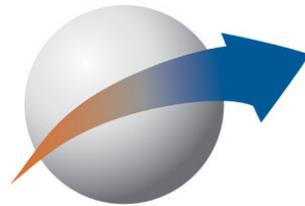


Rogeaquito

Transparent Energy Scenario Thinking

Technical Description of Rogeaquito Model and Framework



Redesigning the Economy to Achieve Carbon Transition

THE SHIFT
PROJECT

Document

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|----------------|--|
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| Date | May 2013 |
| Version | V1.3 |
| Nom du fichier | Rogeaulito technical description |
| URL | |

Abstract

The sustainability of our lifestyle has now been questioned for several years. Presently this is already a subject of concern at world level. Energy and the energy system as a whole both lie at the heart of debates, on national and international scenes. Indeed, this sector which provides the real fuel of the economy of modern societies is facing numerous questions such as its impact on climate, the scarcity of its resources, their prices and their stocks, as well as the importance that should be allowed to the nuclear production. These become even more pregnant as the economic environment becomes more difficult, reducing options for decisions. The various energy scenarios published this last decade attempt to cope with this concern and attempt to provide possible narratives for our future. Such a prospective work can take the form of either trend, exploratory or backcasting scenarios, depending on the approach. As part of this effort, TSP has developed its own tool dedicated to the construction of energy scenarios: Rogeaulito. It focuses on physical parameters to set up both energy demand and supply of different sectors and resources. In contrast with most scenarios the modeling process does attempt to balance the final energy demand with the primary energy supply. It rather insists on, the detection of possible gap appearing between a demand and a possible supply when both are based on realistic assumptions. It thus focuses on discrepancies and tries rather to highlight the consumption and production systems limitations. By doing so, we promote iterative approaches to identify possible options to bridge the gap between demand and supply. This document is a technical introduction of Rogeaulito. First it describes the principles underlying the tool and the working of the modeling process. Then, it delves in more detail into the Rogeaulito modules which quantitatively describes our model for final energy demand, primary energy supply, and conversion sector. The latter is used to convert the primary resources into final energy carriers. A mathematical method at the heart of the modules that TSP employs within the central Conversion Module relies on matrix formulation. This document does not pretend to be a user guide nor a demonstration of Rogeaulito utilization, but rather a presentation the levers and cursors available to the user in order to tailor her description of the global energy system and how they enter the calculations performed by the tool interface.

Keywords

Energy, Scenario, Modeling, Unbalanced, Primary Supply, Final Demand

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List of acronyms

CHP: Combined Heat and Power

Gboe (or Gb): Giga Barrel oil equivalent (10^9 barrels)

GHGs: Green House Gases

Gtce: Giga ton coal equivalent

GTL: Gas-to-liquid

Gtoe: Giga ton oil equivalent

IEA: International Energy Agency

ktoe: kilo ton oil equivalent (l'abbreviation de kilo est un k minuscule)

MES: Missing Energy Supply (or energy gap). It corresponds to the gap between a given induced desired demand and a possible supply. By convention, the Missing Energy Supply is positive when the induced demand exceeds the supply and set to 0 otherwise.

Mtoe: Mega ton oil equivalent

TSP: The Shift Project

Acknowledgements

We acknowledge the seminal ideas by Bernard Rogeaux in particular for the introduction of the concept of Missing Energy Supply. The name of the tool is intended to be a sign of recognition of his invaluable contributions to the domain of energy scenario building and analysis.

We would like also to thank the EDF-R&D-Mescalito Team (Christophe Marchand, François Cattier and Prabodh Pourouchottamin) for their constant support. Their inputs proved to be of major importance for the development of Rogeaullito.

Finally we would like also to thank Hubert Flocard for the exhaustive and valuable review he provided to the present publication.

Concept

Rogeaullito is an innovative energy scenario modeling tool. Based on physically and sociologically motivated inputs it first independently describes the energy demand and the energy supply. In a second step it confronts them in order to highlight any potential energy gap that might appear, reflecting the limits of the inputs. In this way we emphasize the potential crises that would happen if the inputs turned out to be confirmed. This approach is motivated by the observation that most current energy scenarios rather than accepting the inconsistencies resulting from their initial assumptions, tend to hide them by applying ad-hoc economy-balancing feedback loops whose justification is often not clearly stated and may sometimes contradict the essence of the initial assumptions. We believe that in many instances this comes from improperly taking into account some basic physical considerations regarding either the behavior and potential of society and/or the

big companies. Rogeaulito's approach is different in that it rather tries to identify discrepancies between demand and supply side arising from any given set of assumptions regarding either of each. It also reveals where the discrepancies are the highest pointing thus to where main efforts should be accomplished. Thus we believe, that Rogeaulito could prove of timely interest in the critical period that our societies have entered. Indeed the economic-crisis, energy-issue, resources-depletion and climate-change threats we are now facing put even more pressure on making the optimal decisions and not deceiving oneself into incorrect options. We believe that understanding the issues and developing the energy system by properly taking into account the physical implications on material welfare and natural physical and technical limitations are some of the objectives that Rogeaulito can contribute to achieve.

The introduction presents the code and the main parameters which determine its outcomes. Then, the structure of Rogeaulito is presented. First we introduce the essential concepts along with the mathematical formulation of the four major components of Rogeaulito. In a further section we describe the conversion matrices. Finally we present our conclusion remarks and the perspectives opened by the present work.

Introduction – Energy scenarios and modeling approach

The Rogeaulito modeling tool

The origin of Rogeaulito comes from two mere observations. The first one is that the majority of forecast scenarios begin by modeling demand (often on the basis of socio-economic considerations or aspirations, resulting in uninterrupted economic growth), and matching it with the necessary level of supply, plus price adjustments where necessary. The reasoning adopted whether implicitly or explicitly– is that when prices rise, it is possible to access more resources and therefore to serve more consumers. The second is that we have recently begun to see the superimposition of different approaches based on the view that energy supply will be increasingly constrained by physical limits (on resources, technological performance, etc.), thereby imposing an upper limit on supply, to which demand will have to adapt.

In order to reconcile these two apparently contradictory viewpoints, TSP has decided to build a software package called Rogeaulito , which allows to simulate supply and demand on the basis of distinct methods, and compare the outcomes to draw conclusions that neither of the two approaches described above can provide individually.

In practical terms, this model:

1. Describes a **possible supply-side scenario** subject to constraints (in terms of extractable stocks of fossil fuels and uranium, areas available for cultivation of biomass, capital investment in terms of ‘unlimited’ resources, such as wind and sun, etc.).
2. Describes a **desired demand** from the ‘consumer-driven’ point of view (demand generated in terms of number of units of vehicles, residential /office buildings, factories, etc. and average consumption per unit, all trended over time). This demand is the reflection of the social aspirations of the society.
3. Calculates the equivalent of the **desired demand in primary energy terms**.
4. **Compares** this **desired primary energy demand** with the maximum **supply possible** given the constraints described in Point 1.

The desired demand is a projection of the social aspirations of the society while the possible supply copes with the physical limits of the resources and the willing to invest.

Figure 1 presents in details these four main steps that lead to the main Rogeaulito’s output: a graph displaying the possible supply and the overall primary energy demand that is not satisfied (in grey).

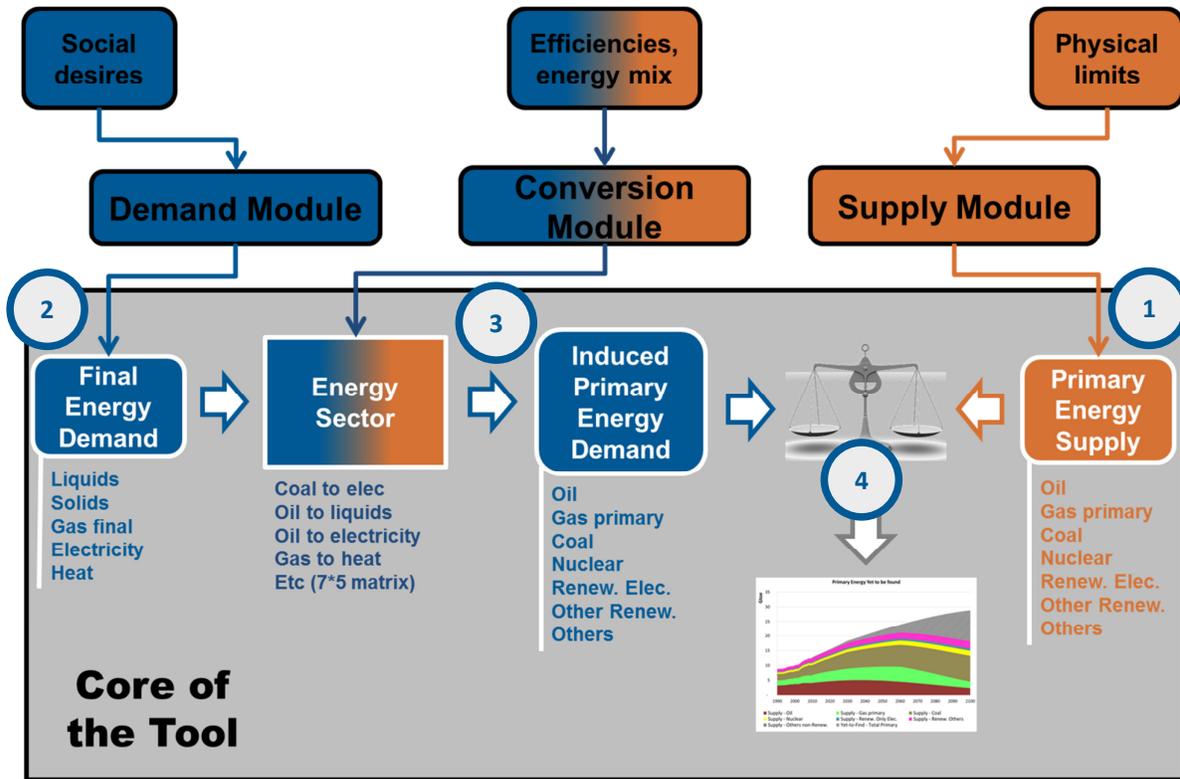


Figure 1: Rogeaulito's process

This working method highlights any *Missing Energy Supply* (MES) in which the trend in energy supply falls short of meeting projected demand. This then forms the basis for calculating iterations to provide a quantitative evaluation of the initiatives required to ensure that demand does not exceed constrained supply, which is the precondition for further crisis-free development of the society in which we all live. It then becomes possible to describe and quantify the long-term policies that will enable demand to be limited to within the maximum possible supply. [Figure 2](#) and [Figure 3](#) are the graphs obtained from a scenario variant performed with Rogeaulito. The global *Missing Energy Supply* is presented in grey on [Figure 2](#), above all the possible supply for each type of primary energy. [Figure 3](#) provides a more detailed analysis with the *Missing Energy Supply* by primary energy (in light) directly displayed above the corresponding primary energy supply (in dark).

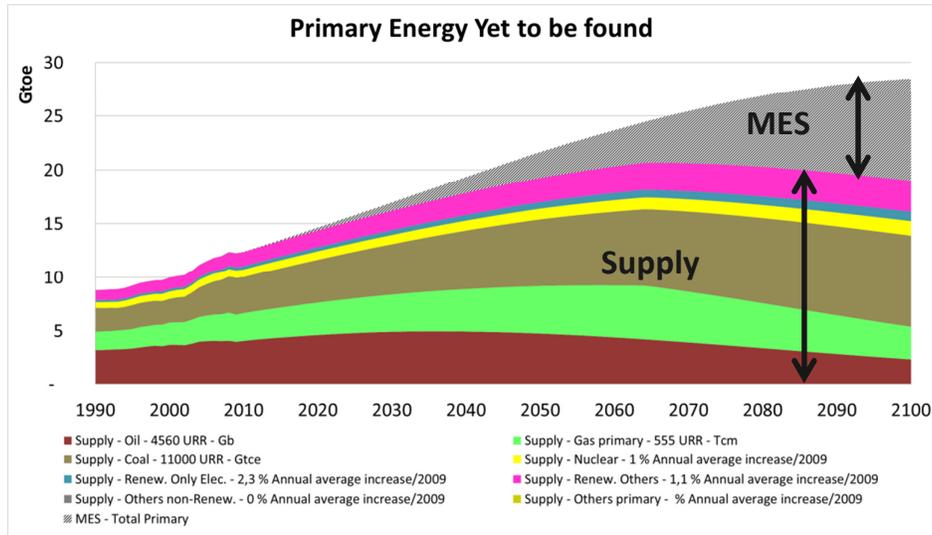


Figure 2: Missing Energy Supply graph

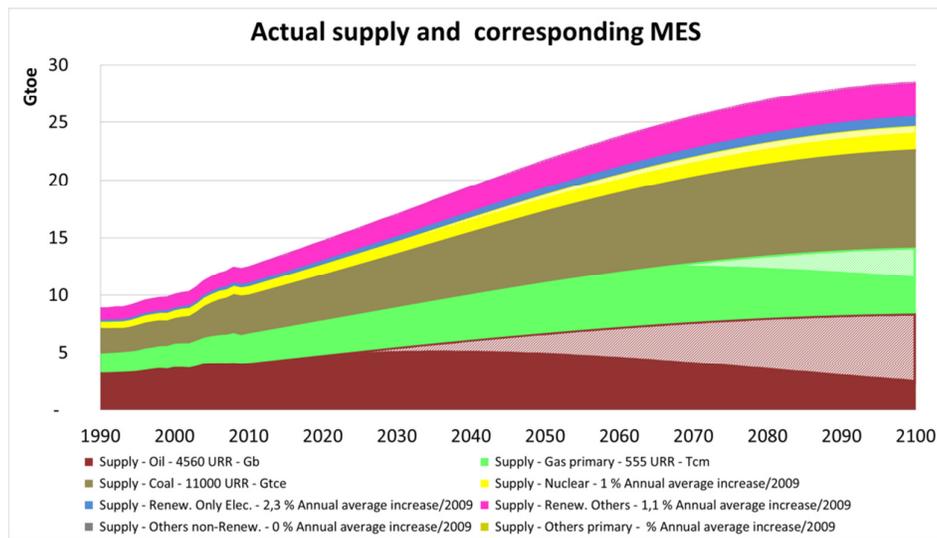


Figure 3: Missing Energy Supply by primary energy (light fillings)

Unlike classical economic models, this approach also provides an understanding of how quantities may be regulated in systems other than that of the free market (shortages, rationing, stringent regulation, etc.), which cannot be achieved by models based on demand and price elasticity.

Compared with sector-based approaches (limited to transport, housing or industry, for example), this method offers the advantage of taking account of transfers between sectors of consumption and the potential trade-offs between sectors against a background of global optimization.

This ends up the explanation of the global approach intended by the Rogeaulito model. The following section focuses on the description of the four main parts compounding Rogeaulito, and by which the designing scenario process is made possible. The Core of Rogeaulito will be presented first, followed by the three modules: the demand, the supply and the conversion. For each one of these four Rogeaulito's elements, the presentation is led alongside what follows: after a literal description, the

material focuses on the mathematical representation of the model, using the expression of the different parameters and variables, and its corresponding development through a Microsoft Excel implementation.

Rogeaullito - The structure and the processes

The presentation of Rogeaullito's components that follows is intended to provide good insight about the way the model has been designed. Prior to start this, some key elements are introduced below to let the reader know about the vocabulary and the conventions that are going to be widely used in this document.

1. Preliminary notions

1.1. Primary and final energy

When it comes to energy considerations, this is of main importance to understand the differences between primary energy, final energy, and useful energy. The following definition can be provided:

- **Primary energy:** represents the energy resources under their primary state as we can find them in nature. It can either be fossil energies such as coal, oil and gas or uranium, biomass wind and solar energy. In Rogeaullito, we use as a primary energy base B_p the following entities :

$B_p = \{\text{Oil, Gas (primary), Coal, Nuclear, Renewables Only for Electricity, Renewables for Other Uses, Others Non-renewable, and Others Primary Products}\}$

- **Final energy:** describes the energy as it is delivered to the end-user to enable him to run his own devices, such as gasoline for car, electricity for TV, town gas for heating and cooking, etc. It is measured and billed at the delivery point. As for the primary energy, we use a final energy base B_f :

$B_f = \{\text{Liquid fuels, Gas (final or town gas), Solid Fuels, Electricity, Heat and Other Final Energies}\}$

- **Service:** this term is more conceptual than the previous ones. It embodies the actual service provided by the use of a given final energy. Heat, mobility and mechanical work are good examples of services issued from final energy utilization.

