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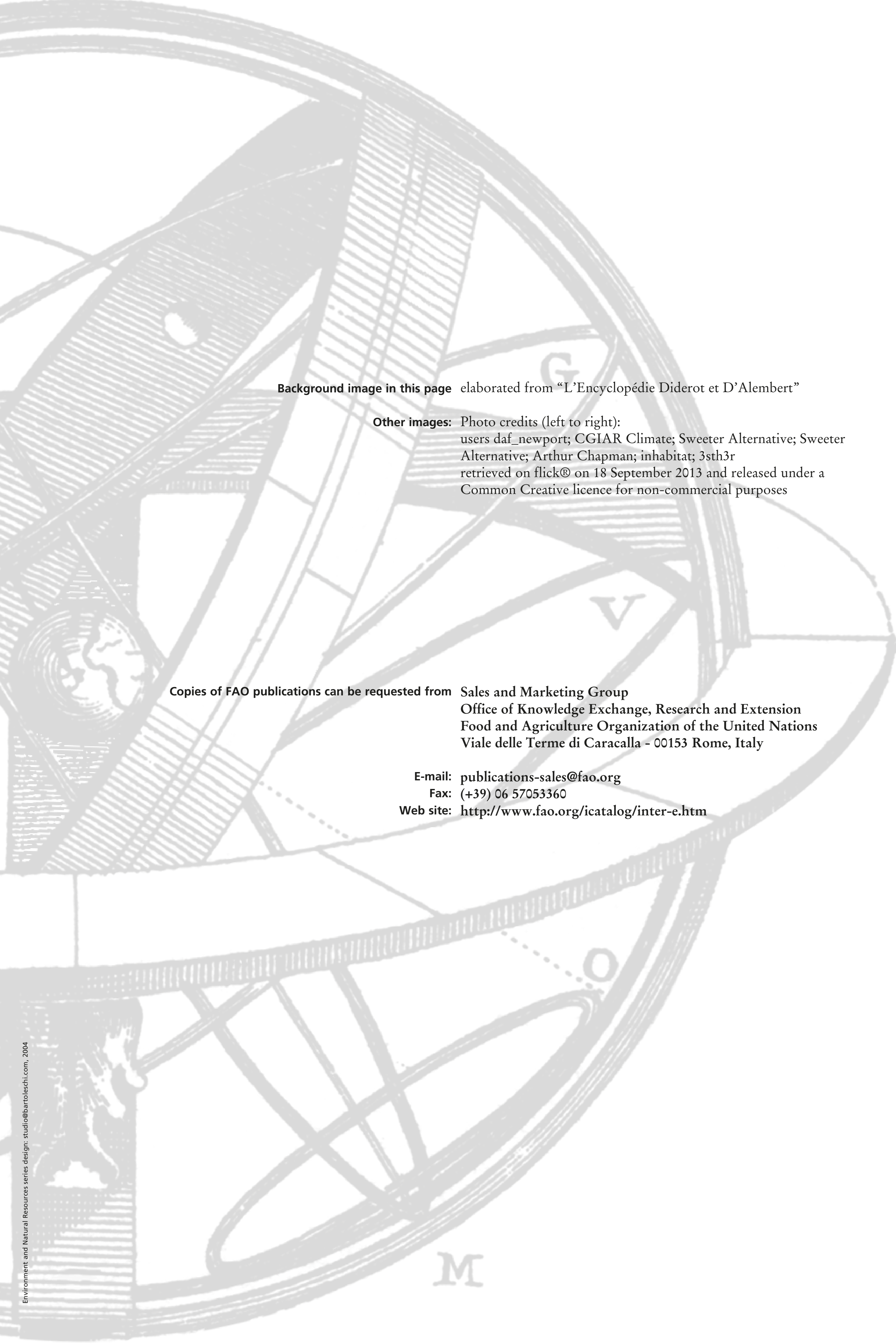
ENVIRONMENT CLIMATE CHANGE [ENERGY] MONITORING AND ASSESSMENT



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Mario Giampietro*, Richard J. Aspinall*, Sandra G.F. Bukkens*, Juan Cadillo Benalcazar*, François Diaz-Maurin*, Alessandro Flammini**, Tiziano Gomiero*, Zora Kovacic*, Cristina Madrid*, Jesús Ramos-Martín*, Tarik Serrano-Tovar*

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[ENERGY]

ABBREVIATIONS

CSP concentrated solar power
EC energy carrier
GHG greenhouse gases
GIS geographic information system
MSP minimum support price
PES primary energy sources

Compartments of the socioeconomic system
AG agricultural sector
BM building & manufacturing sector
EM energy & mining sector
HH household sector
PW paid work sector
SG service & government sector
TR transport sector

Fund elements
HA human activity
PC power capacity
ML managed land
THA total human activity
TPC total power capacity
TML total managed land

Flow elements
ET energy throughput
GER gross energy requirement (in joules)
NFS net food supply (in joules)
GWR gross water requirement (in hm3)
NSEC net supply of energy carriers
GSEC gross supply of energy carriers
TET total energy throughput (on a year basis)
TWT total water throughput (on a year basis)
TFT total food throughput (on a year basis)

Flow/fund ratios
ELP economic labour productivity
EMR energy metabolic rate (in MJ/hour)
SEH strength of the exosomatic hypercycle
EROI energy return on the investment

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INTRODUCTION

Human wellbeing relies upon the availability and wise management of food, energy and water. These are basic production factors 'flowing' within the economic system and their management is important to maintain the ecosystem which regulates the conditions for life. The interconnections between these resources, what is usually called the food, energy and water nexus, make clear that the management of each of them cannot be considered in isolation but should be seen as part of an integrated system. These interconnections which exist not only among natural resources but also among different levels or scales of assessment, between local and global processes of resources use, and between social and economic aspects of a society, highlights the complex issues involved in addressing these challenges in ways that also make effective use of the possible changes resulting from new policies or new interventions.

This report presents the results of the application of an integrated analysis approach, the Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism (hereafter MuSIASEM), to three case studies: (i) An analysis of the option to produce biofuel from sugarcane in the Republic of Mauritius; (ii) An exploration of the future of grain production in the Indian state of Punjab; (iii) An assessment of two alternative energy sources to produce electricity in the Republic of South Africa.

MuSIASEM, originally developed for analyzing the metabolic pattern of *energy* of modern society, is now extended to consider the energy-food-water nexus thus characterizing *simultaneously* the metabolic pattern of energy, food and water in relation to socio-economic and ecological variables. This challenge had not yet been addressed as such. The work in this project was focused on three objectives:

1. Developing and consolidating an integrated accounting method by implementing the MuSIASEM rationale to characterize *simultaneously* energy, food, and water flows and their interrelations for a complex system (society) interacting with its environment;
2. Application of the accounting method to three case studies, including data collection and analysis, with the aim to show its potential to assess (a) the desirability, viability and feasibility of the actual metabolism of socioeconomic systems (diagnosis) and (b) the feasibility of development scenarios and policy options (simulation) so as to generate usefulness quantitative analysis (integrated set of indicators) for governance;
3. Generation and presentation of the results in a user-friendly format.

