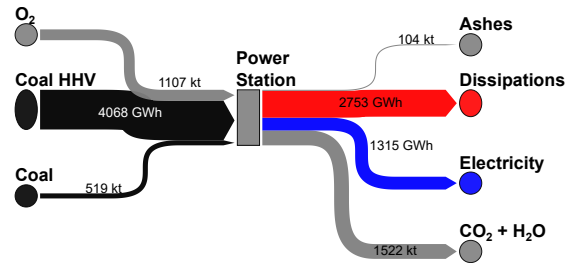


Figure 5: Sankey diagram of the correct result including the proposed multi-units handling

We have taken this case into account in our approach to merging and reconciling industrial sectors. When a sector is crossed by at least two flows of “incompatible” units (for which both types of balance sheets are required) as is the case for the power plant, we add a level of representation by creating a “copy” of the sector for each “incompatible” unit. In this way, we will be able to represent each aspect and

reconcile our data according to each unit. This gives us figure 5.

Finally, the third case is about the composition of the flows. It is possible that we want to respect a material balance with different types of mass unit. It is therefore interesting and useful to know the percentage of each component of a product for reconciliation. If we take the example of the milk industry, it is possible to set (also via a constrained optimization method) the transformation coefficients of the processes as well as the compositions of the different products in order to simultaneously satisfy the balances in total, dry, fat and protein mass: Courtonne et al. (2019).

2.3 Summary of the methodology

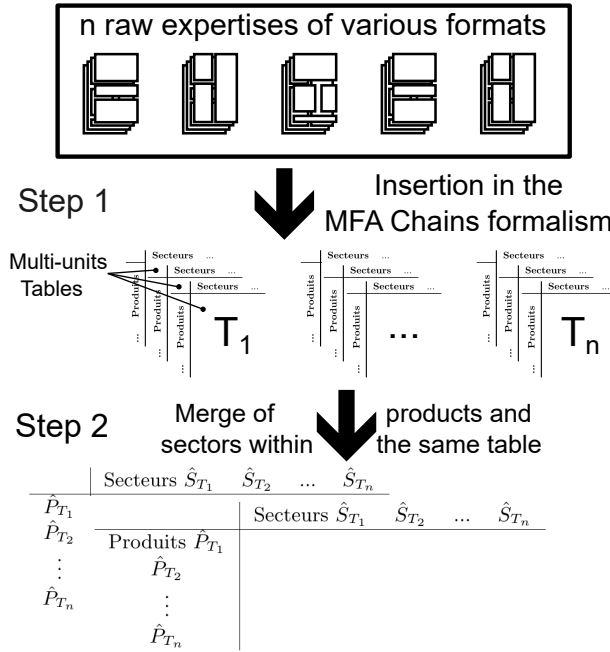


Figure 6: Schematic summary of the supply chain fusion method

Thus, to summarize, we first start from several raw sectoral expertises that may have different formats and origins. We transcribe them (step 1 figure 6) in the formalism described here, i.e. we create tables for each expertise and each relevant unit. Then, we merge them into one and the same table, always tak-

ing into account the multi-units (step 2 figure 6).

In figure 6, the T_x represent the different tables and \hat{P}_{T_x} (resp. \hat{S}_{T_x}) all the products (resp. sectors) of the table T_x which are not in the previous tables. Indeed, if they contained all the products (or sectors) it would simply be a table concatenation. Here we can write that each row (resp. column) is constructed according to these equations :

$$\begin{aligned} \hat{P}_{T_1} &= P_{T_1}, \\ \forall i \in [2; n], \quad \hat{P}_{T_i} &= P_{T_i} \setminus (\bigcup_{1 \leq j < i} P_{T_j} \cap P_{T_i}) \\ &\text{(resp. } \hat{S}_{T_i} \text{ et } S_{T_{j/i}}) \end{aligned}$$

Where P_{T_i} (resp. S_{T_i}) represents all products (resp. sectors) present in the table T_i , \hat{P}_{T_i} (resp. \hat{S}_{T_i}) is described above, and n represents the number of tables to be merged.

From an operational point of view, we use spreadsheets to store our data and our algorithms are implemented in the *Python* language with sometimes external libraries like *Pybind11* to speed up the computation time.

3 Applications to data sets

We have started to collect and structure data on the French national economy. We decided to use as a starter the 2015 data from negaWatt¹ present in the Sankey diagram of their 2015-2050 scenario² in order to reproduce it. Thus, we were able to put the 2015 data of the scenario in our formalism and to represent it with our tools (see figure 7 in the appendix).