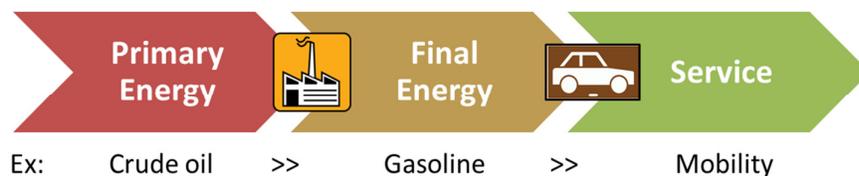


Figure 4: The 3 types of energy

Figure 4 shows a possible chain between primary and useful energy, passing through the final energy form.

1.2. The energy vectors

When one talks about energy demand, it implies final energy carriers while the supply refers to primary energy carriers. The energy carriers are gatherings of several energy products that IEA have

listed and specifically sorted out. The [Appendix 2](#) presents this projection of the products into two main bases, Bp, the primary base, and Bf, the final base. The number of main energy carriers within each base has been set arbitrarily by TSP. There are 7 carriers for the primary base, 5 for the final one. Thus, when it comes to describe either an energy demand or supply, we use the vector form to express them in the right base, with the right carriers. [Table 1](#) introduces possible final demand and primary supply vectors, with the energy amounts expressed in Gtoe. **In Rogeaulito, all the energy quantities are expressed in ktoe, or kilo ton oil equivalent.**

| Primary Energy | Gtoe | Final Energy | Gtoe |
|-------------------|------|--------------|------|
| Oil | 3.9 | Liquids | 3.5 |
| Gas primary | 2.5 | Gas final | 1.3 |
| Coal | 3.4 | Solids | 1.8 |
| Nuclear | 0.7 | Electricity | 1.4 |
| Renew. Only Elec. | 0.3 | Heat | 0.3 |
| Renew. Others | 1.3 | Others final | - |
| Others non-Renew. | 0.03 | | |
| Others primary | - | | |

Table 1: Example of a Demand Vector and a Supply Vector (IEA, World Energy Balance, 2009)

Therefore, the convention used in the next section, especially when equations are introduced, is the following:

- Square brackets [] mean that we express the variable under the vector form, either in Bf or Bp bases. It is also used for matrix expressed in both bases (a vector is a specific matrix).
- Thus, a [...] × [...] multiplication represents a matrix operation.
- Without these square brackets, we deal with classical variable representing a single quantity.

In order to establish properly the vector spaces in which the modeling process takes place, [Box 1](#) introduces the two bases presented above and the set of elementary vectors that compounds them.

Given Bp a vector space:

$$\dim(Bp) = 7$$

The canonical basis $\{bp_i\}$ of Bp is compound of unitary vector $[bp_i]$.

$$[bp_i] = (\delta_{1,i}, \delta_{2,i}, \dots, \delta_{7,i}) = \begin{bmatrix} \delta_{1,i} \\ \delta_{2,i} \\ \delta_{3,i} \\ \delta_{4,i} \\ \delta_{5,i} \\ \delta_{6,i} \\ \delta_{7,i} \end{bmatrix} \text{ where}$$

$$\delta_{i,j} = 1 \text{ when } i = j$$

$$\delta_{i,j} = 0 \text{ when } i \neq j$$

with i and $j \in \llbracket 1; 7 \rrbracket$.

A given primary energy quantity $ep_{i,y}$, representing an annual energy flow of the carrier i , for the year y , can be defined as:

$$ep_{i,y} \times [bp_i]$$

given $ep_{i,y}$ a real number $\in IR_+$, usually expressed in toe (ton oil equivalent)

i refers to a specific primary energy carrier. Thus, it is possible to set the references as follows:
 $i=...$ 1 for Oil, 2 for Gas (primary), 3 for Coal, 4 for Nuclear, 5 for Renew. Only Elec., 6 for Renew. Others and 7 for Others non-Renew.

Therefore, a primary energy vector for the year y , as presented previously in Table 1, is mathematically defined as:

$$[PS_y] = \sum_{i=1}^7 ep_{i,y} \times [bp_i] \text{ and } [PS_y] \in Bp \text{ defined by the canonical base } \{bp_i\}$$

Same description is provided for the vector space Bf referring to the final energy carriers:

$$\dim(Bf) = 5$$

The canonical basis $\{bf_i\}$ of Bf is compound of unitary vector $[bf_i]$.

$$[bf_i] = (\delta_{1,i}, \delta_{2,i}, \dots, \delta_{5,i}) = \begin{bmatrix} \delta_{1,i} \\ \delta_{2,i} \\ \delta_{3,i} \\ \delta_{4,i} \\ \delta_{5,i} \end{bmatrix} \text{ where}$$

$$\delta_{i,j} = 1 \text{ when } i = j$$

$$\delta_{i,j} = 0 \text{ when } i \neq j$$

with i and $j \in \llbracket 1; 5 \rrbracket$.

A given final energy quantity $ef_{i,y}$, representing an annual energy flow of the carrier i , for the year y , can be defined as:

$$ef_{i,y} \times [bf_i]$$

given $ef_{i,y}$ a real number $\in IR_+$, usually expressed in toe (ton oil equivalent).

i refers to a specific final energy. Thus, it is possible to set the references as follows:

$i=...$ 1 for Liquids, 2 for Gas (final), 3 for Solids, 4 for Electricity and 5 for Heat.

Therefore, a final energy vector for the year y , as presented previously in Table 1, is mathematically defined as:

$$[FD_y] = \sum_{i=1}^5 ef_{i,y} \times [bf_i] \text{ and } [FD_y] \in Bf \text{ defined by the canonical base } \{bf_i\}$$

The reader understood that $[PS_y]$ is the standard notation for expressing a given primary energy supply vector, while $[FD_y]$ represents a given final energy demand vector, y standing for the year considered.

Box 1: the primary and the final bases

1.3. Time considerations

Modeling with Rogeaulito has been designed to be simple and clear. Therefore, the way energy quantities are built does not involve more than basic additions and multiplications of different parameters that are up to the user to set. These cursors have been selected by TSP according to the energy flow we wanted to model and the physical parameters that looked relevant to be highlighted. This approach is introduced in Figure 5 where the cursor setting is clearly presented: the user must prolong the evolution of the cursors until 2100, relying on the 20 past years' historical data.

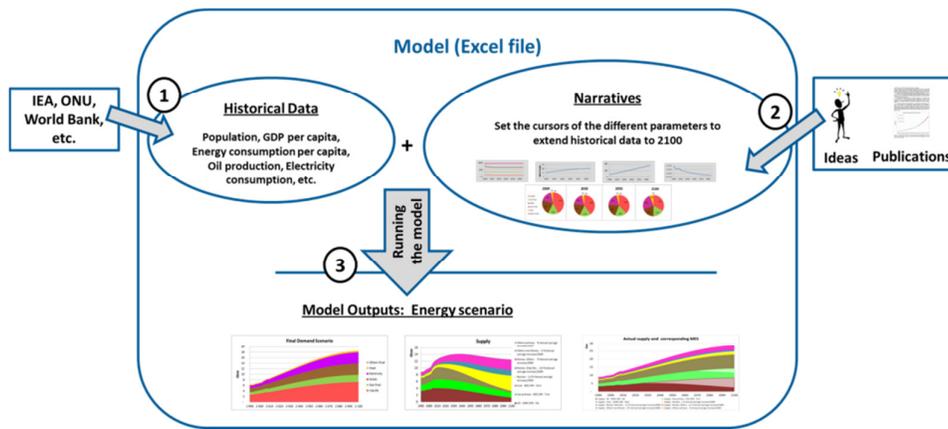


Figure 5: Modeling with Rogeaulito

We want here to clearly mention that Rogeaulito does not pretend to be a dynamic simulation tool but a confrontation one operating within a prospective framework for energy system study. The dynamic evolution with time for all parameters, represented by the cursors, is actually exogenous and set by hand by the user with a set of shapes described by Appendix 3. These shapes, representing different type of evolution, are illustrated in Figure 6. To summarize, each cursor is provided with this set of shapes that the user must edit to get its time evolution. We remind here that the time range considered in Rogeaulito is 1990-2009 for the historical data, and 2010-2100 for the prospective years.

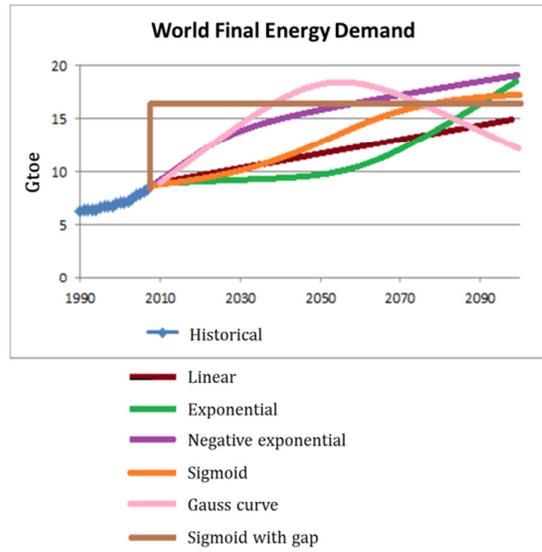


Figure 6: Different evolution types for the cursors

2. Rogeaulito, the Core

The core of Rogeaulito is the part where the final calculations to get the results from a given work are operated. From three inputs coming respectively from the demand module, the supply module and the conversion module, Rogeaulito Core confronts, for each year y from 2010 to 2100, a final energy demand to a primary energy supply to reveal the energy that might be lacking in the future to make both of them match. To do so, the final energy vector $[FD_y]$ designed with the demand module is converted into an equivalent primary energy demand with the help of a set of conversion parameters $[Cp_y]$ issued from the conversion module, and intended to integrate the different losses of the energy sector and the primary/final mix. This enables Rogeaulito Core to compare the demand, now expressed in primary terms, with the supply vector $[PS_y]$ designed with the supply module. This difference, between demand and supply, results in the *Missing Energy Supply* vector $[MES_y]$. By convention, the MES cannot be inferior to 0, and when this occurrence is observed, the MES is automatically set to 0. [Box 2](#) gathers the fundamental equations that enable the calculation of the MES.

For every year $y \in [2010; 2100]$, the following equations are to be considered

Given a final demand vector for the year y :

$$(1)$$

$$[FD_y] = \sum_{i=1}^5 ef_{i,y} \times [bf_i]$$

Where

$[FD_y]$ is a 5 lines and 1 column matrix expressed in Bf

Given the conversion parameters for the year y :

$$[Cp_y]$$

$[Cp_y]$ is a 5 lines and 7 columns matrix expressed in the vector space $Bf \times Bp$

The induced primary equivalent demand can be described as:

$$(2)$$

$$[FD_y]^T \times [Cp_y] = \left[\sum_{i=1}^5 ef_{i,y} \times [bf_i] \right]^T \times [Cp_y]$$

By deduction, the induced equivalent demand for the primary energy j is:

$$\sum_{i=1}^5 ef_{i,y} \times Cp_{i,j,y}$$

Therefore, for the primary energy j , we define $MES_{j,y}$ as:

$$(3)$$

$$\forall j \in \llbracket 1; 7 \rrbracket$$

$$\text{If } \sum_{i=1}^5 ef_{i,y} \times Cp_{i,j,y} - ep_{j,y} > 0, \mathbf{MES}_{j,y} = \sum_{i=1}^5 ef_{i,y} \times Cp_{i,j,y} - ep_{j,y}$$

$$\text{If } \sum_{i=1}^5 ef_{i,y} \times Cp_{i,j,y} - ep_{j,y} \leq 0, \mathbf{MES}_{j,y} = \mathbf{0}$$

Where

$MES_{j,y}$ is the Missing Energy Supply of the year y for the primary energy j

$Cp_{i,j,y}$ is the set of conversion parameters of the year y

for the final energy i and the primary energy j

Then, the MES vector is built:

$$(4)$$

$$[\mathbf{MES}_y] = \sum_{j=1}^7 \mathbf{MES}_{j,y} \times [\mathbf{bp}_j] = \sum_{j=1}^7 (\sum_{i=1}^5 ef_{i,y} \times Cp_{i,j,y} - ep_{j,y}) \times [\mathbf{bp}_j]$$

Or globally presented as

$$(5)$$

$$[\mathbf{MES}_y] = \left[[\mathbf{FD}_y]^T \times [\mathbf{Cp}_y] \right]^T - [\mathbf{PS}_y]$$

Where

$[\mathbf{MES}_y]$ is the Missing Energy Supply vector for the year y expressed
in the vector space Bp

$[\mathbf{FD}_y]$ is a final energy demand vector for the year y expressed in the vector space Bf

$[\mathbf{Cp}_y]$ is the set of conversion parameters for the year y , expressed in both Bp and Bf

$[\mathbf{PS}_y]$ is a primary energy supply vector for the year y expressed in the vector space Bp

Box 2: Calculation of the Missing Energy Supply

The way $[FD_y]$, $[PS_y]$ and $[Cp_y]$ are designed is further explained in the following parts, dealing respectively with the demand module, the supply module and the conversion module.

3. The Demand Module

The Demand Module is the component of Rogeaulito that allows the design of final energy demand scenarios. A sectoral breakdown of the society and the economic world is proposed in which a purely physical approach or a Kaya description (see [Appendix 1](#)) is possible, as presented by the equations (6) and (7). The sectors considered are *Buildings, Industry, Transport, Agriculture and Fishing, and Others and Non-energy Uses*. Each sector can be split into several sub-sectors. The sectors and sub-sectors breakdowns have been selected in compliance with the IEA convention. The detail of the global breakdown considered in this module is presented by [Figure 7](#). The physical approach reveals its interesting features when it comes to treating each sector and sub-sector by setting physical cursors. These cursors, when combined, give an energy demand per capita for the given sector. Then, the energy mix of the demand relative to the sector studied must be set to express it within the final base B_f . As the population evolution must be set as well, the multiplication of the later by the final demand per capita gives a final energy demand for the sector, and all the sectors summed gives the final energy demand for the global system considered (8). For the Kaya's description, the GDP factor is introduced via the GDP per capita and the energy intensity of the GDP. An extension by sector is available, as presented by the equation (9).

Given the final energy mix of the year y for a given final energy demand:

$$[M_y] = \sum_{i=1}^5 \%_{i,y} \times [bf_i]$$

Where

$[M_y]$ is the final energy mix of the demand for the year y expressed in the vector space B_f

$\%_{i,y}$ is the share of the final energy i in the final demand for the year y

And the final energy mix of the year y for a given final energy demand of the sector k :

$$[M_{k,y}] = \sum_{i=1}^5 \%_{i,k,y} \times [bf_i]$$

Where

$[M_{k,y}]$ is the final energy mix of the demand for the year y and

the sector k , expressed in the vector space B_f

$\%_{i,k,y}$ is the share of the final energy i in the final demand of the sector k for the year y

Two approaches to design the demand:

Physical approach

(6)

$$[FD_y] = epc_y \times [M_y] \times Pop_y$$

Or Kaya's equation

(7)

$$[FD_y] = GDPc_y \times E_y \times [M_y] \times Pop_y$$

The physical approach and the Kaya's description can be a combination of the different sectors:

(8)

$$[FD_y] = \sum_k epc_{k,y} \times [M_{k,y}] \times Pop_y$$

Where epc_k is deduced by simple operations between a given consistent set of physical cursors, which multiplied together give an energy demand per capita, for the sector considered (see [Figure 7](#) for the specific breakdown by sub-sectors).