This report provides a summary of the final results and is organized in three sections: chapter 1 provides a general description of the multi-scale integrated assessment of society and ecosystem metabolism applied to the nexus-assessment; chapter 2 illustrates the application of the developed approach to the three case studies; and chapter 3 summarizes lessons learned in terms of strength and weakness of the proposed tool.

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CHAPTER 1

MUSIASEM AS A TOOL TO ANALYZE THE NEXUS BETWEEN FOOD, ENERGY, AND WATER SECURITY

1.1. MUSIASEM AND ITS UNDERLYING CONCEPTS

The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is an innovative approach to accounting that integrates quantitative information generated by distinct types of conventional models based on different dimensions and scales of analysis. It builds on several innovative concepts derived from Bioeconomics and Complex Systems Theory, such as the flow-fund model, multi-purpose grammars and impredicative loop analysis. The application of these concepts allows the *simultaneous* use of technical, economic, social, demographic, and ecological variables in the analysis of the metabolic pattern of modern societies, even if these variables are defined within different dimensions of analysis and non-equivalent descriptive domains and refer to different hierarchical levels and scales. Given this special feature, MuSIASEM allows us to effectively analyze the nexus between energy, food, and water, considering heterogeneous factors such as population dynamics, greenhouse gas (GHG) emissions and land-use changes at the national or sub-national level. The accounting system is able to integrate data from national statistics and/or other readily available datasets (e.g. FAO Food Balance Sheets) with data from Geographic Information Systems (GIS). It can be employed for diagnostic as well as for simulation purposes.

It can be used for diagnostic purposes or to simulate scenarios.

As diagnostic tool, the accounting system is used to characterize the existing metabolic pattern of the socio-economic system under analysis by providing information on:

1. Population, work force, technological capital, managed land, and total available land (defined as *fund elements*);
2. Flows of food, energy, water, and money (defined as *flow elements*). For each of these flows the total requirement is defined, the fraction for internal consumption, the losses, the degree of self-sufficiency (internal supply), and imports and exports;A series of flow/fund ratios characterizing the rate (per hour of human activity) and density (per hectare of managed land) of the above flows across different scales (including the whole society and each one of the lower-level compartments defined in the accounting scheme, such as the various economic sectors). These ratios are then compared against reference values describing 'typical' socio-economic systems;

and on how these streams of information are integrated and interact among them.

As simulator tool, MuSIASEM provides a feasibility, viability, and desirability check of proposed scenarios, allowing to:

1. Check the *feasibility* of proposed scenarios by looking at the compatibility of the system with the boundary conditions. These external constraints are checked by comparing the required local flows to both the supply and sink side of the local interface with the environment. This analysis can be obtained by characterizing the required flows (dictated by the internal characteristics of the socio-economic system) with GIS data. The MuSIASEM methodology uses an *environmental impact matrix* for this purpose;
2. Check the *viability* of proposed scenarios by looking at the congruence between the requirement and the supply of flows across different compartments. This check can be done at different scales after characterizing the rate (per unit of time) and the density (per unit of area) of the various flows in the chosen scenarios. For example, data on consumption aggregated at the level of the whole society must result congruent with the technical coefficients (e.g. yields, productivity of production factors, requirement of specific processes) describing the supply at local scales. The MuSIASEM methodology uses a *multi-level, multi-dimensional matrix* for this task and a so-called *SUDOKU strategy* to check the congruence of values across the different scales and dimensions of analysis;
3. Check the *desirability* of viable scenarios by comparing the resulting metabolic pattern (flow/fund ratios) at the level of end-uses (specific functions at the local scale, such as sugarcane production, public transportation) to benchmark values of flow/fund ratios (expected features of the functions expressed) characteristic of given types of socioeconomic systems.

The concepts on which MuSIASEM is based includes the *flow-fund model*, borrowed from bioeconomics, and three conceptual tools – the *multi-scale accounting*, the *multi-purpose grammar* and the *impredicative loop analysis* – derived from the complexity theory.

The flow-fund conceptual model: It lies at the basis of MuSIASEM as it has proven extremely useful in the characterization of the metabolic pattern of social systems. In MuSIASEM, *fund elements* are those elements of the observed system that are transformative agents expressing the functions required by society. Funds are used but they are not consumed, they remain "the same" across the duration of the analysis. They represent "what the system is made of". Examples of fund elements are human beings, managed land uses, rivers, and technological capital. The idea of sustainability implies that these fund elements have to be maintained and reproduced in the metabolic process through the duration of the analysis. Fund elements correspond (to a certain extent) to production factors (labour, capital, land) in the economic narrative.

Flow elements, on the other hand, are those elements that appear or disappear (i.e. their attributes change) over the duration of the analysis, such as outputs that are generated or inputs that are consumed by the socio-economic process. The analysis of the transformation of flows tells us "what the system does" in relation to its context/

environment (at the large scale) and with regard to its internal components (at the local scale). Examples of flow elements are consumption and production of food, exosomatic energy (fossil energy, electricity), water (for drinking, domestic use, irrigation, industrial processes) and other key materials.

In stark contrast to traditional input/output analysis (e.g. energy input per unit of output, water footprint per unit of crop produced, energy intensity of the economy), the MuSIASEM approach always characterizes flows in relation to funds (e.g., energy input per hour of labour, water consumed per hectare of land in production, energy consumption per year per capita, GDP per year per capita). This feature is essential because it allows us to account for the special nature and the size of the system under analysis. For any metabolic system (e.g., a person, a society) expected relations between specific flow and fund elements are defined in both *qualitative* and *quantitative* terms and, therefore, benchmarks are defined for flow/fund ratios (intensive variables) of known typologies of metabolism (e.g., typical yield per hectare for corn, typical labour productivity per hour, acceptable wage per hour) and the relative size (extensive variable) of the specific investigated system (how many hectares of corn, how many hours of labour).

Indeed, the very identity of a flow depends on its end-use and therefore a flow (e.g. energy carrier) is always fund-specific (e.g. horses eat hay while tractors 'eat' fuel). This *qualitative* relation determines what attributes should be used to characterize a given flow and hence which flows are admissible in the accounting. For example, drinking water (flow) for human beings (fund) must satisfy certain criteria (e.g. absence of toxic substances and harmful microorganisms) to qualify as such and so must irrigation water (flow) for cropland (fund) (e.g. salinity level).