In addition, we choose to work on the coupling between mobility and energy. We have thus carried out a simplified inventory of the French private car fleet (Warburg et al., 2011) focusing on diesel and petrol cars. We produced from that the graph presented in the appendix (figure 9) and we have also reduced and aggregated the energy sector to focus on the mobility aspect (figure 8). Then we merged these two energy sources (figure 10).

¹www.negawatt.org

²www.negawatt.org/scenario/sankeys/2015

4 Discussion

Our methods and associated software are designed to facilitate the modeling of a complex economic structure. The SUTs filled with the flows labeled as “may exist” allow us to better understand the structure of the studied economy and thus to easily draw interaction graphs. Once the structure is established, it is “only” necessary to collect the data corresponding to the flows, which is the most time-consuming task when we want to model an economy. But the reconciliation system helps us to reduce the time spent on this task by calculating some missing flows. Our tool can be useful for understanding the interactions between sectors of an economy and their impacts on the environment. The aggregation system allows us to have a certain freedom in the way we model precisely a given sector and to visualize it in more or less detail. It also gives us an answer to multi-unit systems which can be challenging because national economies use energy and material flows. One of the recurring problems when working on production lines is the double counting of flows when gathering information. However, our reconciliation system coupled with our visualization tool prevents this type of problem and easily detects a flow counted twice. This article is a proof of concept; in coming work we will apply this methodology to all the supply chains for which expertise exists.

5 Conclusion

This article proposes a first methodology to allow to represent by intervals flows whose information is difficult to collect and also to gather data under the same formalism by merging the available expertise to create a single table at the desired scale. In this way, we are building a bridge between the work mentioned in the introduction and the analysis of material flows of supply chains (Courtonne et al., 2015; Courtonne, 2016). As mentioned above, this work is part of a project that wishes to build a national physical table of our economy. However, the creation of this table is not the only objective; we wish to work on the multi-scale aspect of this table, i.e. to be able

to descend from the national to the regional, or even infra-regional level. A medium-term objective is to use the formalism and methods presented in participatory territorial foresight exercises, for example to scenarize alternative economic arrangements in a territory and evaluate them according to criteria of sustainability or resilience. This is therefore the first step towards a multi-scale environmental assessment of our economy.