(9)

$$[FD_y] = GDPc_y \times \sum_k E_{k,y} \times [M_{k,y}] \times Pop_y$$

Where

epc_y and $epc_{k,y}$ are respectively the final energy demand per capita for the year y ,
global and for the sector k (ktoe/cap)

$GDPc_y$ is the GDP per capita $\left(\frac{\$}{cap}\right)$ for the year y

E_y and $E_{k,y}$ are respectively the energy intensity of the GDP for the year y ,
global and for the sector k^1 (ktoe/\$)

Pop_y is the population(cap) for the year y

Box 3: Calculation of the final demand vector

The final demand vector $[FD_y]$ expressed in the base Bf is the output of the Demand Module, and is directly used by the Core of Rogeaulito to operate the calculation as seen in the corresponding section.

¹ Ek is obtained by dividing final energy consumption of the demand sector k by the global GDP (not a sectoral economic turnover)

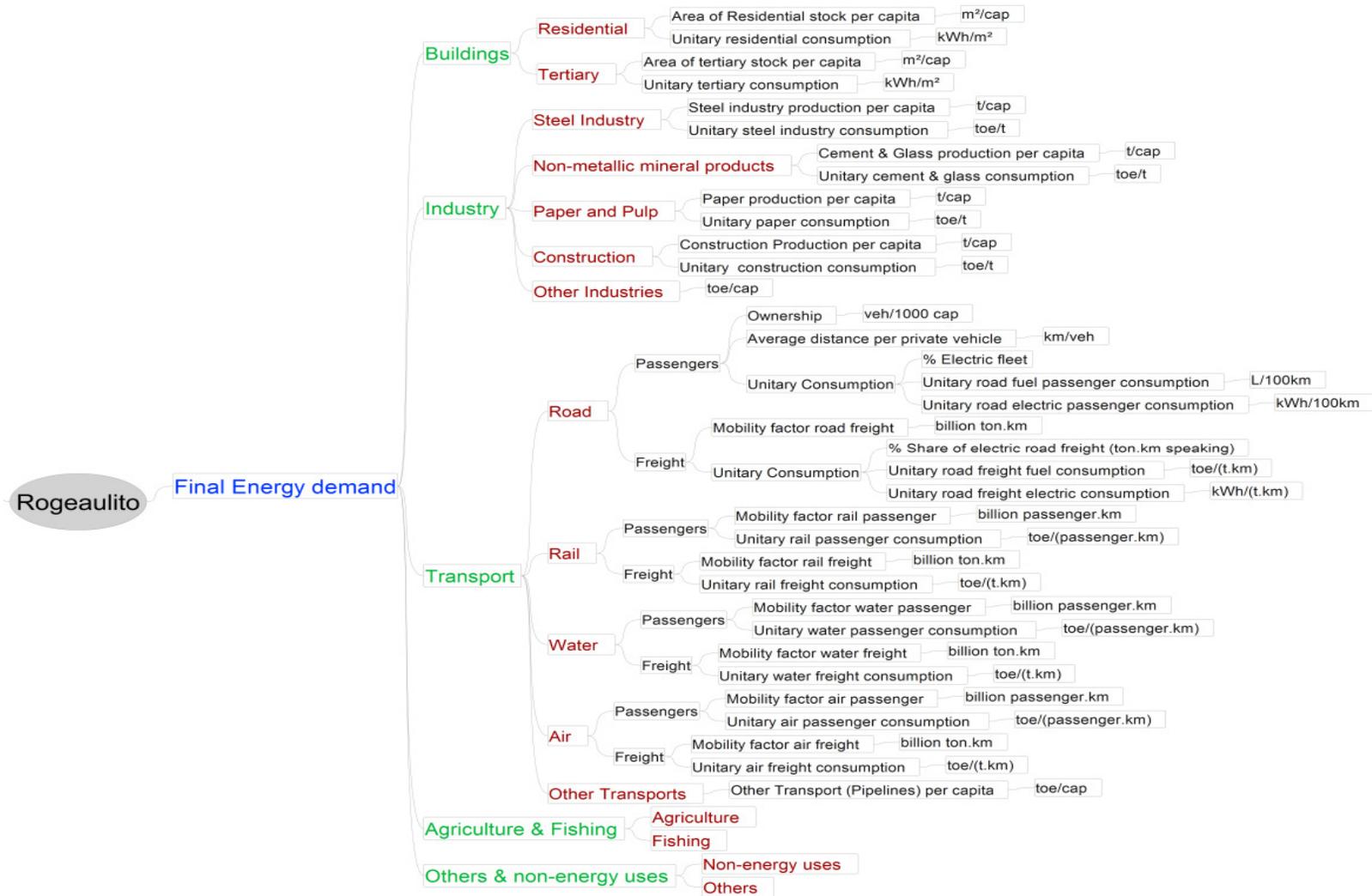


Figure 7: The sectorial breakdown and the physical approach of the Demand Module

4. The Supply Module

The Supply Module is the component of Rogeaulito that allows the design of possible primary energy supply scenarios. Still in compliance with the IEA convention, seven major primary energy resources, split into their corresponding sub-resources, are to be set under physical considerations. The breakdown of the primary energy products and the different physical cursors enabled by the tool design are presented in [Figure 8](#). The purpose is to define the evolution of the energy production of each one of these resources. The physical approach has been developed according to the characteristics of each one of these energy carriers. Therefore, three main groups can be identified in this supply designing process:

1. The fossil fuels (Oil, Gas, Coal) projections are provided with logistic curves setting to illustrate the typical production profile and the finite aspect of the Ultimate Recoverable Resources (URR) that we can actually extract from the ground. We typically obtain bell-shaped curves corresponding to the URR allocated by the user and the shape of production curve defined.
2. The power plants (Nuclear, Renewables for electricity): the setting relies on the installed capacity and the load factor.
3. The other primary energy resources (Other Renewables, Others non-renewable) can be adjusted directly with the energy production or, for the Biomass case, by the use of specific parameters such as the area and the energy yield per hectare.

Once the different primary energy resources adjusted, the Supply Module gathers the data under a primary supply vector expressed in the base B_p , and given by the equation

(10).

(10)

$$[PS_y] = \sum_{j=1}^7 ep_{j,y} \times [bp_j] = \sum_{j=1}^7 \sum_k ep_{j,k,y} \times [bp_j]$$

Where

ep_{j,y} and *ep_{j,k,y}* are respectively the net primary energy supply from the primary resource *j*, and from the primary sub – resource *k* of the primary resource *j*, for the year *y*, expressed in the vector space B_p (ktoe).

1/ For fossil fuels, basically, the logistic curves used are issued from Hubbert's work:

(11)

$$ep_{j,y} = \frac{a \times URR \times \exp(-a \times (y - ym))}{(1 + \exp(-a \times (y - ym)))^2} \quad \text{with } j \in \{1; 3\}$$

Where

$ep_{j,y}$ is the primary energy supply from the fossil fuel resource j for the year y

(Gb for oil, bcm for gas, Mtce for coal)

y is the year considered

URR are the Ultimate Recoverable Resources (Gb for oil, bcm for gas, Mtce for coal)

$$a = \frac{URR \times (Production(y_0) + \frac{production\ slope(y_0-5; y_0)}{URR})}{Cumulated\ Production(y_0)^2 \times (\frac{URR}{Cumulated\ Production(y_0)} - 1)} \quad \text{constant depending on historical data}$$

$$ym = \frac{1}{a} \times \ln \left(\frac{URR}{Cumulated\ Production(y_0)} - 1 \right) + y_0 \quad \text{year at which half of the URR has been extracted}$$

For further information about the different variants of logistic curves proposed in the Supply Module, the reader is invited to refer to the

Appendix 4.

2/ For power plants, the primary supply is calculated as follows:

(12)

$$ep_{j,y} = \sum_k ep_{j,k,y} = \sum_k P_{j,k,y} \times 8760 \times cf_{j,k,y} \quad \text{with } j \in \{4;5\}$$

Where

$P_{j,k,y}$ is the installed capacity of the power plant type k of the primary energy j ,
for the year y

$cf_{j,k,y}$ is the capacity factor, or load factor, of the power plant type k
of the primary energy j , for the year y

3/ The last group of primary energy resources is set with a direct production cursors $ep_{j,y}$, except for biomass, whose following equations describe the particular way it is approached:

First, we set the possible energy potential of the biomass:

(13)

$$BS_y = BS_{forest,y} + BS_{crops,y} + BS_{waste,y} = A_{forest,y} \times EY_{forest,y} + A_{crops,y} \times EY_{crops,y} + BS_{waste,y}$$

Where

BS_y is the primary energy potential of the biomass resource for the year y (MJ)

$BS_{forest,y}, BS_{crops,y}, BS_{waste,y}$ are respectively the biomass energy potential
for forest, crops and waste for the year y (MJ)

$A_{forest,y}, A_{crops,y}$ are respectively the area considered for forestry
and crops biomass production for the year y (ha)

$EY_{forest,y}$ and $EY_{crops,y}$ are respectively the energy yield of
the forest and crops lands for the year y (MJ/ha)

Then, we need to set to what the biomass is going to be allocated, and the efficiency of the corresponding processes:

(14)

$$\theta_{l,y} + \theta_{s,y} + \theta_{g,y} = 1$$

(15)

$$0 \leq \eta_{l,y}, \eta_{s,y}, \eta_{g,y} \leq 1$$

Where

$\theta_{l,y}, \theta_{s,y}, \theta_{g,y}$ are respectively the shares of biomasse allocated to liquid, solid and gazeous fuels production for the year y
 $\eta_{l,y}, \eta_{s,y}, \eta_{g,y}$ are respectively the conversion efficiencies for biomass to liquid, biomass to solid and biomass to gas processes for the year y

Finally, we get the primary energy supply provided by the biomass resource:

(16)

$$ep_{biomass,y} = BS_y \times \theta_{l,y} \times \eta_{l,y} + BS_y \times \theta_{s,y} \times \eta_{s,y} + BS_y \times \theta_{g,y} \times \eta_{g,y}$$

Where

$ep_{biomass,y}$ is the primary energy supply issued from biomass for the year y (MJ)

Box 4: Calculation of the primary energy supply vector

The primary supply vector $[PS_y]$ expressed in the base Bp is the output of the Supply Module, and is directly used by the Core of Rogeaullito to operate the calculation as seen in the corresponding section.

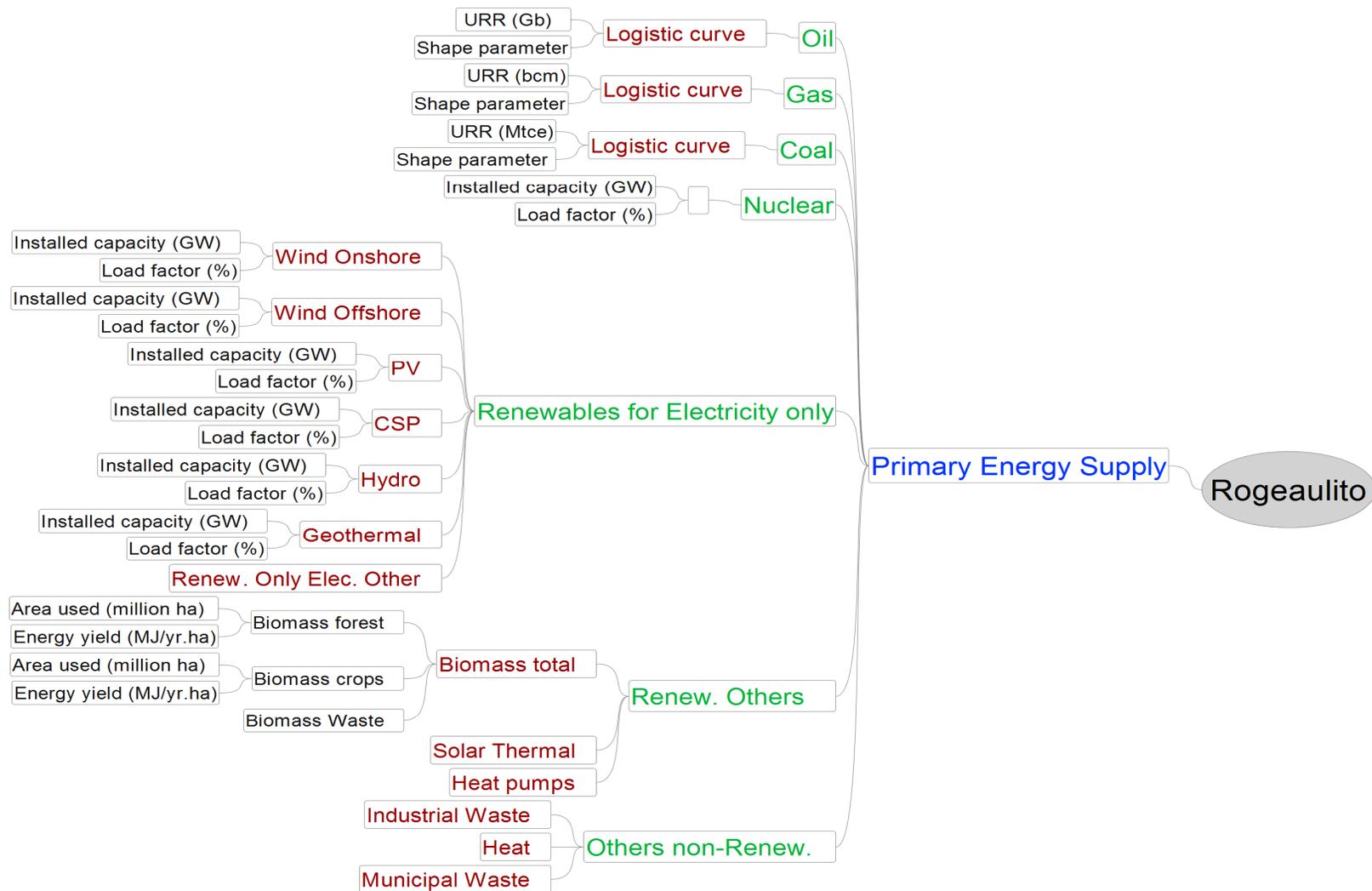


Figure 8: The primary energy breakdown and the physical approach of the Supply Module

5. The Conversion Module

The Conversion Module is a model of the energy sector that stands in between the two main sides of the energy system, the final demand and the primary supply. It makes a link between them. When talking about the energy sector in Rogeaulito, we consider all the extraction, transformation and transportation units lying in between our primary energy resources and our final energy consumption. Concretely, the set of parameters adjusted in this module are intended to convert a desired final energy demand vector into an equivalent primary energy demand so as to compare it with a possible primary supply vector within the same referential, i.e. the primary energy base Bp.

Briefly summarized, the hypotheses embedded in the conversion module impact the way primary energy supplies are converted into final energy in the projections. The two main groups of parameters at stake are related to the allocation of energy carriers and the efficiency of their transformations. The objective of the conversion module is to allow an exploration of the consequences of a variation of these parameters on a future modeled energy system.

5.1. The approach

The various transformation units considered in this module are the one identified in the IEA database. They consist in the following ones:

Heat and electricity power plants

AUTOCHP & MAINCHP refer to plants producing both heat and electricity. It is either main activity producers or auto producers.

AUTOELEC & MAINELEC refer to plants producing electricity only. It is either main activity producers or auto producers.

AUTOHEAT & MAINHEAT refer to plants producing heat only. It is either main activity producers or auto producers.

Heat specific

TBOILER gathers electric boilers used to produce heat.

THEAT regroups the heat pumps. Private heat pumps from the residential sector are not included here.

TELE is the heat recuperated from chemicals processes and intended to generate electricity.

Coal and gas factory

TBLASTFUR is the production of recovered gases from the different type of blast furnaces of the iron industry.

TBLENDGAS includes all the gases that may be blended with natural gas.

TGASWKS are the town gas manufacturers.

TBKB are manufacturer of lignite briquettes.

TCHARCOAL is the coal issued from solid biofuels.

TCOKEOVS are coke and coke oven gas manufacturers.

“To liquids” technologies

TCOALLIQ are the processes intended for synthetic oil production from coal, oil and tar sands.

TGTL gathers the processes converting natural gas into liquid fuel.

Refineries and petro chemistry

TREFINER represents the refineries that convert crude oil into finished oil products.