As regards the *quantitative* aspects, the nature of metabolic systems allows to define for the various fund elements (e.g., human beings, cropland, rivers) a range of admissible values for the ratio flow/fund that guarantees the survival and reproduction of these fund elements. For example, a human being must consume on average about 10 MJ of food per day, not much more and not much less; different crops require different quantities of irrigation water per hectare. The flow-fund rations are also typical of certain systems and can therefore characterize certain societies (e.g. an agriculture-based society).

Thus, basing the analysis of metabolic patterns on the flow-fund model it becomes possible to integrate in a coherent way various pieces of quantitative information referring to different dimensions of analysis (biophysical, agronomic, economic, demographic, and ecological).

In particular, in order to bridge the socio-economic and the ecological view, MuSIASEM uses simultaneously two complementing but non-equivalent definitions of fund elements, one relevant for socio-economic analysis (human activity and power capacity/technology) and one relevant for ecological analysis (land uses/land covers, water funds), at all levels and scales considered (e.g. local crop field, watershed, whole country). In this way, it provides an integrated characterization of society's metabolic pattern and its effect on the metabolism of the embedding ecosystems by combining non-equivalent systems of accounting.

Multi-level/Multi-scale accounting: Society is viewed and analyzed as a nested hierarchical system using the concept of "holons" developed by Koestler (1968). Each component of the system (e.g. the agricultural sector) is part of a larger whole (e.g. the paid work sector), which is in turn part of a still larger whole (e.g. the society) embedded in an even larger process determining boundary conditions (e.g. large-scale ecological processes). At the same time, each part can be analyzed by looking at its lower-level components (the paid work sector is composed of the agricultural sector, energy sector, service sector, etc.), which in turn can be analyzed in still smaller parts. The definition of the identity of the various components at the different scales is based on the identification of a structural and functional relation (the holon) that can be seen (in different ways) from both the higher (as a function) and lower (as a structure) hierarchical level.

Multi-purpose grammar: A grammar can be defined as a series of norms and formulating rules based on these norms to be followed by users of the *language*. It is different from a model in the sense that it provides a description based on an expected set of relations over semantic categories and then it establishes an expected set of relations between semantic and formal categories (data and formal systems of inference). For this reason a grammar is semantically open (e.g. "cheap labour" can be formalized in different ways depending on the year and type of society; the categories describing activities in the agricultural sector can be chosen using different criteria of accuracy). A multi-purpose grammar defines the relevant characteristics of the system as depending on other characteristics and therefore can be tailored and calibrated to specific situations and adjusted to include new relevant qualities in the analysis (see Giampietro et al., 2012).

Impredicative loop analysis: The impredicative loop analysis concept is borrowed from theoretical ecology. Unlike conventional (linear) deterministic models, MuSIASEM accommodates the chicken-egg predicament typically encountered in the description of complex systems. Having established a relation between the characteristics of the whole and those of the parts of the system in semantic terms, the grammar can be formalized in quantitative terms (using proxy variables) by generating a set of forced relations of congruence between the characteristics of the parts and those of the whole. These forced relations of congruence imply that the characteristics of the parts must be compatible with those of the whole and vice-versa, but they do not define a linear causal relation (hence the label "impredicative").

The application of a multi-purpose grammar to perform an impredicative loop analysis across the nested hierarchical organization of the system makes it possible to construct a multi-level, multi dimensional matrix that shows strong similarities with the popular Sudoku game. Indeed, when discussing the option space (i.e. possible scenarios of change) of a system whose metabolic pattern has been characterized in this way, it is possible to identify the existence of a series of congruence constraints across levels (characteristics of parts/characteristics of whole) and, *at the same time*, congruence constraints across dimensions (money flows, water flows, energy flows, technical requirements, labour requirements). The definition of these constraints is similar to the rules for a Sudoku grid.

1.2. HOW THE TOOL WORKS

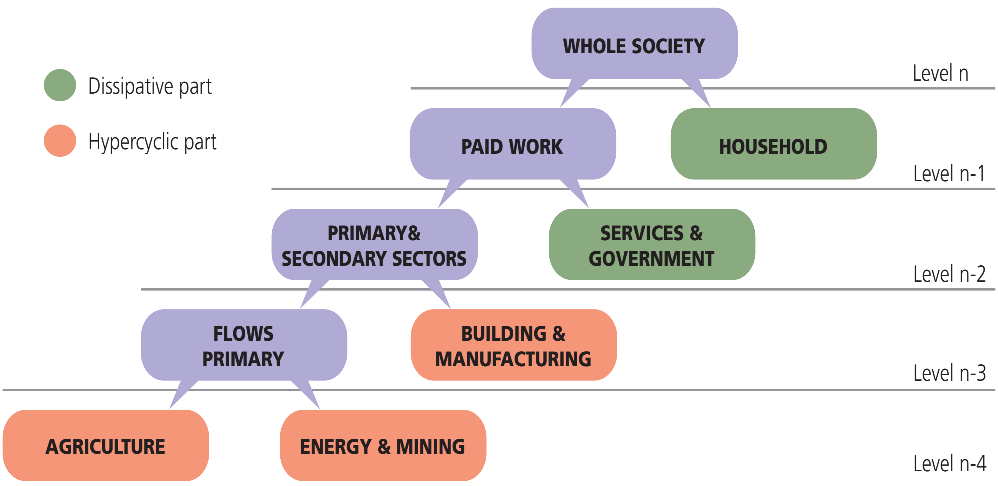
The approach involves the following six steps:

STEP 1: Definition of the socio-economic system as a set of functional compartments essential to guarantee its survival, reproduction and adaptability

This first step involves the definition of the nested hierarchical structure of functional compartments of society. The boundaries of the overall system are defined, at level n, and a set of lower-level compartments at level (n-1) (e.g., household sector, paid work sector) are defined within this "whole" on the basis of the functions expressed in society (e.g. reproducing human labour, generation of income). These lower-level compartments can then be further subdivided (level n-2, n-3, etc.) depending on the aim of the study. The definition of compartments must provide closure at all levels (the sum of the size of the parts must equal the size of the total) and be mutually exclusive (no double counting). Moreover, it must be practical for data collection: the data required to define both the size and the characteristics of individual compartments must be amenable to subdivisions practiced in national statistics. The nested hierarchical structure used in our case studies is illustrated in Figure 1.

Figure 1

The nested hierarchical structure of socio-economic compartments in society



The socio-economic sectors can also be aggregated into two macro-compartments expressing emergent properties observable only at a larger scale (Figure 1): (1) a *hypercyclic* part[1] that generates the required flows (food, energy, mineral, water), technology and

1 The terms *hypercyclic* and dissipative come from theoretical ecology. The hypercycle is that part of a complex system that drives the functioning of the entire system (itself and the rest). The dissipative part, on the other hand, uses the surplus of resources provided by the hypercycle and is responsible for the reproduction and adaptability of the system.

infrastructures for its own use as well as for use by the rest of society; and (2) a *dissipative* part that consumes the surplus generated by the hypercyclic part and allows for adaptability and reproduction of the fund elements. This distinction allows to analyze the viability of the dynamic equilibrium of the various flows (energy, food, water) (see step 5).