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Annexes

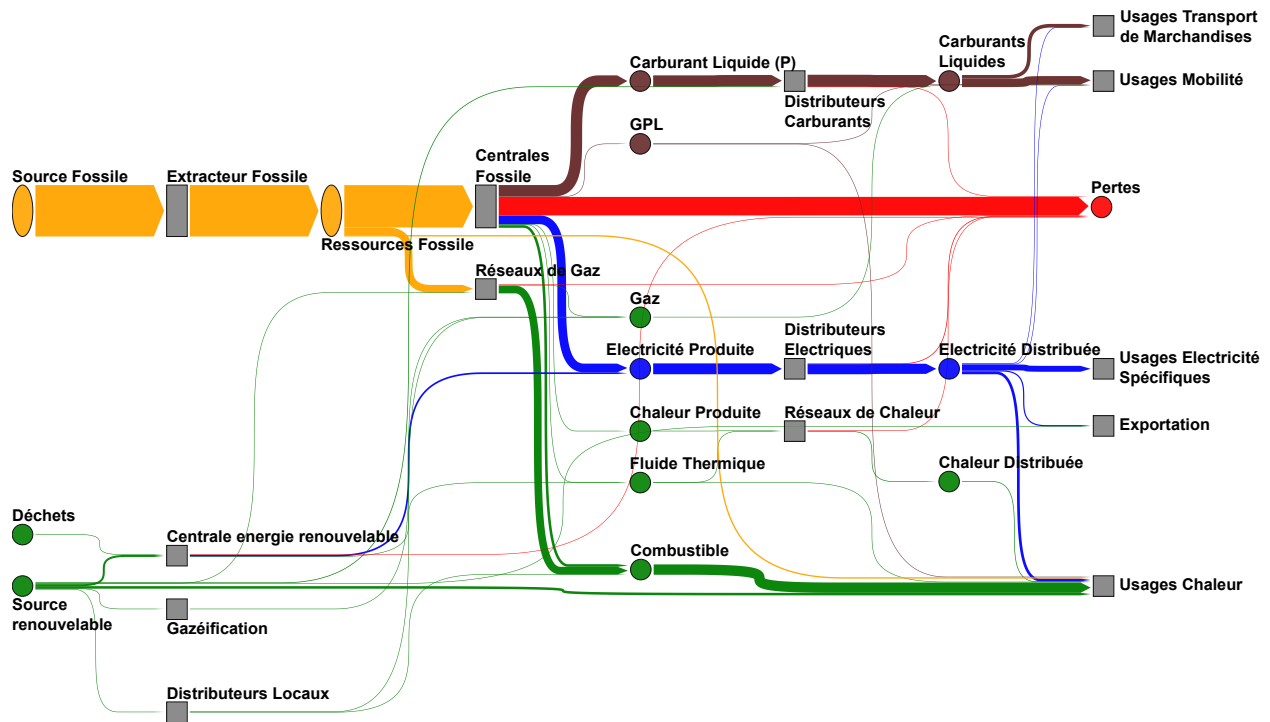


Figure 7: Visualization of negaWatt data transcribed in our formalism

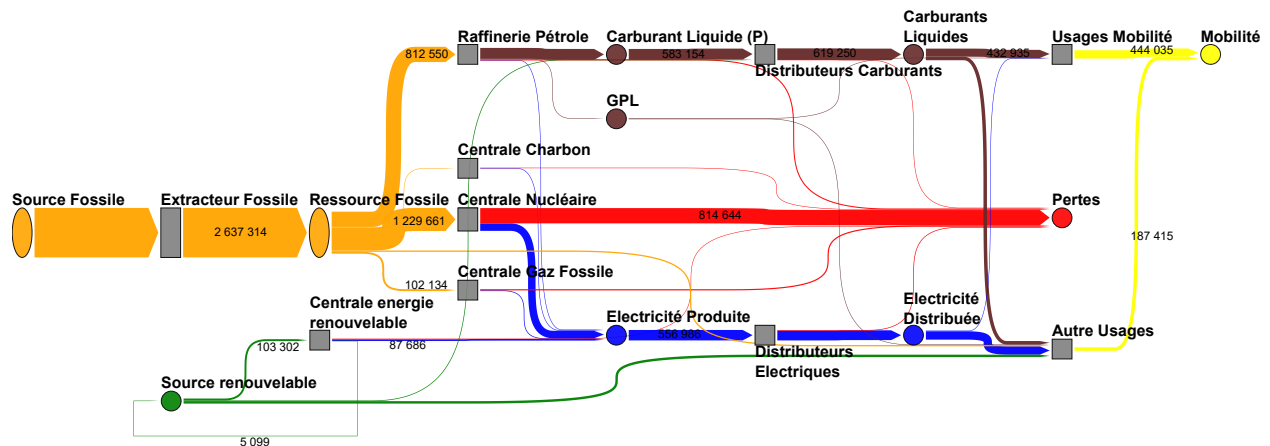


Figure 8: Energy Supply chain centered around the mobility part [Data extracted from the year 2015 of the negaWatt scenario]