TPETCHEM are the backflows treatment of the products from the petrochemical industry.

Others

TPATFUEL gathers all the manufacturers of patent fuels.

TNONSPEC gathers all the non-specified transformations.

Box 5: IEA's transformation units' codes

We reproduce in [Appendix 5](#) the detailed descriptions of transformation flows addressed by the IEA statistics scope (IEA, Energy Balances Of OECD Countries, 2012).

All the transformation units are affected with statistics figures corresponding to their activity within the energy system, i.e. quantities of which products they transform into which products. The whole constitutes an overall detailed view of the energy system. Our goal within the modeling task we need to carry out for Rogeaullito's development is to design a Conversion Module that will represent under simplified parameters the complexity of the actual system. To do so, the modeling work must handle the raw statistics data to process, synthesize and represent them under clear and simple format. Basically, the data process method relies on the identification of the energy pathways and on the projection of the energy products on their corresponding base product (in $\{bp_i\}$ or $\{bf_i\}$). We pass from a multi-dimensional system to a simpler one, described by a two vector spaces, Bp and Bf, whose respective dimensions of 7 and 5 give a maximum dimension of 35. The objective is to isolate the main energy flows and make possible the adjustments of a set of relevant cursors.

These cursors are the standards used in the Conversion Module, so their characteristics and specifications must comply with the final expectations defined as:

- Being able to set the main efficiencies of the transformations processes in which energy carriers are converted (simulating technology evolution or yield improvement/deterioration).
- Being able to change the allocation of the primary energy to consider the uses changes.
- Being able to simulate an evolution of the losses in energy transportation/distribution processes.

Concretely, these considerations are going to provide a losses vector and a conversion matrix, the later gathering the efficiencies and primary energy allocation data.

The data processing of the IEA database, the basements of the Conversion Module, is presented further within section 5.2.

Therefore, what we consider as the main parameters are:

- The conversion efficiencies
- The auto-consumption of the transformation units
- The distribution losses (for final energy)
- The share of primary energy non-transformed, i.e. the amount of energy going directly to our final consumption without any conversion.
- The primary mix of the final energy carriers.

Figure 9 displays the different losses through the whole chain.

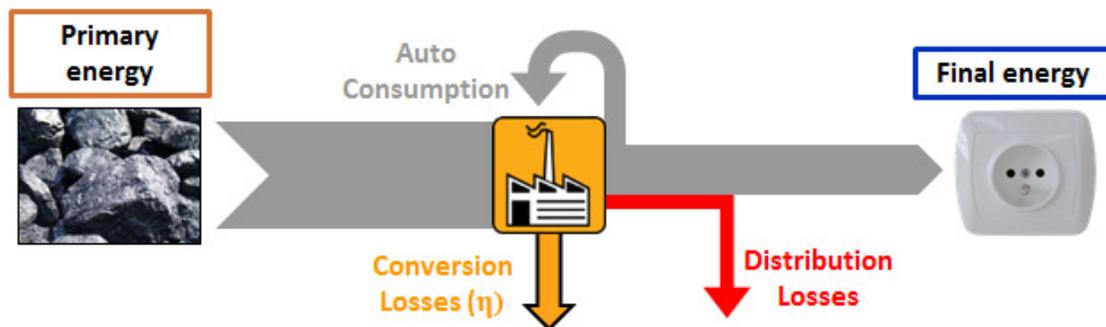


Figure 9: Losses from primary to final energy

These parameters are adjustable in the Conversion Module. Counter to the Demand and Supply modules, the setting is not made year by year but for three milestone years: 2030, 2050 and 2100. A linear interpolation is performed downstream to get the yearly data we need. What we set step by step in this module are the following parameters:

Step 1

- The efficiencies of the electricity and heat power plants according to the primary energy converted by the plant.
- The share of CCS technologies within the heat and electricity power plant fleet.
- The efficiencies of the rest of the transformation/conversion units

Step 2

- The auto-consumption of the all the transformation/conversion units, expressed as a percentage of the demand for each final energy (base Bf).
- The distribution losses for each type of final energy, expressed as a percentage of their corresponding demand (base Bf).

Step 3

- The share of non-transformed primary energy within the supply side. It is important to remove these quantities since they do not go through all the conversion process with the related losses. They are expressed for each primary energy resource as a percentage of the total amount of their quantity supplied (base Bp).

Step 4

- The primary mix of each type of final energy. This corresponds to a Bf/Bp matrix in which the primary origins of the final carriers are set.

Step 5

What we obtain from these settings are the outputs of the Conversion Module that are going to be used in Rogeaulito to convert the final demand vector [FD]. We will first introduce these outputs and the role they play before explain more in detail how we obtain them from the different parameters set previously. Among them, the conversion matrix [MC] plays a crucial role.

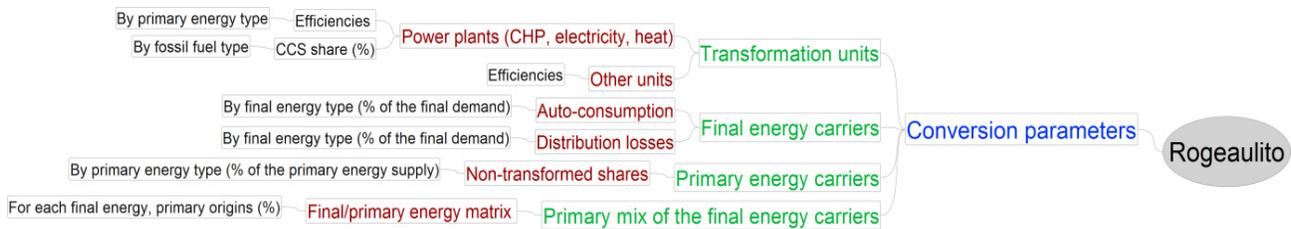


Figure 10: The parameters to be set in the Conversion Module

For the Conversion Module, $y \in \{2010; 2030; 2100\}$

Step 1

Transformation units

Power plants

First, we set the efficiencies by primary energy. Let's write it down:

$$(17)$$

$$[Eta_{p,y}] = \sum_{j=1}^7 eta_{p,j,y} \times [bp_j] = \begin{bmatrix} eta_{p,oil} \\ \dots \\ eta_{p,non\ renew.} \end{bmatrix} \quad \text{with } j \in \llbracket 1; 7 \rrbracket \quad \text{matrix } (7;1)$$

Where

p gathers the three types of power plants, CHP, electricity and heat

$[Eta_{p,y}]$ is the efficiency vector for the power plant type *p*, for the year *y*,
expressed in the vector space Bp

$eta_{p,j,y}$ is the efficiency for the primary energy j of the power plant p , for the year y

Before going further, we need to choose whether we apply some CCS technologies. The CCS deployment is responsible of decreasing the efficiencies of the thermal power plants. This is why for each type of power plant (CHP, electricity, heat) and each type of fossil fuel used (oil, gas, coal), we set the share of CCS in the fleet and the influence on the efficiencies (number of point lost):

(18)

$$eta_{p,jccs,y} = eta_{p,j,y} \times (1 - CCS_{p,j,y}) + (eta_{p,j,y} + PL_{p,j,y}) \times CCS_{p,j,y} \quad \text{with } j \in \llbracket 1; 3 \rrbracket$$

Where

$eta_{p,jccs,y}$ is the efficiency of the power plant type p for the fossil fuel j after having applied CCS, for the year y

$CCS_{p,j,y}$ is the share of CCS technologies present in the power plant fleet for the type p and the fossil fuel j , for the year y

$PL_{p,j,y} \leq 0$ is the point loss for the efficiency $eta_{p,j,y}$ of the power plant type p operated with fossil fuel j , for the year y

We can now get the new vector for the power plant efficiencies:

(19)

$$[Eta_{pccs,y}] = \sum_{j=1}^3 eta_{p,jccs,y} \times [bp_j] + \sum_{j=4}^7 eta_{p,j,y} \times [bp_j] \quad \text{matrix } (7;1)$$

Where

$[Eta_{pccs,y}]$ is the efficiency vector for the power plant type p after CCS setting, for the year y , expressed in the vector space B_p

Overall transformation units

Then, the calculation of the global efficiencies is made with proportion to the shares of primary energy type in the primary energy consumption of the plants. With the help of the primary mix of the power plants, we establish their global efficiency:

(20)

$$[Eta_{p,y}] = [Eta_{pccs,y}] \times [M_p] \quad \text{matrix } (7;1)$$

Where

$Eta_{p,y}$ is the global efficiency for the power plant type p (CHP, electricity or heat), for the year y

$[M_p]$ is the primary mix of the consumption of the power plant type p ,

*kept as a constant in the model in order to decrease software development complexity,
and expressed in the vector space Bp*

Finally, we set the efficiencies for the other transformation units, to get the efficiency table:

$$[Eta_{all,y}] \quad \text{for the year } y$$

$[Eta_{all,y}]$ is a 18 lines and 1 column matrix, the 18 lines corresponding to the 18 transformation units included in the Conversion Module. It is exported in a special model in Access in which some data processing codes aggregate the IEA energy flows with the use of $[Eta_{all,y}]$. This specific process, whose purpose is to deal with all the major transformation units' efficiencies, calculates a corresponding and aggregated $[Eta_y]$ matrix. The methodology applied here is presented in the next section 5.2. $[Eta_y]$ is reused afterwards in the Conversion Module to calculate the conversion matrix $[MC_y]$, as presented in step 5.

$[Eta_y]$ can be expressed as follows:

(21)

$$[Eta_y] = \sum_{j=1}^7 \sum_{i=1}^5 eta_{i,j,y} \times [bf_i] \times [bp_j]^T \quad \text{matrix (5;7)}$$

Where

*eta_{i,j,y} is the aggregated efficiency for the overall conversion process
between primary energy j and final energy i, for the year y*

Step 2

Auto consumption setting:

(22)

$$[AC_y] = \sum_{i=1}^5 AC_{i,y} \times [bf_i]$$

Distribution losses setting:

(23)

$$[DL_y] = \sum_{i=1}^5 DL_{i,y} \times [bf_i]$$

Where

*$[AC_y]$ is the auto consumption vector for final energy,
for the year y, expressed in the vector space Bf*

*AC_{i,y} is the auto consumption referring to the final energy i, for the year y,
expressed as a percentage of the final energy demand for i*

$[DL_y]$ is the distribution losses vector for final energy, for the year y ,
expressed in the vector space B_f

$DL_{i,y}$ is the distribution losses referring to the final energy i , for the year y ,
expressed as a percentage of the final energy demand for i

Step 3

Shares of non-transformed primary energy:

$$(24)$$

$$[NoT_y] = \sum_{j=1}^7 NoT_{j,y} \times [bp_j]$$

Where

$[NoT_y]$ is the non – transformed vector for primary energy,
for the year y , expressed in the vector space B_p

$NoT_{j,y}$ is the non – transformed share referring to the primary energy j , for the year y
expressed as a percentage of the primary energy supply for j

The shares of non-transformed primary energy are used to calculate the matrix $[Eta_y]$ previously introduced in step 1.

At this step, we can write the following equation:

$$(25)$$

$$[Eta_y] = f([Eta_{all,y}], [NoT_y])$$

Step 4

The primary share of the energy j for the final energy i mix can be written as:

$$\%_{i,j,y} \quad \text{with } i \in [1; 5] \text{ and } j \in [1; 7], \text{ for the year } y$$

The primary distribution within the final energy distribution can be expressed by the following matrix (5;7):

$$(26)$$

$$[N(R_f)_y] = \sum_{j=1}^7 \sum_{i=1}^5 \%_{i,j,y} \times [bf_i] \times [bp_j]^T$$

$$= \begin{bmatrix} \%_{el,oil} & \%_{el,gasp} & \%_{el,coal} & \%_{el,nuc} & \%_{el,renew.el} & \%_{el,renew.} & \%_{el,oth.} \\ \%_{liq,oil} & \%_{liq,gasp} & \%_{liq,coal} & \%_{liq,nuc} & \%_{liq,renew.el} & \%_{liq,renew.} & \%_{liq,oth.} \\ \%_{gasf,oil} & \%_{gasf,gasp} & \%_{gasf,coal} & \%_{gasf,nuc} & \%_{gasf,renew.el} & \%_{gasf,renew.} & \%_{gasf,oth.} \\ \%_{sol,oil} & \%_{sol,gasp} & \%_{sol,coal} & \%_{sol,nuc} & \%_{sol,renew.el} & \%_{sol,renew.} & \%_{sol,oth.} \\ \%_{heat,oil} & \%_{heat,gasp} & \%_{heat,coal} & \%_{heat,nuc} & \%_{heat,renew.el} & \%_{heat,renew.} & \%_{heat,oth.} \end{bmatrix}$$

Where

$[N(R_f)_y]$ is the matrix gathering the primary mix of each final energy,
for the year y , expressed in the vector space $B_f \times B_p$

$\%_{i,j,y}$ is the primary share of the energy j for the final energy i , for the year y

The big matrix presented in the equation (26) introduces the way this energy mix is written.

Step 5: outputs

Finally, by aggregating the parameters set, we build up the outputs of the module that are going to be used in Rogeaulito. $[AC_y]$ and $[DL_y]$ matrices are kept as they are.

As presented in step 1, we get the $[Eta_y]$ matrix, aggregation of the different energy flows and conversion efficiencies of the energy sector, in a single simplified matrix. Combined to $[N(R_f)_y]$ we can calculate a matrix that enable the conversion between a final demand into the equivalent primary one, the matrix $[MC_y]$:

(27)

$$[MC_y] = \sum_{j=1}^7 \sum_{i=1}^5 \frac{\%_{i,j,y}}{eta_{i,j,y}} \times [bf_i] \times [bp_j]^T \quad \text{matrix (5;7)}$$

This actually represents a term by term division between the matrix $[N(R_f)_y]$
and the matrix $[Eta_y]$.

Where

$[MC_y]$ is the conversion matrix expressed in the vector space $B_f \times B_p$

We can then introduce the global conversion factor, $[Cp_y]$, that gathers the three main conversion data set and required to run Rogeaulito Core: $[AC_y]$, the auto-consumption factor, $[DL_y]$, the distribution losses factor, and $[MC_y]$, the conversion matrix.

(28)

$$\forall i \in [1; 5] \text{ and } \forall j \in [1; 7]$$

$$Cp_{i,j,y} = (1 + AC_{i,y} + DC_{i,y}) \times MC_{i,j,y}$$

(29)

$$[Cp_y] = \sum_{j=1}^7 \sum_{i=1}^5 Cp_{i,j,y} \times [bf_i] \times [bp_j]^T \quad \text{matrix (5;7)}$$

Where

$MC_{i,j,y}$ is the conversion matrix element for the final energy i , relative to the primary energy j , for the year y

$Cp_{i,j,y}$ is the conversion parameter for the final energy i , relative to the primary energy j , for the year y

$[Cp_y]$ is the set of conversion parameters, expressed as a matrix in the vector space $B_f \times B_p$, for the year y

Box 6: Conversion Module's operations

The matrix $[Cp_y]$ is the output of the Conversion Module sent to Rogeaulito Core to enable the conversion of final energy demand vectors into their corresponding primary energy equivalent ones. The following section will explain the data process performed prior to the development of the Conversion Module, as stated previously. The main purpose is to describe the method leading to the identification of the energy pathways, the projection of the energy products into the primary and final bases, and the way we get the matrix $[MC_y]$ from the efficiencies we set and the non-transformed shares of primary energy we consider. This method is still applied in the conversion module to calculate $[MC_y]$ considering the user's settings.