The selection of sub-compartments (below the n-1 level) should be given due importance as it not only allows to single out certain aspects of societal functioning but also permits to confront large-scale (i.e. top-down assessments based on aggregated statistics) with local-scale assessments (i.e. bottom-up assessments based on technical coefficients observed at the local level). This double check is essential in the analysis of the robustness of scenarios for the metabolic pattern given that at all times the characteristics of the whole and the main compartments observed at the larger scale must be compatible with those of the sub-compartments and lower-level elements observed at the local scale.

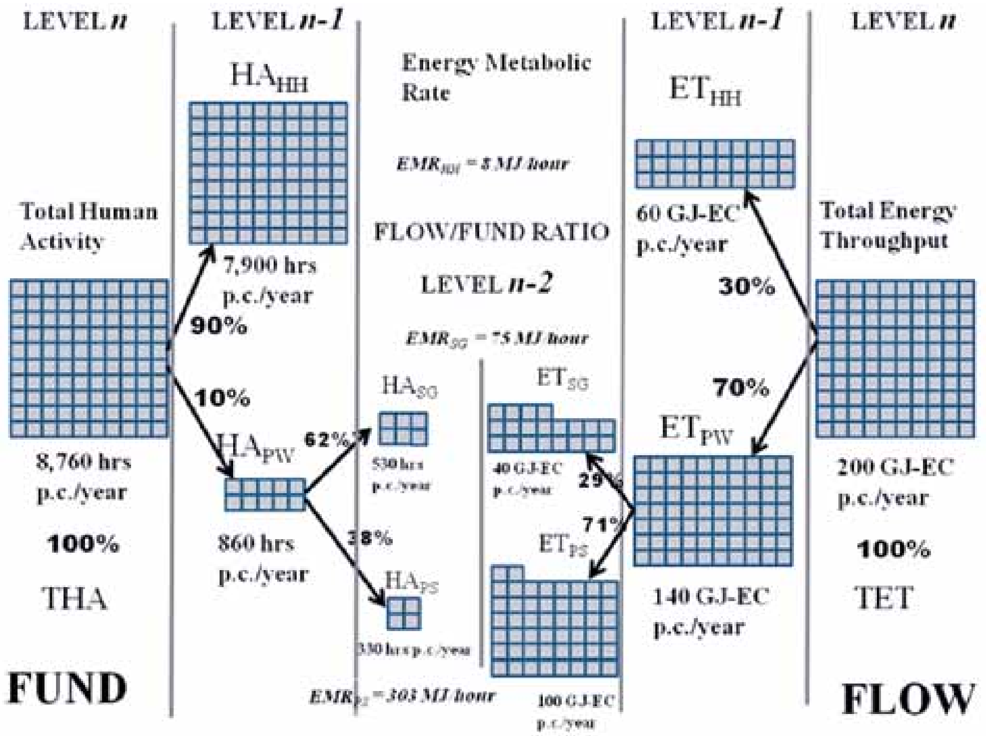
STEP 2: Quantitative definition of the profile of investment of fund elements over the functional compartments of the system

This step involves the selection of relevant fund elements and their quantification across the various functional compartments of the system (defined in the first step). In the case studies of this report, three fund elements are selected - human activity, power capacity, and managed land - and assess their allocation over the various socio-economic sectors of society. This step typically results in the generation of dendrograms[2] in which the total amount of fund element assigned to the whole society (on a year basis) is repeatedly split up moving further down its nested hierarchical structure. This procedure is illustrated in Figure 2 for the fund element human activity (left side of graph) and the flow element energy (right side of graph). Note that the first bifurcation for human activity depends on demographic (the dependency ratio) and socio-economic variables (work load, length of education, retirement age, absence, unemployment), while the branching within the Paid Work sectors depends on the characteristics of the economy. Clearly the depth of the dendrogram depends on the goal of the study and the availability of data for the fund (and flow) element in question.

2 A *dendrogram* is a tree diagram frequently used to illustrate the arrangement of the clusters produced by hierarchical clustering.

Figure 2

Dendrogram representing the profile of investment of the fund element human activity and the flow element energy

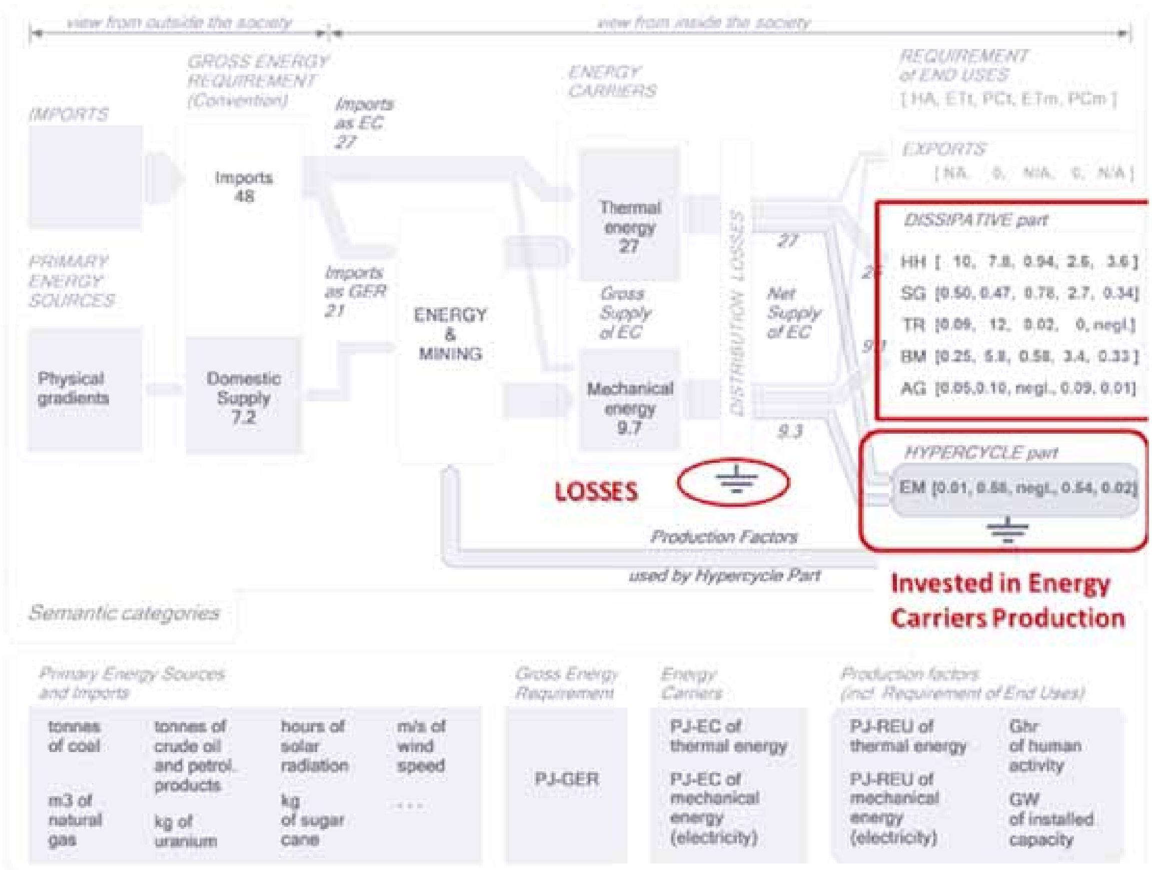


STEP 3: Quantitative definition of the flows required for expressing the functions