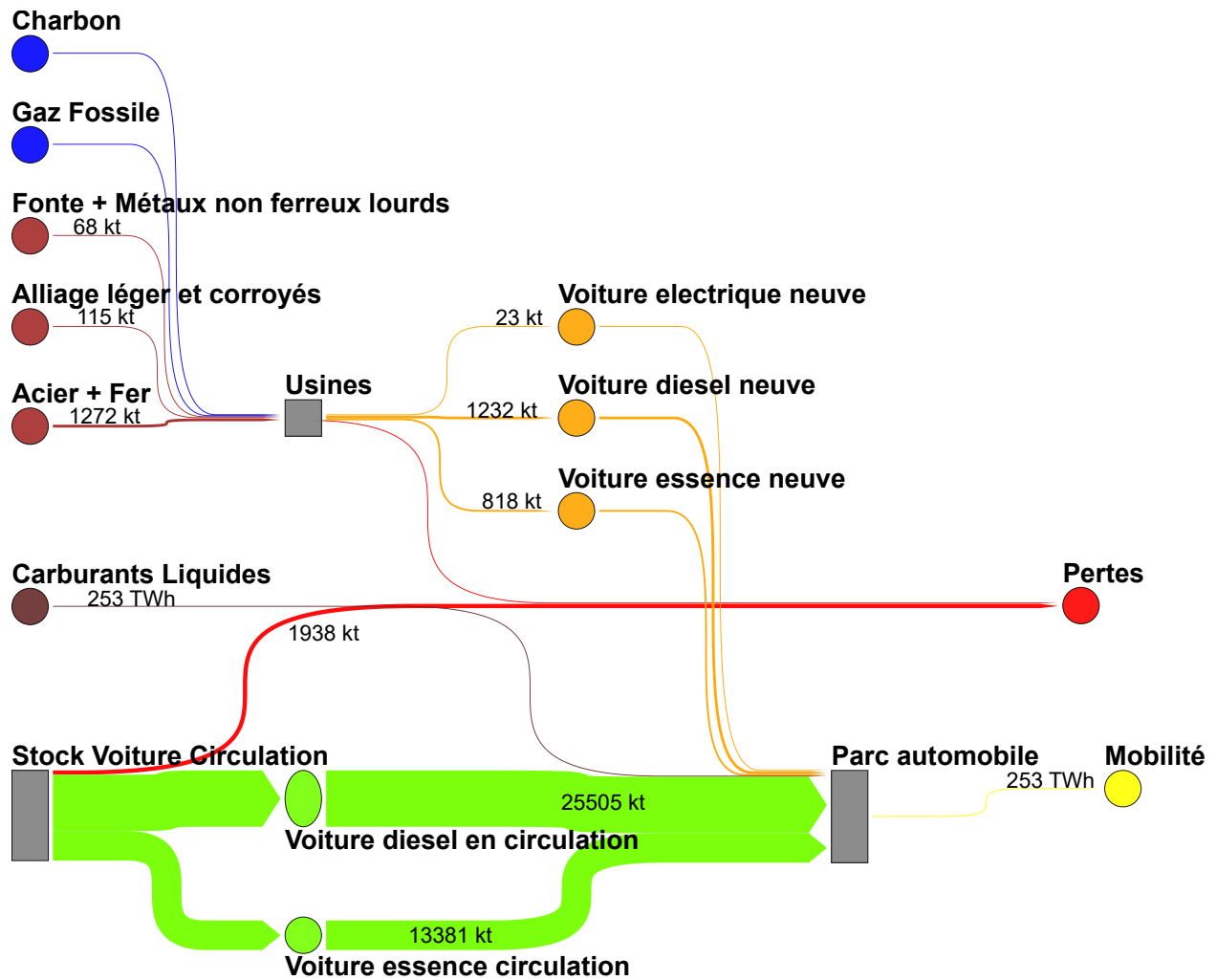


Figure 9: Automotive supply chain centered on Diesel and Gasoline [Data extrated from Warburg et al. (2011)]

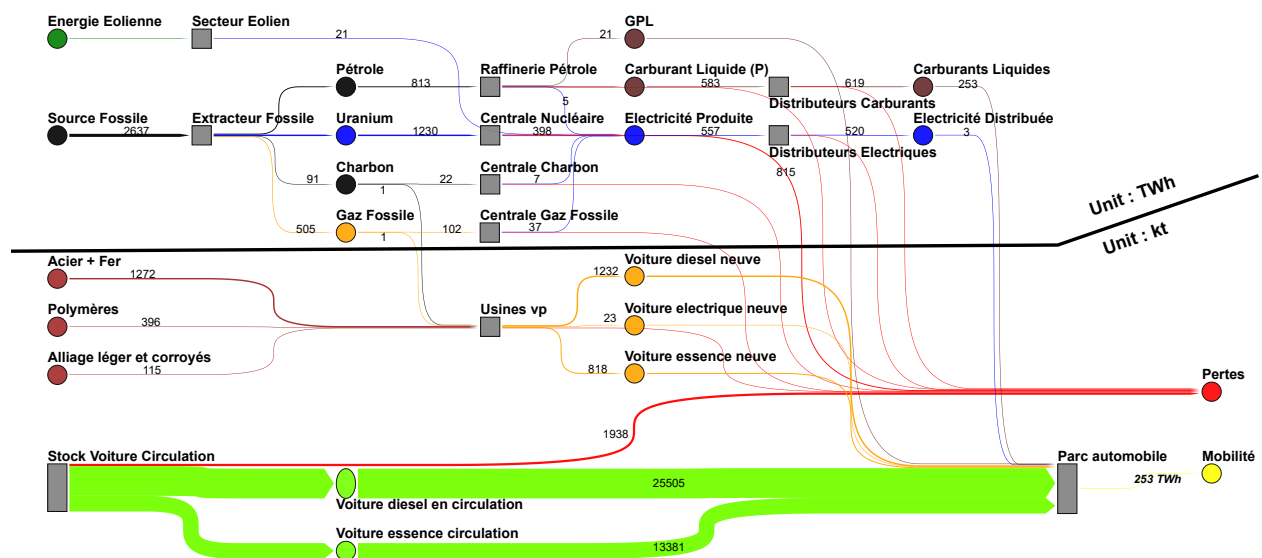


Figure 10: Merger Energy-Mobility 2015

Some nodes do not respect the material balance, this comes from the fact that not all flows and nodes are displayed for a better visibility but they exist in our data. Moreover, the thickness of the arrows for two different units cannot be compared: the size factor between units is arbitrary.