5.2. Getting [MC]

Aims and objectives

Concretely, the conversion module provides Rogeaulito with conversion matrices, distribution losses factors and auto-consumption factors for the three milestone years considered: 2030, 2050 and 2100. As we need yearly based information, data in-between years are interpolated. The conversion matrix gathers the three parameters yet to be considered, the conversion efficiencies, the non-transformed shares and the primary mix of the final energy. Let's keep in mind the following equations:

(21) and (25)

$$[Eta_y] = f([Eta_{all,y}], [NoT_y]) = \sum_{j=1}^7 \sum_{i=1}^5 eta_{i,j,y} \times [bf_i] \times [bp_j]^T$$

(26)

$$[N(R_f)_y] = \sum_{j=1}^7 \sum_{i=1}^5 \%_{i,j,y} \times [bf_i] \times [bp_j]^T$$

(27)

$$[MC_y] = \sum_{j=1}^7 \sum_{i=1}^5 \frac{\%_{i,j,y}}{eta_{i,j,y}} \times [bf_i] \times [bp_j]^T$$

$[Eta_y]$ is a **matrix** which gathers the **global conversion efficiencies** from primary to final energy. $[Eta_y]$ come from the processing of the transformation efficiencies and data that can be identified in the IEA database. For our yearly based model, we need the historical value for $[MC_y]$, and therefore $[Eta_y]$, between 1990 and 2009. This is why we have developed a method to process IEA data and get them under the format we need, which is the matrices presented above.

Handling the modeling process

This section is an introduction to the data processing description we provide afterwards. It is dedicated to present what are the needs and what is at stake.

First of all, it must be reminded that the Conversion Module has to consider some specific points to build up from a mere final energy demand vector the corresponding one in the primary base with all the energy losses and the assumed energy allocation between final and primary energy. These points have been described in the section 5.1. From all of them, we are able to convert the final energy demand vector into an equivalent one in terms of primary energy, applying a calculation method which is illustrated by [Figure 11](#).

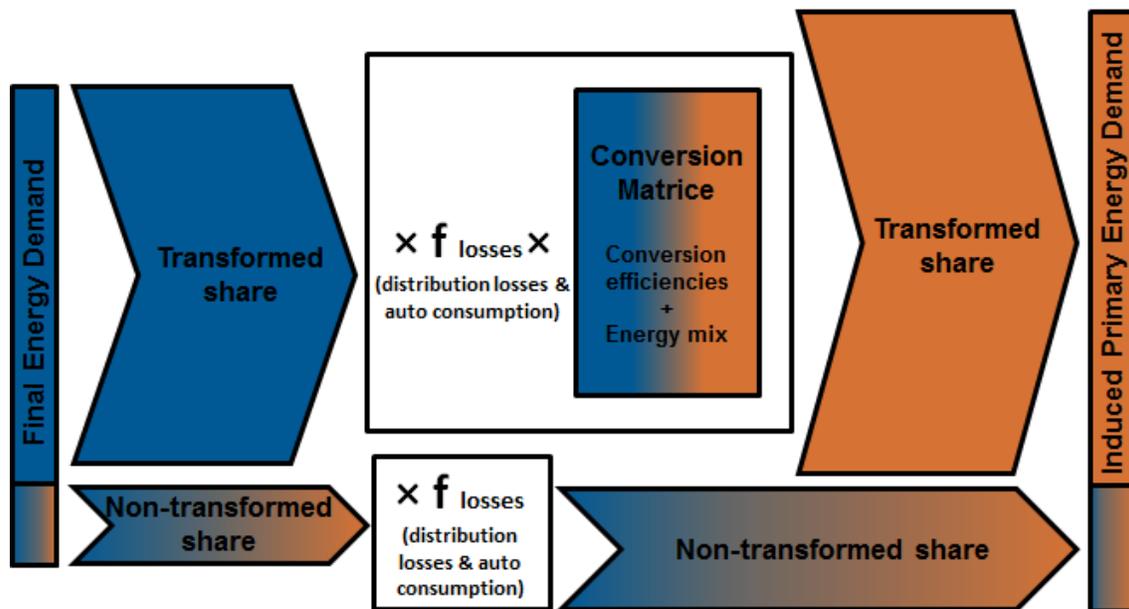


Figure 11: From the demand to the induced demand

To summarize, obtaining the induced primary energy demand from the wished demand requires us to set:

- The energy mix between final and primary energy
- The efficiencies of the transformation units (conversion losses)

- **The distribution losses**
- **The auto consumption of the transformation units**

All data is contained in the IEA database, from 1990 until 2009. Nevertheless, to actually get them we have to operate some calculations within the database. Indeed, IEA database is made of lines with their corresponding values and they do not provide us directly with the desired information. **This data processing is the critical step for the development of the conversion module since it has to be carefully done in order not to miss some energy or to double account some of it.** As related before, we need to process thousands of data lines to represent the energy system characteristics in our simplified dimension space (Bp, Bf, 7 and 5 carriers each). This is the subject of the following sections. They deal with the *Thinking process* and the *Access development* tasks. They will mainly focuses on the method applied to find out the **energy allocation between final and primary energy** and **efficiencies of the transformation sector** since these two pieces of information enable us to set the conversion matrices. The finding of **distribution losses** and the **auto consumption** is also described in the ending part.

Data processing – Thinking process

Before starting any thinking activity on the conversion between primary and final energy, we need to set a list of specifications that we want to meet at the end for this data process.

Table 2 presents them and their purpose. One of the most important one is the ability of computerizing the process we will set up to quickly generate the date we require.

| Specifications | Purpose |
|---|--|
| Set a method than can be computerized | Automate data handling from the IEA database |
| Get the data for the whole time range considered: 1990-2009 | Get historical data to provide formatted useful information on the conversion module |

Table 2: Specifications table of the data treatment method we develop

Step 1 – The IEA Database

Here is introduced a didactic description of IEA statistics content in order to realize and understand the raw information that we process. For a given geographical zone and year, a line is made of a flow, a product and an energetic value (in ktoe). To be able to identify easier the interactions between flows and products, we have sorted out the lines in a matrix for a given year and a given zone as presented in Figure 12. **A minus value means that the product is consumed by the flow whereas a positive value means that the product is actually generated by a flow.** Each line of the matrix is isoenergetic, meaning that the energy conservation is verified.

| | Lignite | Peat | Other Coals | Crude Oil | Biomass | Heavy Oil | Briquettes | Electricity | Heat | Losses |
|--------------------|---------|-------|-------------|-----------|---------|-----------|------------|-------------|------|--------|
| Briquettes Factory | - 3.8 | - 1.0 | - 0.2 | | | | 4.7 | | | 0.3 |
| Refinery | | | | - 8.0 | | 7.5 | | | | 0.5 |
| CHP Plant | | | | | - 3.0 | - 7.5 | | 3.5 | 4.5 | 2.5 |

Figure 12: Example of IEA database sorted out in a matrix (in Mtoe)

Then it is interesting to imagine what this matrix actually represents. Figure 13 provides a visual representation with the energy flows gathered in the previous matrix. We can notice that these flows going from primary energy to the final one constitute energy pathways involving several energy products passing through different flows. It implicitly means that each one of these pathways is characterized by a given primary energy, an overall efficiency (which includes each specific efficiency) and a given final energy.

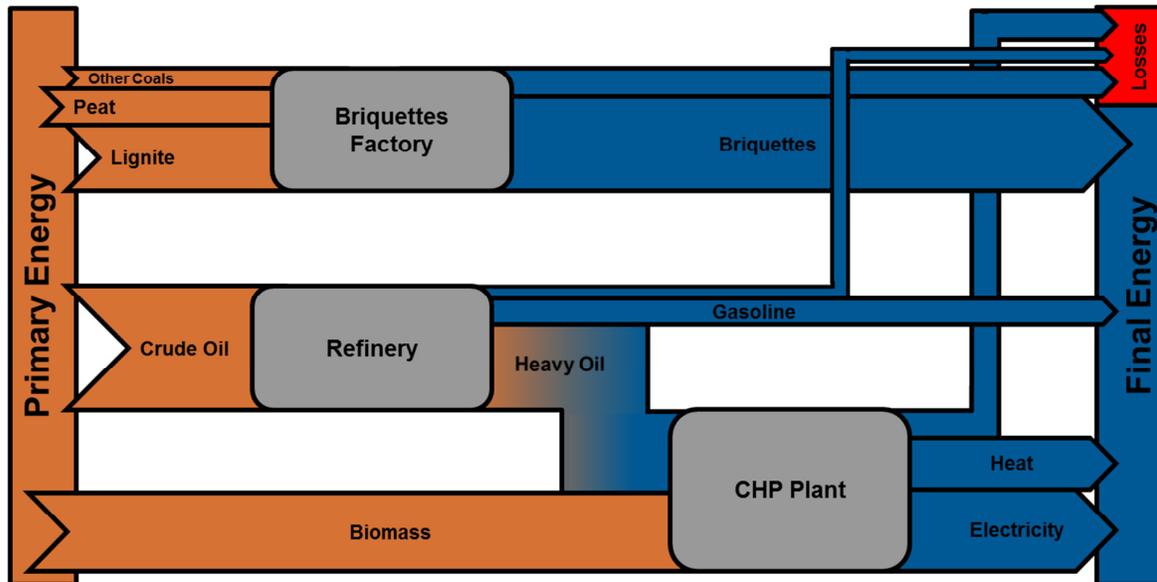


Figure 13: Energy pathways between primary and final

For instance, we can describe the following pathway from Figure 12 and Figure 13, presented in Table 3:

| Primary Energy (Product 1) | Flow 1 | Intermediate Product (Product 2) | Flow 2 | Final Energy (Product 3) |
|----------------------------|----------|----------------------------------|-----------|--------------------------|
| Crude Oil | Refinery | Heavy Oil | CHP plant | Electricity |

Table 3: Example of an energy pathway

On the Figure 14 we can draw this given pathway to clearly identify the values involved. Black arrows correspond to energy flows while red ones highlight the losses. It is then possible to complete the previous table with Table 4 gathering the efficiencies and the energy quantities.

| | Lignite | Peat | Other Coals | Crude Oil | Biomass | Heavy Oil | Briquettes | Electricity | Heat | Losses |
|--------------------|---------|------|-------------|-----------|---------|-----------|------------|-------------|------|--------|
| Briquettes Factory | -3.8 | -1.0 | -0.2 | | | | 4.7 | | | 0.3 |
| Refinery | | | | -8.0 | | 7.5 | | | | 0.5 |
| CHPPlant | | | | | -3.0 | -7.5 | | 3.5 | 4.5 | 2.5 |

Figure 14: An energy pathway drawn in the matrix

This pathway presented as an example is a good scheme to keep in mind in order to understand the whole process we are going to design to get the conversion data we have listed in the previous section. It indeed highlights the specific points we are going to deal with, such as pathways and efficiencies.

| Type of the entity | Primary Energy (Product 1) | Flow 1 | Intermediate Product (Product 2) | Flow 2 | Final Energy (Product 3) |
|--------------------|----------------------------|---------------|----------------------------------|---------------|--------------------------|
| What? | Crude Oil | Refinery | Heavy Oil | CHP plant | Electricity |
| Specific value | 8 Mtoe | $\eta = 94\%$ | 7.5 Mtoe | $\eta = 47\%$ | 3.5 Mtoe |

Table 4: Specific values of a given energy pathway

Step 2 – Finding all the pathways

Now that we are used to the IEA database, we have to identify all the pathways existing within the transformation sector lines in order to build up a global table such as presented with the [Table 4](#). To accomplish this critical task, we have to notice first that the global transformation sector, which can be partially illustrated by [Figure 13](#) for instance, is made of elementary components that we are going to call *node*. [Figure 15](#) presents a typical node which is actually compound of primary energy products going in a *flow* (transformation unit) which produces final energy products as outputs. Sometimes the input or output of a given *node* can be intermediate energy products such as heavy oil which comes from crude oil and can be burnt to generate electricity (it is in between primary and final energy, so called “intermediate”).

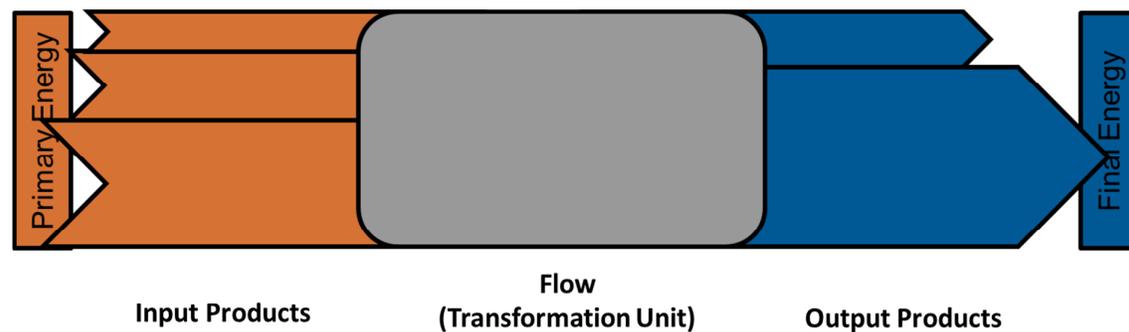


Figure 15: Elementary component or node

The initial objective is to cope with the tremendous database by focusing on the parameters whose evolution is of primary order. Primary order means that we consider them as essential for Rogeaulito, since their variations can involve strong consequences on the overall system when looking at the results. It is therefore primordial to reduce the number of data by aggregating them according to their importance and the energy products involved. This work enables to decrease the number of lines while improving the visibility, the accessibility of the data.

Prior to reduce the number of data we want to consider, we have to find out the energy pathways. The pathways are revealed when we “dismantle” one by one all the *nodes* establishing the transformation data lines within the IEA database. To “dismantle” a *node*, we need to consider the different input and output products as well as the efficiency of the *flow* (transformation unit), which is likely equivalent as considering the conversion losses. As presented in [Figure 16](#), from a mere *node* involving N input products and P output products, we obtain N x P different pathways representing all the possible combination of (*primary energy ; final energy*) couples that are actually existing inside a *node*.

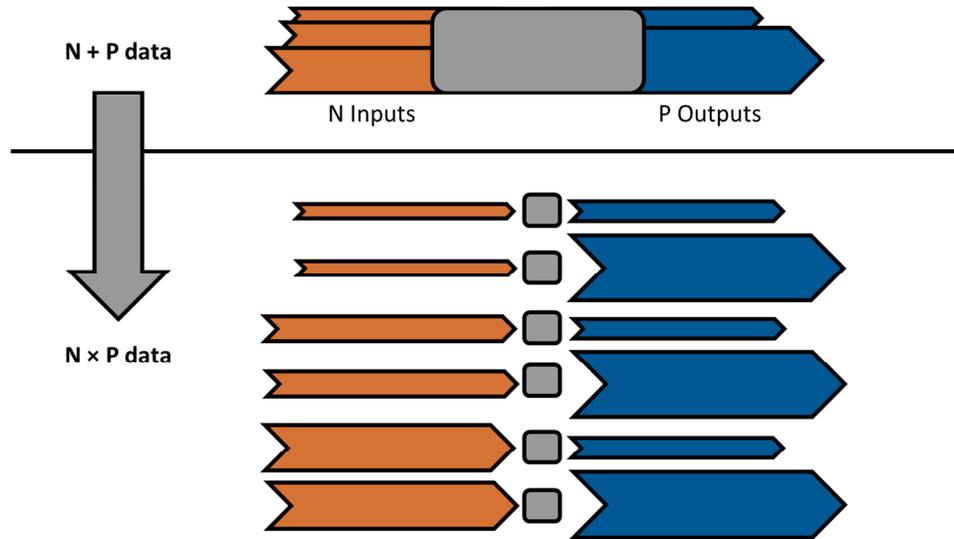
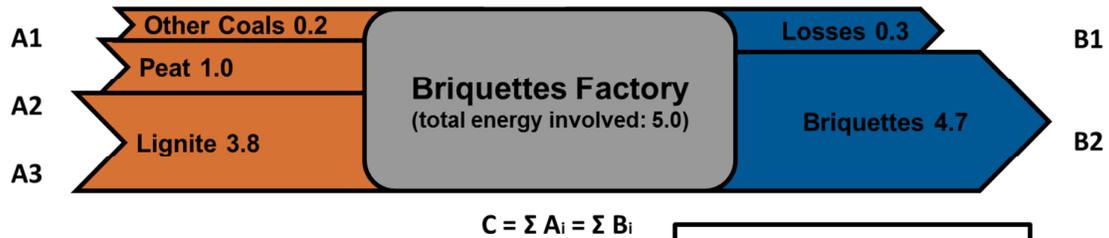


Figure 16: N + P products give N x P new pathways

In order not to lose any information in this process, we need to carefully distribute the overall energy passing through the *flow* between all the new pathways built. To do so, we apply a specific calculation presented in Figure 17 which allows us to calculate the share of a given primary energy and a given final energy involved in each one of the pathways. Basically, a calculation is compound of the energy value of the products considered, the total energy amount passing through the *flow*, the losses of the *flow* (conversion losses) and the efficiency of the flow. This calculation enables us to involve the efficiency of a transformation unit or *flow* in the creation of the new pathways that somehow embody the actual energy distribution between primary and final products.