This step involves the definition and quantification of the various flows (food, energy, water, money) used by the selected fund elements associated with the various functional compartments at different levels. For this purpose, the MuSIASEM approach makes use of a series of grammars that describe the internal loops associated with the supply and consumption of the various flows. The grammars developed for energy, food, and water and used in the case studies of this report are illustrated in Figures 3, 4, and 5, respectively.

Figure 3

Example of energy grammar (from the case study of Mauritius)



Four pieces of information are essential for the construction of these grammars:

Gross supply/requirement: the overall flow that must be produced or made available through imports;

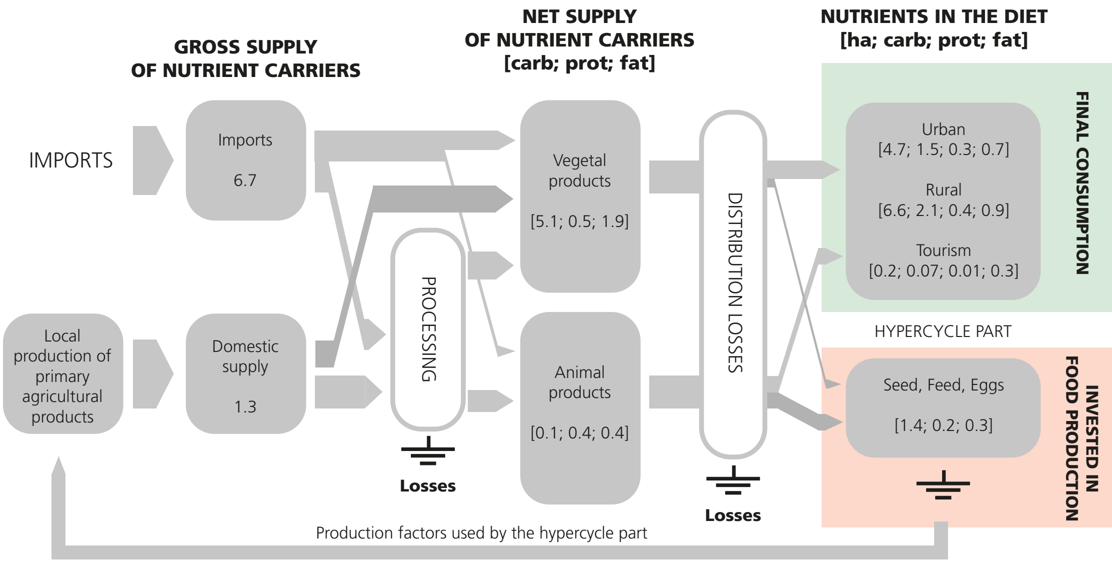
Net supply/requirement for "end uses": the net flow required by the various functional compartments to guarantee final uses. The characteristics of these "end uses" are defined by the grammars both in quantity and quality;

Losses: the fraction of the flow that does not make it to final consumption because it is lost in the network;

Internal autocatalytic investment: the share of the flow that must be invested in its own production. This specifically concerns the metabolic pattern of energy and food, where a fraction of the net supply is consumed internally by the compartment producing the flow. Indeed, energy carriers are used in the energy sector to produce energy carriers, and food products (seeds, eggs and crops used as feed) are used in the agricultural sector to produce food products. This internal investment in an autocatalytic loop is therefore not "available" for consumption by the other compartments.

Figure 4

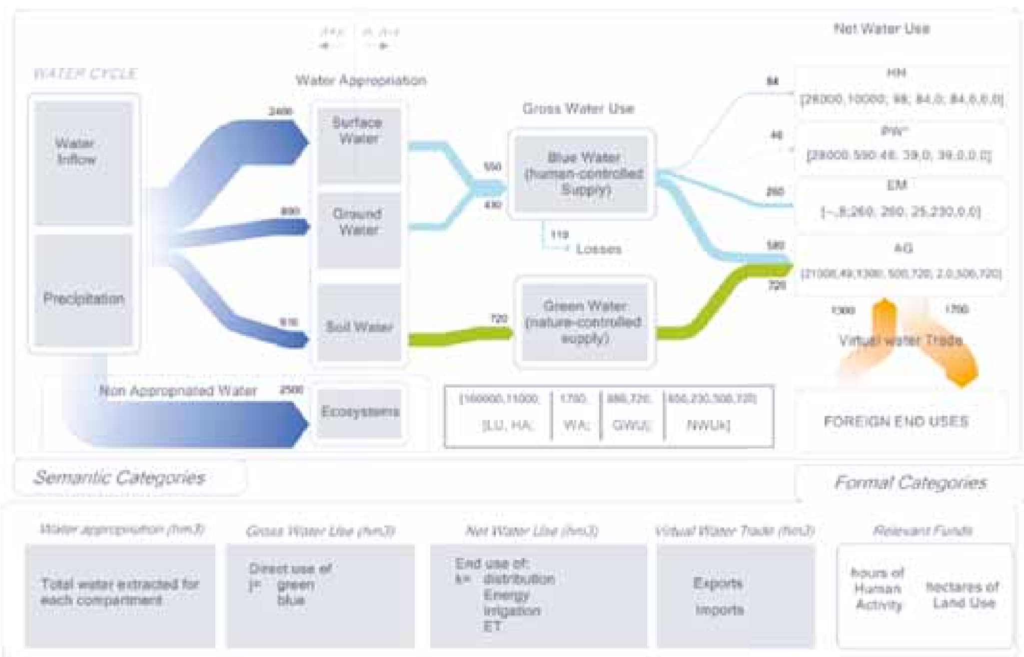
Example of food grammar (from the case study of Mauritius)



PRIMARY ENERGY SOURCES AND IMPORTS	UNIT	ENERGY CARRIERS	PRODUCTION FACTORS
Tonnes of vegetables and fruits	Net food supply [PJ]	Carbohydrates (carb)	Hours of human activity
Tonnes of animal products	Human activity [Gh]	Proteins (prot)	Hectares of land use
Tonnes of cereals		Fats (fat)	
Tonnes of other products			

Figure 5

Example of water grammar (from the case study of Mauritius)



STEP 4: The multi-level, multi-dimensional matrix describing the metabolic pattern across hierarchical levels and dimensions of analysis

Having defined and quantified the funds and flows, MuSIASEM makes use of a multi-level, multi-dimensional *matrix* of flow and fund elements to combine and represent the various descriptions given by the dendrograms (step 2) and the grammars (step 3) (see for example Table 1).

Table 1

Multi-level matrix characterizing the metabolic pattern of Mauritius

		Flow elements			Fund elements			Money (billion USD)
		Food (PJ)	Energy (PJ-GER)	Water (hm^3 extraction)	HA (Mhr)	PC (GW)	Land (Kha)	
Consumption	HH	5.9	16	98	10,000	1.5	28	n/a
	PW*	0.8	37	11	600	1.1		8,200
	AG	1.3	negligible	100	39	negligible	21	210
	EM	n/a	2.2	260	8	0.03	negligible	180
	exp_{pw*}	n/a	n/a	3	590	n/a	n/a	50% GDP
	exp_{ag}	negligible	0.36	1,100	39	0.02	51	2.5% GDP
	Whole	8	56	1,700	11,300	6.0	100	9,800 (GDP)
Supply	Imports	6.7	19	n/a	n/a	n/a	n/a	63% (GDP)
	Domestic supply	1.3	7	1,700	11,300	6.0	100	9,800

In this way it is possible to obtain an integrated characterization combining non-equivalent quantitative descriptions of the metabolic pattern across different hierarchical levels/scales (e.g. the whole, its compartments, and their subsectors) and different dimensions (e.g. demographic, economic, biophysical dimensions) of analysis.

Indeed, confronting the distribution profiles of the flow elements (energy, food, water, money) to those of the fund elements (human activity, power capacity, managed land) across the different functional compartments (HH, SG, BM, AG and EM) a set of *flow/fund ratios* are obtained (see example in the centre of Fig. 2) that effectively describes (diagnoses) the characteristics of the metabolic pattern of a society:

- The specific flow/fund ratios calculated at the different levels describe how the various compartments perform at their own scale of operation (e.g. the energy throughput per hour of human activity in the agricultural sector or in a given crop system; the GDP per hour of human activity in the paid work sector or in the energy and mining sector; the water throughput per hectare in the agricultural sector or of a given land use).
- The relative sizes of lower-level fund elements compared to society as a whole provide information on the structural relation between the functional parts and the whole. This information is useful to categorize the socio-economic system. For

example, in developed countries the percentage of the total work force in agriculture is typically less than 5%, while that in the service sector more than 65%. This type of large-scale picture also provides useful information on the degree of seriousness of environmental constraints (e.g. What is the fraction of total managed land allocated to agriculture? Is there still room for expansion? What is the fraction of total agricultural land put to high external input agriculture?).

- Information on the degree of openness of the system (e.g. What share of the total consumption of flows is internally generated and what share is imported?).

It is important to keep in mind that the values of the various fund and flow elements affect each other at different scales and in relation to different dimensions. For instance, the GDP per capita and Gross Value Added of the various economic (sub)sectors not only impose constraints on society in relation to the distribution of human activity (labour time), level of capitalization (e.g. power capacity) and land uses across the set of economic sectors but, at the same time, are also determined by these factors.

To complete the picture the effects of imports and exports on the functioning of the society should be considered, first of all, in terms of required gross supply for the various flows. This calculation requires considering: (i) what is the required net supply of the compartments operating inside the society, an information determined by the characteristics of the given set of fund elements (final consumption); (ii) what is produced within the system; (iii) what is lost; (iv) what fraction of this production has to be re-invested in the process of internal production. These pieces of information are all required to understand the characteristics of the network of transformations associated with the given set of fund elements (internal supply). With this information the net effect of the terms of trade can be assessed[3].

In conclusion, by comparing the distribution profiles of the energy, food, water, and waste flows to the distribution profile of the fund elements (e.g. human activity, power capacity, managed land) across the different functional compartments (HH, SG, BM, AG and EM) it is possible to generate a set of benchmark values (i.e. the resulting flow/fund ratios defined in each compartments), that describe the characteristics of the metabolic pattern of a society. This analysis can also identify the degree of *openness* of the system, that is which fraction of the total consumption is internally generated and which fraction is imported.

STEP 5: Checking the viability and desirability domain for the metabolic pattern (definition of the internal constraints of sustainability)

A metabolic pattern is *viable* if, given the structural constraints (supply of production factors/fund elements), it is capable of generating an adequate internal supply of the various

3 When the requirement of gross supply of a given flow (food, energy or water) is not matched by the local net supply (after considering losses and internal consumption) imports are the only way to guarantee the stability of the metabolism of that flow.

flows it consumes (food, energy, manufactured goods, infrastructures, services). Viability is checked by cross-verifying the stability of the *dynamic* budgets of the individual flows (food, energy, water, money). For example, the total flow of food consumed by society must be provided by the agricultural sector or imported. This food supply has to be secured with only a limited share of the production factors (human labour, power capacity, managed land) employed in either producing or importing food (= producing and selling other products of an equivalent economic value). In the same way, the total flow of energy carriers consumed by society must be supplied by the energy and mining sector or imported, while using only a limited share of the production factors. The same applies to money, water and other flows. As the sum of the production factors (human labour, managed land, power capacity) must equal society's total endowment, an integrated set of forced relations across the dynamic budgets can be obtained. This is what is called the *Sudoku* effect.

At the macro level of analysis, the *desirability* of the metabolic pattern refers to the internal pressure on a socioeconomic system to allocate a relatively large share of fund elements (human activity, power capacity) and consumed flows (energy, food and water) to the household sector, the service & government sector and the transportation sector (together the so-called *dissipative compartment*), so as to guarantee a relatively high standard of living. It concerns the question whether society can afford a large so-called *societal overhead* on human labour in the primary and secondary sectors (i.e. how large is the surplus generated by the hypercyclic compartment?). Therefore desirability is strictly related also to behavior and cultural background of societies, who would be ready to accept certain changes and reject others.

Desirability at this level is checked by the so-called *Bio-Economic Pressure (BEP)*, defined as the ratio of production factors and flows allocated to the dissipative compartment to the total amount of fund and flow elements. It has been proved (Giampietro et al. 2012) that in modern societies the larger is this ratio, the better are the indicators of development[4].

At the local level, the desirability check concerns a comparison of the resulting metabolic pattern at the level of end-uses (e.g. net energy supply per hour of labour in biofuel production) to reference values of flow/fund ratios (expected features of the functions expressed) characteristic of given types of socioeconomic systems.