We can involve the efficiency of the Transformation Unit : $\eta = \frac{\sum B_i - Losses}{\sum B_i} = \frac{C - Losses}{C}$

Then:

$$\text{Final Distribution: } \frac{A_x \times B_y}{C - B1 (Losses)} \times \eta$$

$$\text{Primary Distribution: } \frac{A_x \times B_y}{C - B1 (Losses)}$$

Figure 17: Calculation made in order to dismantle a node (in Mtoe)

As it is easier to look at tables and diagrams to fully understand the process described before, [Table 5](#) gathers the results of the dismantling of the *node* presented in [Figure 17](#), giving the value of the primary and final shares of energy and the products involved in the pathways. These shares of primary and final energy are called primary and final distribution, as stated before.

| Primary product | Final Product | Primary Distribution (corresponding primary energy amount in Mtoe) | Final Distribution (corresponding final energy amount in Mtoe) |
|-----------------|---------------|--|--|
| Other Coals | Briquettes | 0.20 | 0.19 |
| Peat | Briquettes | 1.00 | 0.94 |
| Lignite | Briquettes | 3.80 | 3.57 |
| Other Coals | Losses | 0.01 | 0.01 |
| Peat | Losses | 0.06 | 0.06 |
| Lignite | Losses | 0.24 | 0.23 |

Table 5: Energy involved in the pathways resulting of the dismantling of the node

The reader can notice that the efficiency of the *flow* treated inside this *node*, *Briquettes Factory*, is equal to 94% (Energy Output divided by Energy Input). This efficiency is applied in the calculation of all the pathways and stands in the value calculated. The “efficiency information” is therefore saved and constitutes a constant parameter of each new pathway.

With this “dismantling” process, we have passed from an aggregated version of energy pathways between primary and final energies to a detailed and controllable one giving us the corresponding amount of each type of energy going through a given pathway. **Thus, thanks to this process, we are now able to get for each *flow* (transformation unit) the primary/final energy distribution as well as the efficiency of the *flow* considered. Doing that for all the *flows* present in the transformation sector, we are able to find out all the energy pathways from primary to final energies with the corresponding efficiencies applied through them.**

Nevertheless, we have to consider that the *nodes* which are for *each one of them* characterized by a given *flow*, must be treated according to where this flow stand in the overall transformation sector. For instance, extracted oil is refined in a refinery first before going to a power plant then. The idea to do so is to understand in which order the *flows* are sorted out inside the transformation sectors. Therefore, we did this short work by studying the processes to finally come to a map of the transformation sector. This map is coherent with what we can imagine at first about the transformation sector, i.e. refineries, coal and gas factories stand upstream, with petrochemical industries afterwards whereas power plants stand downstream, at the end of the transformation sector.

It is now possible to build up all the ascendance between primary and final energy. Step by step, we dismantle each *node* to substitute it by new pathways that are going to be involved in the dismantling of the next nodes (especially if the right side of the pathway is occupied by an intermediate product).

This process must be computerized on Access to deal with all the data we have. This task is presented in [Appendix 6](#).

Distribution losses and auto consumption

When a transformation unit produces a given final energy amount, it always occurs that a part of it is used for the unit's own needs whereas some of it is lost later on during the transportation process, as illustrated by [Figure 9](#). Thus, before converting the final demand with the help of the conversion matrix, we need to enlarge this demand with the distribution losses plus the auto consumption for each final energy carrier constituting the final demand vector.

The first step is to get the historical data. Within the IEA database, these two pieces of information corresponds to precise lines that are directly actionable. The idea is to express these energy losses as a ratio of the total final energy consumption. Then, we can set factors taking into account both of these losses by which we multiply the final demand vector set in the demand module to enlarge correctly. [Figure 18](#) illustrates the factors found for the world in 2009. The share of losses is directly readable, with for example 10% of auto consumption and 10% of losses for the electricity, at world scale.

| Bf | Liquids | Gas final | Solids | Electricity | Heat | Others final |
|----------------------------|---------|-----------|--------|-------------|--------|--------------|
| Auto Consumption | 6,18% | 18,61% | 5,18% | 10,10% | 12,67% | 0,00% |
| Distribution Losses | 0,13% | 1,39% | 0,10% | 10,07% | 7,86% | 0,00% |
| Total (factor) | 1,06 | 1,20 | 1,05 | 1,20 | 1,21 | 1,00 |

Figure 18: Auto consumption and distribution losses, as shares of the final energy consumption

Referring to what we wanted to establish at the beginning of this section, we have meet our needs since we have obtained:

- **The conversion matrices**, involving the **conversion efficiencies** and the **primary/final energy mix**
- **The losses factor** integrating the **auto consumption of the transformation units** and the **distribution losses** for each type of final energy.

All the historical data are now established, and we use them to feed the conversion module in which the end-user has to set these data for the future years.

Misnomer and Glossary

Energy production: this expression might be used pretty often in this paper to make the speech more convenient and fluid. The actual good term to speak about energy is *conversion*. It does not exist indeed any energy production but conversions to one form of energy to another.

Core of Rogeaulito

$[MES_y]$ is the Missing Energy Supply vector for the year y expressed in the vector space Bp

$MES_{j,y}$ is the Missing Energy Supply of the year y for the primary energy j

$[FD_y]$ is a final energy demand vector for the year y expressed in the vector space Bf

$[Cp_y]$ is the set of conversion parameters for the year y , expressed in both Bp and Bf

$Cp_{i,j,y}$ is the set of conversion parameters of the year y

for the final energy i and the primary energy j

$[PS_y]$ is a primary energy supply vector for the year y expressed in the vector space Bp

Demand Module

$[M_y]$ is the final energy mix of the demand for the year y expressed in the vector space Bf

$[M_{k,y}]$ is the final energy mix of the demand for the year y and

the sector k , expressed in the vector space Bf

$\%_{i,y}$ is the share of the final energy i in the final demand for the year y

$\%_{i,k,y}$ is the share of the final energy i in the final demand of the sector k for the year y

epc_y and $epc_{k,y}$ are respectively the final energy demand per capita for the year y ,

global and for the sector k (ktoe/cap)

$GDPc_y$ is the GDP per capita $\left(\frac{\$}{cap}\right)$ for the year y

E_y and $E_{k,y}$ are respectively the energy intensity of the GDP for the year y ,

global and for the sector k^2 (ktoe/\$)

Pop_y is the population(cap) for the year y

Supply Module

$ep_{j,y}$ and $ep_{j,k,y}$ are respectively the net primary energy supply from the primary

resource j , and from the primary sub – resource k of the primary resource j ,

² E_k is obtained by dividing final energy consumption of the demand sector k by the global GDP (not a sectoral economic turnover)

for the year y , expressed in the base B_p (ktoe).

$ep_{j,y}$ is the primary energy supply from the fossil fuel resource j for the year y

(Gb for oil, bcm for gas, Mtce for coal)

y is the year considered

URR are the Ultimate Recoverable Resources (Gb for oil, bcm for gas, Mtce for coal)

$$a = \frac{URR \times (\text{Production}(y_0) + \text{production slope}(y_0-5; y_0))}{\text{Cumulated Production}(y_0)^2 \times \left(\frac{URR}{\text{Cumulated Production}(y_0)} - 1 \right)} \text{ constant depending on historical data}$$

$$ym = \frac{1}{a} \times \ln \left(\frac{URR}{\text{Cumulated Production}(y_0)} - 1 \right) + y_0 \text{ year at which half of the URR has been extracted}$$

$P_{j,k,y}$ is the installed capacity of the power plant type k of the primary energy j ,
for the year y

$cf_{j,k,y}$ is the capacity factor, or load factor, of the power plant type k
of the primary energy j , for the year y

BS_y is the primary energy potential of the biomass resource for the year y (MJ)

$BS_{forest,y}, BS_{crops,y}, BS_{waste,y}$ are respectively the biomass energy potential
for forest, crops and waste for the year y (MJ)

$A_{forest,y}, A_{crops,y}$ are respectively the area considered for forestry
and crops biomass production for the year y (ha)

$EY_{forest,y}$ and $EY_{crops,y}$ are respectively the energy yield of
the forest and crops lands for the year y (MJ/ha)

$\theta_{l,y}, \theta_{s,y}, \theta_{g,y}$ are respectively the shares of biomasse allocated
to liquid, solid and gazeous fuels production for the year y

$\eta_{l,y}, \eta_{s,y}, \eta_{g,y}$ are respectively the conversion efficiencies for
biomass to liquid, biomass to solid and biomass to gas processes for the year y

$ep_{biomass,y}$ is the primary energy supply issued from biomass for the year y (MJ)

Conversion Module

p gathers the three types of power plants, CHP, eletricity and heat

$[E\eta_{p,y}]$ is the efficiency vector for the power plant type p , for the year y ,

expressed in the vector space B_p

$eta_{p,j,y}$ is the efficiency for the primary energy j of the power plant p , for the year y

$\eta_{p,j,ccs,y}$ is the efficiency of the power plant type p for the fossil fuel j after having applied CCS, for the year y

$CCS_{p,j,y}$ is the share of CCS technologies present in the power plant fleet for the type p and the fossil fuel j , for the year y

$PL_{p,j,y} \leq 0$ is the point loss for the efficiency $\eta_{p,j,y}$ of the power plant type p operated with fossil fuel j , for the year y

$[E_{p,ccs,y}]$ is the efficiency vector for the power plant type p after CCS setting, for the year y , expressed in the vector space B_p

$E_{p,y}$ is the global efficiency for the power plant type p (CHP, electricity or heat), for the year y

$[M_p]$ is the primary mix of the consumption of the power plant type p , kept as a constant in the model, and expressed in the vector space B_p

$\eta_{i,j,y}$ is the aggregated efficiency for the overall conversion process between primary energy j and final energy i , for the year y

$[AC_y]$ is the auto consumption vector for final energy, for the year y , expressed in the vector space B_f

$AC_{i,y}$ is the auto consumption referring to the final energy i , for the year y , expressed as a percentage of the final energy demand for i

$[DL_y]$ is the distribution losses vector for final energy, for the year y , expressed in the vector space B_f

$DL_{i,y}$ is the distribution losses referring to the final energy i , for the year y , expressed as a percentage of the final energy demand for i

$[NoT_y]$ is the non – transformed vector for primary energy, for the year y , expressed in the vector space B_p

$NoT_{j,y}$ is the non – transformed share referring to the primary energy j , for the year y expressed as a percentage of the primary energy supply for j

$[N(R_f)_y]$ is the matrix gathering the primary mix of each final energy, for the year y , expressed in the vector space $B_f \times B_p$

$\%_{i,j,y}$ is the primary share of the energy j for the final energy i , for the year y

$[MC_y]$ is the conversion matrix expressed in the vector space $B_f \times B_p$

$MC_{i,j,y}$ is the conversion matrix element for the final energy i , relative to

the primary energy j , for the year y

*$C_{p_{i,j,y}}$ is the conversion parameter for the final energy i , relative to the primary energy j ,
for the year y*

*$[C_{p_y}]$ is the set of conversion parameters, expressed as a matrix
in the vector space $B_f \times B_p$, for the year y*

Conclusion and perspectives

The present document has presented Rogeaullito through the technical and mathematical description of its four main components. The purpose is to introduce the model principle and the way it has been thought and developed. We have seen several specific points Among them we can retain:

- Rogeaullito enable the design of uncorrelated demand and supply scenarios so as to confront them, based on volume considerations
- This is made possible thanks to the complementary role played by the Demand, the Supply and the Conversion Modules
- To meet its main objectives, Rogeaullito adopts a physical approach. The cursors that set the parameters in the different modules focus on physical aspects.
- The construction and the aggregation of the parameters are simply made with additions and multiplications of the corresponding cursors.

Some implementations and scenario studies are going to be treated in coming publications. These publications will intend to deliver concrete examples about the use of Rogeaullito, the intake of its specificities and the outputs it is able to deliver.

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Appendices

Appendix 1 - Concepts

Kaya's equation

Kaya's equation is a mathematical relation connecting four factors related to the human CO₂ production. The four factors are:

- P: world's population
- g: global GDP per-capita
- e: global energy intensity of GDP

$e = E / G$ with:

- E: World primary energy consumption
- G: global GDP
- f: carbon content of energy used globally

Using F as the global human emissions of CO₂, then:

$$F = P * g * e * f$$

It is possible to use this type of equation to model the world energy consumption, then:

$$E = P * g * e$$

This last relation is the one applied in the demand module.

Appendix 2 - Conventions used for Rogeaullito

The bases

- **Final Base(Bf)** : consists of 7 energy carriers used for the projection of the final consumption flows:
 - Liquids
 - Gas final
 - Solids
 - Electricity
 - Heat
 - Others final (fictive carrier which might be used for a possible new distribution of Bf for the future)

- **Primary Base (Bp)** : consists of 8 energy carriers used for the projection of the production flows:
 - Oil
 - Gas primary
 - Coal
 - Nuclear
 - Renew. Only Elec.
 - Renew. Others
 - Others non-Renew.
 - Others primary (fictive carrier which might be used for a possible new distribution of Bp for the future)
 -

- **The projections of the IEA products within these bases are given in the following table:**

| IEA Products Projection | | | |
|-------------------------|-------------------------------|-----------------|---------------|
| Code | English Description | Primary Base Bp | Final Base Bf |
| ADDITIVE | Additives/blending components | Oil | Liquids |
| ANTCOAL | Anthracite | Coal | Solids |
| AVGAS | Aviation gasoline | - | Liquids |
| BIODIESEL | Biodiesels | Renew. Others | Liquids |
| BIOGASOL | Biogasoline | Renew. Others | Liquids |
| BITCOAL | Other bituminous coal | Coal | Solids |
| BITUMEN | Bitumen | - | Liquids |
| BKB | BKB/peat briquettes | - | Solids |
| BLFURGS | Blast furnace gas | - | Solids |
| BROWN | Brown coal (if no detail) | Coal | Solids |
| CHARCOAL | Charcoal | - | Solids |
| COALTAR | Coal tar | - | Solids |
| COKCOAL | Coking coal | Coal | Solids |

| IEA Products Projection | | | |
|-------------------------|--|-------------------|---------------|
| Code | English Description | Primary Base Bp | Final Base Bf |
| COKEOVGS | Coke oven gas | - | Solids |
| CRNGFEED | Crude/NGL/feedstocks (if no detail) | Oil | Liquids |
| CRUDEOIL | Crude oil | Oil | Liquids |
| ELECTR | Electricity | - | Electricity |
| ETHANE | Ethane | - | Liquids |
| GASCOKE | Gas coke | - | Solids |
| GASDIES | Gas/diesel oil | - | Liquids |
| GASWKSGS | Gas works gas | - | Gas final |
| GBIOMASS | Biogas | Renew. Others | Gas final |
| GEOTHERM | Geothermal | Renew. Others | Heat |
| HARDCOAL | Hard coal (if no detail) | Coal | Solids |
| HEAT | Heat | Others non-Renew. | Heat |
| HEATNS | Heat output from non-specified comb fuels | - | - |
| HYDRO | Hydro | Renew. Only Elec. | Electricity |
| INDWASTE | Industrial waste | Others non-Renew. | Solids |
| JETGAS | Gasoline type jet fuel | - | Liquids |
| JETKERO | Kerosene Type jet fuel | - | Liquids |
| LIGNITE | Lignite/brown coal | Coal | Solids |
| LPG | Liquefied petroleum gases (LPG) | - | Liquids |
| LUBRIC | Lubricants | - | Liquids |
| MANGAS | Elec/heat output from non-spec. manif. gases | - | Solids |
| MOTORGAS | Motor gasoline | - | Liquids |
| MUNWASTEN | Municipal waste (non-Renew) | Others non-Renew. | Solids |
| MUNWASTER | Municipal waste (renew) | Renew. Others | Solids |
| NAPHTHA | Naphtha | - | Liquids |
| NATGAS | Natural gas | Gas primary | Gas final |
| NGL | Natural gas liquids | Oil | Liquids |
| NONCRUDE | Other hydrocarbons | Oil | Liquids |
| NUCLEAR | Nuclear | Nuclear | - |
| OBIOLIQ | Other liquid biofuels | Renew. Others | Liquids |
| ONONSPEC | Non-specified petroleum products | - | Liquids |
| OTHER | Other sources | Renew. Only Elec. | Electricity |
| OTHKERO | Kerosene | - | Liquids |
| OVENCOKE | Coke oven coke | - | Solids |
| OXYSTGS | Oxygen steel furnace gas | - | Solids |
| PARWAX | Paraffin waxes | - | Liquids |
| PATFUEL | Patent fuel | - | Solids |
| PEAT | Peat | Renew. Others | Solids |
| PETCOKE | Petroleum coke | - | Liquids |
| REFFEEDS | Refinery feedstocks | - | Liquids |

| IEA Products Projection | | | |
|-------------------------|--|-------------------|---------------|
| Code | English Description | Primary Base Bp | Final Base Bf |
| REFINGAS | Refinery gas | - | Liquids |
| RENEWNS | Non-specified combust. renewables + wastes | - | Solids |
| RESFUEL | Heavy fuel oil | - | Liquids |
| SBIOMASS | Primary solid biomass | Renew. Others | Solids |
| SOLARPV | Solar photovoltaics | Renew. Only Elec. | Electricity |
| SOLARTH | Solar thermal | Renew. Others | Heat |
| SUBCOAL | Sub-bituminous coal | Coal | Solids |
| TIDE | "Tide, wave and ocean" | Renew. Only Elec. | Electricity |
| TOTAL | Total of all energy sources | - | - |
| WHITESP | White spirit & SBP | - | Liquids |
| WIND | Wind | Renew. Only Elec. | Electricity |