4 In developed societies a large fraction of the fund elements (human activity, power capacity) has to be allocated to the compartments related to both final consumption and transaction activities (HH, SG and TR). In fact, previous studies have shown that the ratio of the total amount of fund elements allocated to these two compartments versus the total amount of fund element (calculated over the multilevel matrix) is a very effective biophysical indicator of development. According to the BEP indicator, the larger is the fraction of production factors allocated in HH and SG, the higher is the level of socio-economic development (the value of BEP). Previous empirical studies have proved that BEP correlated very well with GDP p.c. and with indicators of development used by the World Bank over a very significant sample of world countries over historic series.

STEP 6: Checking the feasibility of the metabolic pattern in terms of resource requirement (supply side) and environmental loading (sink side) - definition of external constraints to sustainability

By looking at the aggregate gross requirement of biophysical flows and the corresponding flow of wastes, the environmental loading of a given metabolic pattern can be assessed: the overall requirement of natural resources on the supply side (either directly used or embodied in imports) and the sink capacity. It is important to realize that the gross requirement (and the resulting flow of wastes) describes the interaction of society with its natural environment and hence does not equal the net requirement of biophysical flows consumed by the various compartments within society. For example, in the assessment of the resource requirement and sink capacity for agriculture, not only the food effectively consumed by the population (the net requirement) is considered, but also the feed crops needed for animal products (the internal autocatalytic loop in the agricultural sector) and the post-harvest losses in the food system. The same applies to the resource requirement (primary energy sources) and sink capacity (CO_2 emission) for the energy sector: not only the final consumption of energy carriers (electricity, fuels and heat) inside society (net requirement) is considered, but also (i) the fossil energy consumed in the double conversion of thermal energy into electricity; (ii) the losses in conversion and distribution, and (iii) the effect of changes in land uses on CO_2 release. The quantitative analysis of the interaction of society with its context (the embedded ecosystems) is articulated in spatial terms across scales, using GIS data. Indeed, levels of environmental loading, defined as the difference between the flow densities of natural land cover and those of managed land uses, have to be assessed simultaneously at different hierarchical levels and scales (e.g. soil, crop field, watershed, national scale, global scale). The scaling of this quantitative information can only be handled by employing GIS.

1.3. THE LINK OF QUANTITATIVE ANALYSIS OF FLOW TO LAND USE

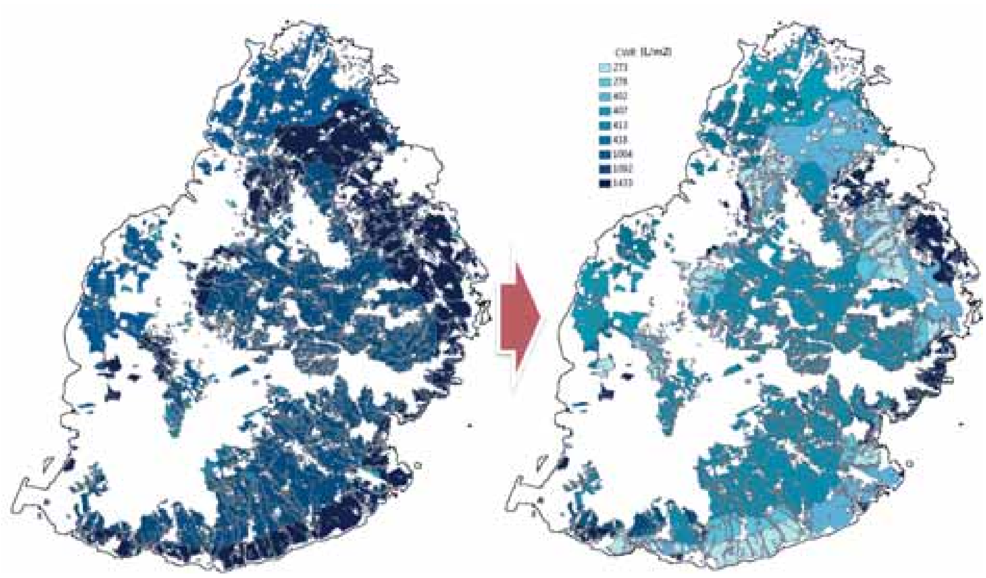
1.3.1 The use of benchmarks for the characterization of land use typologies

The use of benchmarks to characterize the expected characteristics of land uses is essential since it makes it possible to use GIS to scaling up assessments of consumption of energy flows referring to the local scale. That is, after having assessed the amount of water evapotraspirated by two typologies of crop production (e.g. water use per ha of sugarcane and water use per ha of the given mix of food crops) it become possible to scale-up this assessment to the whole sector producing sugarcane in a country assuming a change in the relative area in production. That is, by simply calculating the effects of a change in the mix of hectares in production (between sugarcane and conventional crops) and adjusting the resulting assessment for the different climatic conditions found in the country - determining variations in the expected density of the flow of evapotranspirated water per hectare – one can assess the overall change in the requirement of water for the agricultural sector. An example of this approach is given in Fig. 6 - this assessment has been carried out within the case study of Mauritius (see section 2.1).

This feature of GIS analysis is a perfect complement to link the analysis of biophysical flows to the analysis of socio-economic processes.

Figure 6

Application of GIS to assess water use for sugarcane production



1.3.2 The importance of this link for the analysis of environmental impact

As an expected relation is established between density of flows per hectare (water per ha per year; nitrogen fertilizer per ha per year; crops yields, biomass appropriated per year) determined by the metabolic pattern of society, it becomes possible to establish a bridge between the analysis of the metabolic pattern of society and the impact that this metabolism implies on the metabolism of the ecosystems embedding human society. In fact, theoretical ecology has proved that when analyzing the characteristics of natural ecosystems it is possible to define a set of expected characteristics associated with the metabolic pattern of terrestrial and aquatic ecosystems. This feature is briefly illustrated using examples of possible applications of this approach to 6 practical issues.

Example #1 – assessing the effect of the release into the environment of harmful substances

In the case of the release of harmful substances, the harmful flow as generated by a human activity categorized at a local scale can be identified, that is, an economic activity carried out in a sub-compartment of an economic sector. On the socio-economic side this activity can be associated with a flow of money (e.g. profit, wages and investments), the requirement of fund elements (e.g. job and capital), and a given land use, all associated with these physical flows - e.g. the economic characterization of an industrial infrastructure with a textile plant dumping chemical substance into the near river. Then the density of the flow associated with this aspect of societal metabolism, expressed per unit of land use of the given category, represents the mechanism through which a bridge is established with ecological metabolism.

In fact, when considering the amount of hectares in that particular land use (e.g. hectares for a textile plant) and knowing the expected load of chemical substances to be dumped in by rivers, it becomes possible to connect the socio-economic attributes (flow of added value and the number of jobs generated by the plant) with the environmental load associated with its waste effluents.