The geographical areas

- **World** = Europe, North America, Asia and Rest of the World.
- **Europe** = European Union (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden, United Kingdom)
- **North America** = OECD countries of America (Canada, Mexico and United States)
- **Asia** = OECD and developing countries from Asia and Oceania (Australia, Japan, Korea, New Zealand, Bangladesh, Brunei, Butan, Cambodia, China, Cook Islands, East Timor, Fiji Islands, French Polynesia, India, Indonesia, Kiribati, Laos, Macau, Maldives, Malaysia, Mongolia, Myanmar, Nepal, New Caledonia, North Korea, Pakistan, Papua New Guinea, Philippines, Solomon Islands, Samoa, Singapore, Sri Lanka, Taipei, Thailand, Tonga, Vanuatu, Vietnam)
- **Rest of World** = all other countries

Appendix 3 - Evolution curves for the cursors

To model a given demand vector or supply vector in the corresponding module, we have seen that a set of physical cursors are available. These cursors need to evolve within time, and it is up to the user to set this evolution by hand. Seven kinds of evolution curves compose the selection, and each one of them requires some parameters to be set in order to define the time evolution of a given cursor.

The evolution curve types introduced in Rogeaullito are:

- Linear
- Exponential
- Negative exponential
- Sigmoid
- Gauss curve
- Centered sigmoid
- Sigmoid with gap

For each type of evolution curve, the shape is compounded of series of points. These points meet common constrains, that are the initial year t_0 and the time step of a year. Otherwise, some specific parameters must be set for each curve.

The following sections introduce the equation and parameters for each evolution curve types.

Linear

Linear curve models a linear growth.

Equation

$$f(t) = f(t_0) \times (1 + a \cdot (t - t_0))$$

Parameters

$f(t_0)$: initial value (defined)

a : annual growth in % (to be set)

Exponential

Exponential curve models a symmetrical growth.

Equation

$$f(t) = f(t_0) \times (1 + a)^{(t - t_0)}$$

Parameters

$f(t_0)$: initial value (defined)

a : annual growth in % (to be set)

Negative exponential

Negative exponential curve models an evolution followed by a stable state in the long term.

Equation

$$f(t) = f(t_0) + A \times (1 - \exp(\frac{\ln(1-\%A)}{(t_c-t_0)} \times (t - t_0)))$$

Parameters

$f(t_0)$: initial value (defined)

A : total growth (value reached at the stabilization year) (to be set)

$\%A$: share of the growth matched at the target year t_c , in % (to be set)

t_c : target year (to be set)

Sigmoid

Sigmoid curve models an evolution from an initial level to another stable level, passing by an inflexion point.

Equation

$$f(t) = f(-\infty) + \frac{A}{(1 + \exp(-\frac{4}{\Delta trans} \times (t - (t_0 + Dtrans + \frac{\Delta trans}{2}))))}$$

Parameters

$f(-\infty)$: initial level value (defined)

A : total growth (value reached at the stabilization year) (to be set)

$Dtrans$: delay before transition, in years (to be set)

$\Delta trans$: transition duration, in years (to be set)

Gauss curve

Gauss curve models a symmetrical bell shaped evolution.

Equation

$$f(t) = f(max) \times \exp(\ln(\frac{f(t_0)}{f(max)}) \times \frac{1}{Dmax^2} \times (t - (t_0 + Dmax))^2)$$

Parameters

$f(t_0)$: initial value (defined)

$f(max)$: maximum value (to be set)

$Dmax$: delay before maximum, in years (to be set)

Centered sigmoid

Centered sigmoid curve, likely to negative exponential curve, models an evolution followed by a stable state in the long term. Compare to the classical sigmoid, this one allows to set directly a target value at a given year, without passing by any inflexion point.

Equation

$$f(t) = f(t_0) - \frac{A}{2} + \frac{A}{(1 + \exp(-\frac{2}{D_{max}} \times (t - t_0)))}$$

Parameters

$f(t_0)$: initial value

A : total growth (value reached at the stabilization year) (to be set)

D_{max} : delay before maximum, in years (to be set)

Sigmoid with gap

Sigmoid with gap curve models a direct evolution with a step.

Equation

$$f(t) = f(t_0) + \frac{A}{(1 + \exp(-4 \times (t - (t_0 + D_{trans} + \frac{1}{2}))))}$$

Parameters

$f(t_0)$: initial value (defined)

A : total growth (value reached at the stabilization year) (to be set)

D_{trans} : delay before the step, in years (to be set)

Appendix 4 – Fossil fuels modeling curves

Hubbert logistic curves (UKERC, 2009)

Hubbert curves are well known among fossil fuels specialists. They have a bell shape, displaying a maximum which represents a peak-oil. The general equation of that kind of curves is the following one:

$$Production = \frac{a \times URR \times \exp(-a \times (t - tm))}{(1 + \exp(-a \times (t - tm)))^2}$$

Given

- t – the considered year
- URR – Ultimate Recoverable Resources
- $a = \frac{URR \times (Production(t_0) + production\ slope(t_0 - 5; t_0))}{Cumulated\ Production(t_0)^2 \times (\frac{URR}{Cumulated\ Production(t_0)} - 1)}$

Constant depending on historical data

- $tm = \frac{1}{a} \times \ln\left(\frac{URR}{Production\ cumulée(t_0)} - 1\right) + t_0$
year at which half of the URR has been extracted

Asymmetric Hubbert curves with plateau

From a mere Hubbert curve, it's possible to assign a non-equal share of extracted oil before and after the peak oil. The obtained asymmetric curve is more realistic. In addition a plateau of 15 years maximum (Jancovici, 2011) is modeled.

Before the plateau:

$$Production = \frac{a_1 \times 2 \times URR_1 \times \exp(-a_1 \times (t - tm_1))}{(1 + \exp(-a_1 \times (t - tm_1)))^2}$$

Given

- t – the considered year
- $URR_1 = bp \times URR$
Ultimate Recoverable Resources extracted before the plateau

- $20\% < bp < 58\%$ – the share in % of URR extracted before the beginning of the plateau (UKERC, 2009).

$$a_1 = \frac{2 \times URR_1 \times (Production(t_0) + production\ slope(t_0-5;t_0))}{Cumulated\ Production(t_0)^2 \times \left(\frac{2 \times URR_1}{Cumulated\ Production(t_0)} - 1 \right)}$$

Constant depending on historical data

$$tm_1 = \frac{1}{a_1} \times \ln \left(\frac{2 \times URR_1}{Cumulated\ Production(t_0)} - 1 \right) + t_0$$

Year at which URR_1 has been extracted, i.e. year at which we reach the plateau

The plateau:

$$Production_{plateau} = Production(tm_1) \quad \text{If } tm_1 > t_0$$

$$Production_{plateau} = Production(t_0) \quad \text{If } tm_1 < t_0$$

And with

- $t_{plateau}$ = plateau's duration
The plateau lasts while $t - tm_1 < t_{plateau}$ (max 15 years)
- $URR_{plateau} = t_{plateau} \times Production(tm_1)$

After the plateau:

$$Production = \frac{a_2 \times 2 \times URR_2 \times \exp(-a_2 \times (t - tm_2))}{(1 + \exp(-a_2 \times (t - tm_2)))^2}$$

Given

- t – the considered year
- $URR_2 = URR - URR_1 - URR_{plateau}$
Ultimate Recoverable Resources extracted after the plateau
- $a_2 = 2 \times \frac{Production_{plateau}}{URR_2}$
Constant verifying continuity condition
- $tm_2 = tm_1 + t_{plateau}$
Year at which $URR_1 + URR_{plateau}$ has been extracted, i.e. year at which we leave the plateau

How is bp evaluated?

For increasing production scenarios

$$bp = \frac{Cumulated\ Production(t_0)}{URR} + 0,02 \quad \text{If result } < 58\%$$

If the result gives $bp > 58\%$, we fix it equal to 58%. It implies a shorter plateau. The extra 0, 02 in the formula are aimed at avoiding any sudden change between the growing part of the curve and the plateau.

For the scenario “*History – Extension of Historical Data*”

$bp = 37\%$ (UKERC, 2009)

Appendix 5 - Transformation units description

| Transformation processes | | |
|---|------------|---|
| Flow | Short name | Definition |
| Transformation processes | TOTTRANF | Transformation processes comprise the conversion of primary forms of energy to secondary and further transformation (e.g. coking coal to coke, crude oil to oil products, and fuel oil to electricity). Inputs to transformation processes are shown as negative numbers and output from the process is shown as a positive number. Transformation losses will appear in the "total" column as negative numbers. |
| Main activity producer electricity plants | MAINELEC | Refers to plants which are designed to produce electricity only. If one or more units of the plant is a CHP unit (and the inputs and outputs can not be distinguished on a unit basis) then the whole plant is designated as a CHP plant. Main activity producers generate electricity for sale to third parties, as their primary activity. They may be privately or publicly owned. Note that the sale need not take place through the public grid. |
| Autoproducer electricity plants | AUTOELEC | Refers to plants which are designed to produce electricity only. If one or more units of the plant is a CHP unit (and the inputs and outputs can not be distinguished on a unit basis) then the whole plant is designated as a CHP plant. Autoproducer undertakings generate electricity wholly or partly for their own use as an activity which supports their primary activity. They may be privately or publicly owned. |
| Main activity producer CHP plants | MAINCHP | Refers to plants which are designed to produce both heat and electricity (sometimes referred to as co-generation power stations). If possible, fuel inputs and electricity/heat outputs are on a unit basis rather than on a plant basis. However, if data are not available on a unit basis, the convention for defining a CHP plant noted above should be adopted. Main activity producers generate electricity and/or heat for sale to third parties, as their primary activity. They may be privately or publicly owned. Note that the sale need not take place through the public grid. |
| Autoproducer CHP plants | AUTOCHP | Refers to plants which are designed to produce both heat and electricity (sometimes referred to as co-generation power stations). If possible, fuel inputs and electricity/heat outputs are on a unit basis rather than on a plant basis. However, if data are not available on a unit basis, the convention for defining a CHP plant noted above should be adopted. Note that for autoproducer CHP plants, all fuel inputs to electricity production are taken into account, while only the part of fuel inputs to heat sold is shown. Fuel inputs for the production of heat consumed within the autoproducer's establishment are not included here but are included with figures for the final consumption of fuels in the appropriate consuming sector. Autoproducer undertakings generate electricity and/or heat, wholly or partly for their own use as an activity which supports their primary activity. They may be privately or publicly owned. |

| Transformation processes | | |
|--|------------|---|
| Flow | Short name | Definition |
| Main activity producer heat plants | MAINHEAT | Refers to plants (including heat pumps and electric boilers) designed to produce heat only and who sell heat to a third party (e.g. residential, commercial or industrial consumers) under the provisions of a contract. Main activity producers generate heat for sale to third parties, as their primary activity. They may be privately or publicly owned. Note that the sale need not take place through the public grid. |
| Autoproducer heat plants | AUTOHEAT | Refers to plants (including heat pumps and electric boilers) designed to produce heat only and who sell heat to a third party (e.g. residential, commercial or industrial consumers) under the provisions of a contract. Autoproducer undertakings generate heat, wholly or partly for their own use as an activity which supports their primary activity. They may be privately or publicly owned. |
| Heat pumps | THEAT | Includes heat produced by heat pumps in transformation. Heat pumps that are operated within the residential sector where the heat is not sold are not considered a transformation process and are not included here – the electricity consumption would appear as residential use. |
| Electric boilers | TBOILER | Includes electric boilers used to produce heat. |
| Chemical heat for electricity production | TELE | Includes heat from chemical processes that is used to generate electricity. |
| Blast furnaces | TBLASTFUR | Includes the production of recovered gases (e.g. blast furnace gas and oxygen steel furnace gas). The production of pig-iron from iron ore in blast furnaces uses fuels for supporting the blast furnace charge and providing heat and carbon for the reduction of the iron ore. Accounting for the calorific content of the fuels entering the process is a complex matter as transformation (into blast furnace gas) and consumption (heat of combustion) occur simultaneously. Some carbon is also retained in the pig-iron; almost all of this reappears later in the oxygen steel furnace gas (or converter gas) when the pig-iron is converted to steel. In the 1992/1993 annual questionnaires, Member Countries were asked for the first time to report in <i>transformation processes</i> the quantities of all fuels (e.g. pulverised coal injection [PCI] coal, coke oven coke, natural gas and oil) entering blast furnaces and the quantity of blast furnace gas and oxygen steel furnace gas produced. The Secretariat then needed to split these inputs into the transformation and consumption components. The transformation component is shown in the row <i>blast furnaces</i> in the column appropriate for the fuel, and the consumption component is shown in the row <i>iron and steel</i> , in the column appropriate for the fuel. The Secretariat decided to assume a transformation efficiency such that the carbon input into the blast furnaces should equal the carbon output. This is roughly equivalent to assuming an energy transformation efficiency of 40%. |
| Gas works | TGASWKS | Includes the manufacture of town gas. <i>Note: in the summary balances this item also includes other gases blended with natural gas (TBLENDGAS).</i> |

| Transformation processes | | |
|--|------------|---|
| Flow | Short name | Definition |
| Main activity producer heat plants | MAINHEAT | Refers to plants (including heat pumps and electric boilers) designed to produce heat only and who sell heat to a third party (e.g. residential, commercial or industrial consumers) under the provisions of a contract. Main activity producers generate heat for sale to third parties, as their primary activity. They may be privately or publicly owned. Note that the sale need not take place through the public grid. |
| Autoproducer heat plants | AUTOHEAT | Refers to plants (including heat pumps and electric boilers) designed to produce heat only and who sell heat to a third party (e.g. residential, commercial or industrial consumers) under the provisions of a contract. Autoproducer undertakings generate heat, wholly or partly for their own use as an activity which supports their primary activity. They may be privately or publicly owned. |
| Heat pumps | THEAT | Includes heat produced by heat pumps in transformation. Heat pumps that are operated within the residential sector where the heat is not sold are not considered a transformation process and are not included here – the electricity consumption would appear as residential use. |
| Electric boilers | TBOILER | Includes electric boilers used to produce heat. |
| Chemical heat for electricity production | TELE | Includes heat from chemical processes that is used to generate electricity. |
| Blast furnaces | TBLASTFUR | Includes the production of recovered gases (e.g. blast furnace gas and oxygen steel furnace gas). The production of pig-iron from iron ore in blast furnaces uses fuels for supporting the blast furnace charge and providing heat and carbon for the reduction of the iron ore. Accounting for the calorific content of the fuels entering the process is a complex matter as transformation (into blast furnace gas) and consumption (heat of combustion) occur simultaneously. Some carbon is also retained in the pig-iron; almost all of this reappears later in the oxygen steel furnace gas (or converter gas) when the pig-iron is converted to steel. In the 1992/1993 annual questionnaires, Member Countries were asked for the first time to report in <i>transformation processes</i> the quantities of all fuels (e.g. pulverised coal injection [PCI] coal, coke oven coke, natural gas and oil) entering blast furnaces and the quantity of blast furnace gas and oxygen steel furnace gas produced. The Secretariat then needed to split these inputs into the transformation and consumption components. The transformation component is shown in the row <i>blast furnaces</i> in the column appropriate for the fuel, and the consumption component is shown in the row <i>iron and steel</i> , in the column appropriate for the fuel. The Secretariat decided to assume a transformation efficiency such that the carbon input into the blast furnaces should equal the carbon output. This is roughly equivalent to assuming an energy transformation efficiency of 40%. |
| Gas works | TGASWKS | Includes the manufacture of town gas. <i>Note: in the summary balances this item also includes other gases blended with natural gas (TBLENDGAS).</i> |

| Transformation processes | | |
|--|-------------------|---|
| Flow | Short name | Definition |
| Coke ovens | TCOKEOVS | Includes the manufacture of coke and coke oven gas. |
| Patent fuel plants | TPATFUEL | Includes the manufacture of patent fuels. |
| BKB plants | TBKB | Includes the manufacture of BKB. |
| Oil refineries | TREFINER | Includes the manufacture of finished oil products. |
| Petrochemical plants | TPETCHEM | Covers backflows returned from the petrochemical industry. Note that backflows from oil products that are used for non-energy purposes (i.e. white spirit and lubricants) are not included here, but in non-energy use. |
| Coal liquefaction plants | TCOALLIQ | Includes coal, oil and tar sands used to produce synthetic oil. |
| Gas-to-liquids (GTL) plants | TGTL | Includes natural gas used as feedstock for the conversion to liquids, e.g. the quantities of fuel entering the methanol production process for transformation into methanol. |
| For blended natural gas | TBLENDGAS | Includes other gases that are blended with natural gas. |
| Charcoal production plants | TCHARCOAL | Includes the transformation of solid biofuels into charcoal. |
| Non-specified (transformation) | TNONSPEC | Includes other non-specified transformation. |
| Flows used in the summary balances | | |
| Liquefaction plants | LIQUEFAC | Is equal to the sum of TCOALLIQ and TGTL. |
| Other transformation in the summary balances | TNONSPEC | Is equal to the sum of TCHARCOAL and TNONSPEC. |

Appendix 6 – Conversion data: computerizing the IEA data process

The purpose of computerizing the method described in the section 5.2 is to deal with the tremendous amount of transformation sector data from our IEA database. Indeed, the work presented before is theoretically feasible but would actually be so much time intensive that it does not worth it to do it by hand. To give an idea, IEA energy database introduces 64 energy products and 21 transformation units. Assuming that each half of the products passes through three transformation units in average, we actually face more than hundreds of thousands possible pathways. Moreover, the database is updated each year and one main feature of the Access computerizing would be to run the whole process each year to get the last year data from the transformation sector. Finally, the utilization of a database software, such as Access, to manage our valuable data, provides us safety and reliability.

The purpose of this section is not to explain deeply what is the code developed but more to clarify the methodology used and the main data obtained eventually. When it comes to talk about figures or examples, it often deals with the world version of Rogeaulito, meaning that the data considered are the world's ones.

Here are the steps of the process listed chronologically, with the corresponding table for illustration:

- **1st part: Finding the pathways** – [Table 6](#)
- **2nd part: Projection on the bases Bp and Bf** – [Table 7](#)
- **3rd part: Calculation of the efficiencies of the projected pathways** – [Figure 21](#)
- **4th part: Calculation of the Conversion Matrix** – [Figure 22](#)

1st part – Finding the pathways

As explained previously, we need all the energy pathways between primary and final energy to reveal the simplified main energy flows defined by our framework, passing throughout the transformation sector. The dismantling of all the *nodes* making the global transformation sector is the method applied. We used to call it the “dominos method” since it consists in joining elementary pathways resulting of the dismantling of a *node* to build up the global pathways. [Figure 19](#) shows that a global pathway can be represented as a set of dominos putting next to the other.

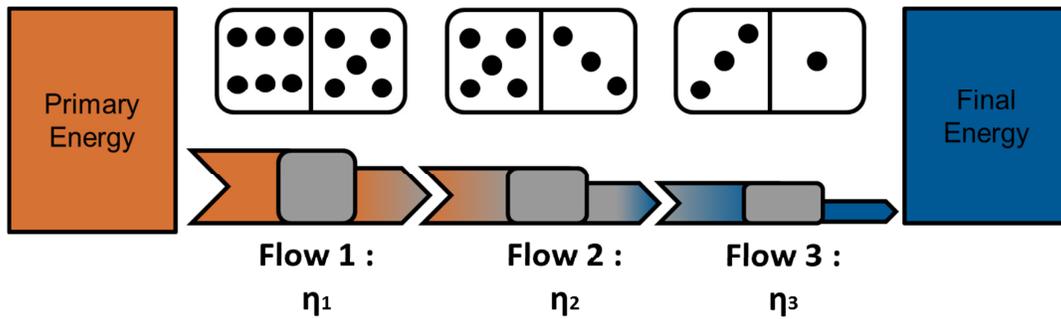


Figure 19: A global pathway ⇔ dominos' chain

A single domino is the picture of an elementary pathway, i.e. a pathway resulting of the dismantling of a given node. Then, joining the elementary pathways when they match (same output for the left pathway than the input for the right pathway), we create new pathways that are going to lead us step by step to the final energy side. This process is figuratively presented by Figure 20 which illustrates the principle of this “dominos method”.

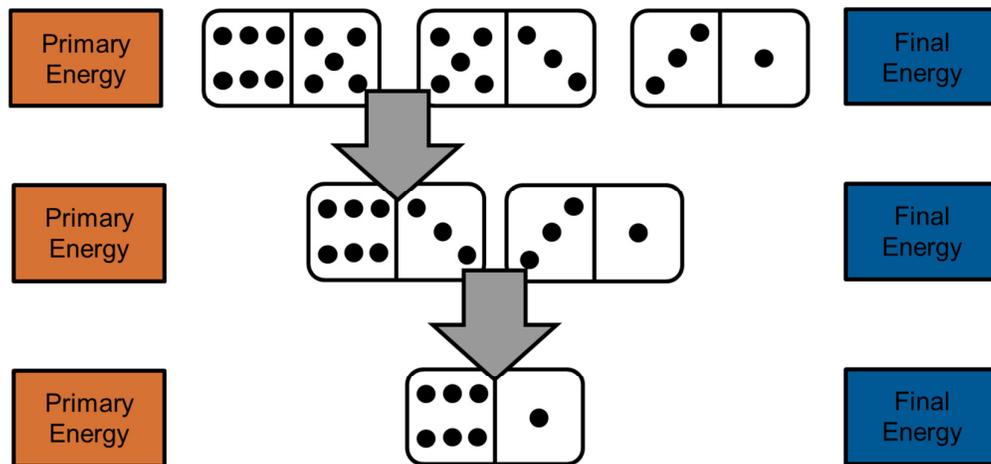


Figure 20: Dominos method to get a global pathway

Let's focus on the example we have seen before in Table 4, section 5.2:

Primary Energy - Crude Oil >> Refinery >> Heavy Oil >> Power Plant >> Electricity - Final Energy

This constitutes a global pathway coming from the dismantling of two *nodes*, the first one around *refinery*, and the second one around *power plant*. From the whole process run on Access, we finally get about 13 000 global pathways for 2009 for instance (world data), out of the hundreds of thousands we got at the beginning (64 products and 21 transformation units). Most of these pathways are not relevant since they actually represent residual energy flows which appeared to balance the overall process. Thus, we filter these insignificant pathways to keep the meaningful ones. Therefore, we finally get less than 500 hundred global pathways for 2009. These pathways are sorted out in a table such as Table 6 which gives an idea of what we can find in it:

- **The primary energy**

- **The final energy**
- **The path**, i.e. the list of the *flows* (transformation units) crossed by the pathway
- **The primary distribution**, i.e. the amount of the primary energy considered going to the final energy considered (destination side)
- **The final distribution**, i.e. the amount of the final energy considered coming from the primary energy considered (origin side).

| Primary Energy | Final Energy | Path | Primary Distribution (in Mtoe) | Final Distribution (in Mtoe) |
|----------------|--------------|----------------------------|--------------------------------|------------------------------|
| Crude Oil | Electricity | Refinery >> Power plant | 8.0 | 3.5 |
| Lignite | Briquettes | Briquettes factory | 3.80 | 3.57 |
| ... | | | | |

Table 6: Example of a table gathering global pathways (from Access)

2nd part – Projection of the pathways

We have to project IEA products on the bases Bp and Bf that we have set, according to the correspondence specified in [Appendix 2](#). For example, [Table 6](#) becomes [Table 7](#) where the products are substituted by their corresponding one in the projection bases.

| Primary Energy in Bp | Final Energy in Bf | Path | Primary Distribution (in Mtoe) | Final Distribution (in Mtoe) |
|----------------------|--------------------|----------------------------|--------------------------------|------------------------------|
| Oil | Electricity | Refinery >> Power plant | 8.0 | 3.5 |
| Coal | Solids | Briquettes factory | 3.80 | 3.57 |
| ... | | | | |

Table 7: Global pathways after projection of the products on Bp and Bf

Once we have projected all the global pathways, we can sum the ones involving the same primary and final energies. This aggregation is necessary to pass from 500 hundred pathways to $7 \times 5 = 35$

pathways that actually constitute the size of the conversion matrix we are going to calculate. Putting the value projected in matrices for the primary distribution and the final distribution gives us the [Rf] and [Rp] matrices that the reader can observe in Figure 21. [Rf] and [Rp] are the distribution matrices. They represent the energy mix respectively in primary terms for the final side and in final terms for the primary side.

3rd part – Calculation of [Eta]

We are now able to calculate the global efficiency of all projected and aggregated pathways, performing a division term by term of the final distribution matrix and the primary distribution matrix. It eventually gives us the [Eta] matrix. This calculation is presented in Figure 21.

| Rf | Bf\Bp | Oil | Gas primary | Coal | Nuclear | Renew. only Elec. | Renew. Others | Others non-Renew. |
|--|-------------|-----------|-------------|---------|---------|-------------------|---------------|-------------------|
| Final distribution - World, 2009 | Liquids | 3 637 738 | 3 212 | 7 710 | - | - | 52 509 | - |
| | Gas final | 269 | 1 522 286 | 5 572 | - | - | 11 358 | - |
| | Solids | 1 197 | 105 | 921 450 | - | - | 1 023 104 | 7 759 |
| | Electricity | 101 011 | 344 893 | 813 841 | 286 489 | 123 931 | 48 057 | 5 364 |
| | Heat | 17 441 | 151 045 | 121 270 | 1 718 | 57 | 30 643 | 3 862 |

÷ (term by term)

| Rp | Bf\Bp | Oil | Gas primary | Coal | Nuclear | Renew. only Elec. | Renew. Others | Others non-Renew. |
|--|-------------|-----------|-------------|-----------|---------|-------------------|---------------|-------------------|
| Primary distribution - World, 2009 | Liquids | 3 670 868 | 6 941 | 18 141 | - | - | 52 509 | - |
| | Gas final | 475 | 1 522 497 | 9 846 | - | - | 11 358 | - |
| | Solids | 2 094 | 189 | 1 081 753 | - | - | 1 074 035 | 7 759 |
| | Electricity | 247 678 | 785 666 | 1 991 247 | 700 320 | 304 844 | 116 009 | 11 665 |
| | Heat | 23 980 | 218 579 | 182 883 | 2 988 | 105 | 36 529 | 5 464 |

=

| Eta | Bf\Bp | Oil | Gas primary | Coal | Nuclear | Renew. only Elec. | Renew. Others | Others non-Renew. |
|----------------------------------|-------------|------|-------------|------|---------|-------------------|---------------|-------------------|
| Efficiencies - World, 2009 | Liquids | 0,99 | 0,46 | 0,42 | - | - | 1,00 | - |
| | Gas final | 0,57 | 1,00 | 0,57 | - | - | 1,00 | - |
| | Solids | 0,57 | 0,55 | 0,85 | - | - | 0,95 | 1,00 |
| | Electricity | 0,41 | 0,44 | 0,41 | 0,41 | 0,41 | 0,41 | 0,46 |
| | Heat | 0,73 | 0,69 | 0,66 | 0,58 | 0,54 | 0,84 | 0,71 |

Figure 21: Calculation of the [Eta] matrix

As you can notice, the efficiencies obtained are realistic. Nevertheless, some of them can look a bit strange to you, such as Nuclear for instance. Nuclear power plant efficiency is known to have an efficiency of about 33%. In our [Eta] matrix, we have 41%. This is mainly due to the fact that IEA does not split the electricity production between the different types of electricity power plant. They are all included under the terms of *Electricity Producer plants*. Therefore the global efficiency of the couple electricity/nuclear may look unrealistic since it actually represents the global efficiency of the whole electricity production sector. It does not really raise any issue for us since our work is consistent, i.e. it respects the convention of the IEA and enables us to move between primary energy and final energy with the right proportion.

4th part – Calculation of the conversion matrix

Firstly, it would be useful to remind the formula for the calculation of the conversion matrix:

$$[\text{Conversion Matrix}] = [N(\text{Rf}) * 1/\text{Eta}]$$

The calculation of [Eta] has been presented in the 3rd part and we need now to set [N(Rf)]. The first matrix displayed in Figure 21 is the [Rf] matrix. [N(Rf)] is the normalized matrix of the later. To normalize [Rf], we apply the following mathematical norm:

Let E be set of the elements x_{ij} of the [Rf] matrix composed of $i = 5$ lines and $j = 7$ columns.

For all the elements x_{ij} belonging to E, we apply the normative functions

$$f_i : x_{ij} \rightarrow \frac{x_{ij}}{\sum_{j=1}^7 x_{ij}} \quad \forall i \in [1; 5]$$

We then obtain [N(Rf)]. Performing the division term by term between [N(Rf)] and [Eta], we get the conversion matrix. This matrix gathers energy mix and efficiencies information to convert a final energy demand into an equivalent primary energy demand. The conversion matrix for world in 2009 is presented by [Figure 22](#).

| CM | Bf\Bp | Oil | Gas primary | Coal | Nuclear | Renew. only Elec. | Renew. Others | Others non-Renew. |
|---------------------------------------|-------------|-------|-------------|-------|---------|-------------------|---------------|-------------------|
| Conversion matrix - World, 2009 | Liquids | 0,992 | 0,002 | 0,005 | - | - | 0,014 | - |
| | Gas final | 0,000 | 0,989 | 0,006 | - | - | 0,007 | - |
| | Solids | 0,001 | 0,000 | 0,554 | - | - | 0,550 | 0,004 |
| | Electricity | 0,144 | 0,456 | 1,155 | 0,406 | 0,177 | 0,067 | 0,007 |
| | Heat | 0,074 | 0,670 | 0,561 | 0,009 | 0,000 | 0,112 | 0,017 |

Figure 22: Conversion matrix - World 2009

Here was presented the main work performed on Access to find the historical conversion matrices which represent cornerstones within the operation of Rogeaunito.