Using this rationale it is possible to distinguish between:

(i) non-point pollution sources – e.g. the pollution generated by agricultural activities with leakages of phosphorous, nitrogen and/or pesticides residues in the water table – in which the flow of pollutants has a low density, but it is generated on a large area (GIS can be used to scale up the aggregate effect at the level of the watershed);

(ii) point source pollution (e.g. the textile plant dumping harmful chemical in a river) in which the flow of pollutants has a very high density, but the area of this harmful land use is very small. In this case, GIS is used to study the possible effect of this concentrated flow in relation to its possible dispersion and in relation to other point sources present in the same area.

In both cases, it is important to study how the particular flow generated by societal metabolism affects the stability of fund elements of the ecosystems – i.e. the structural and functional elements of ecosystems – whose reproduction and stability is essential for the preservation of ecological integrity (e.g. the health of the river, the contamination of an aquifer, etc.).

Example #2 – stress on the soil due to excessive agricultural pressure

In this case, the issue is dealing with the stress generated by societal metabolism on a very special and valuable type of fund element of terrestrial ecosystem: the soil.

Looking at the expected characteristics of the types of soil considered one can define acceptable values for the flows of nutrients, water and other substances getting through it. The density of these flows must remain in a range compatible with the ecological and physiological processes required for the local reproduction of this fund (soil health).

On the other side, the pattern of societal metabolism defines the characteristics of the vector of "end uses" in agriculture. This implies a certain level of productivity per hectare and per hour of labor, that has to be associated with the use of inputs (e.g. energy, machinery, fertilizer, irrigation). Therefore, depending on the characteristics of the metabolic pattern in the agricultural sector (the vector of "end uses" in agriculture) humans may end up by forcing through the soil a flow of inputs at a speed that may result not compatible with the preservation of soil health (see the Punjab case study).

Example #3 – stress on water funds due to excessive human pressure

Also in this case the stress generated by societal metabolism can be assessed starting form a definition of the characteristics of ecological water funds (e.g. lakes, rivers, aquifers) expected according to the features of ecological metabolism. The characteristics of flow elements associated with societal metabolism (input needed to stabilize water uses) can be considered both in quantity and quality. Depending on the category of water use (e.g. withdrawal for human consumption, for irrigation, for cooling power station) different typologies of impact and different quantitative requirement of water throughput are defined. In general, agriculture is the sector requiring the larger consumption of water (up to 80% of the total consumption of a society) and therefore represents the water use more likely to threaten the integrity of water funds.

Also in this case, the MuSIASEM approach makes it possible to establish a relation between the socio-economic analysis of water use (e.g. the added value gained, job created, food supply for food security) associated with the use of one unit of water, and its compatibility with ecological constraints. In fact the option space associated with sustainability is determined by the need of preserving the existing ecological funds. In this type of analysis it is essential to work in GIS to handle the integrated analysis of the quantity and quality of both ecological funds and societal flows (see the Punjab case study).

Example #4 – stress on terrestrial ecosystems due to excessive human pressure

When dealing with terrestrial ecosystems a similar approach as above can be adopted. The assessment of stress generated by societal metabolism should start form a definition of the types of terrestrial ecosystems that should be expected in a particular area. This definition can be obtained by characterizing their metabolic pattern done in theoretical ecology. It is possible to define for typologies of terrestrial ecosystems:

(i) the expected values of Standing Biomass – a fund element (SB);

(ii) the Gross Primary Productivity (GPP) – a flow element; and (iii) the resulting flow-fund ratio (GPP/SB) and the associated flows of evapotranspiration of water required for moving nutrients per unit of standing biomass – a flow-fund ratio.

Against this set of expected characteristics of the metabolic pattern of a given typology of terrestrial ecosystem, it becomes possible to compare the analogous characteristics of:

(i) fund elements (Standing Biomass);

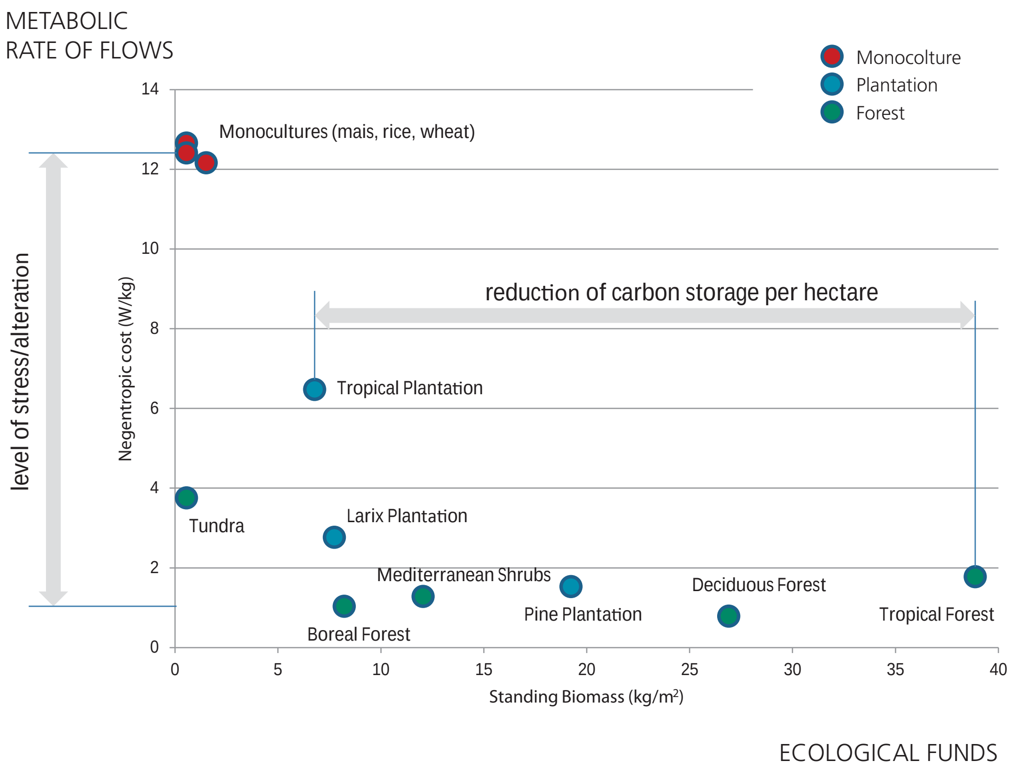
(ii) flow elements (Gross Primary Productivity); and

(iii) flow-fund ratio (GPP/SB) found when analyzing the pattern of biomass production determined by human management.

This analysis shows that the characteristics of the metabolic pattern of annual crops and wood plantations are quite different from the characteristics of the metabolic pattern of the natural ecosystems they have replaced. An example is given in Fig. 7.

Figure 7

The expected characteristics of natural terrestrial ecosystems and managed land uses (cultivations) based on the analysis of funds and flows



By using this method of characterization and quantification of the metabolic plant of terrestrial biomass it becomes possible to characterize the characteristics of typologies of terrestrial ecosystems and typologies of cultivated areas (defined per hectare or unit of land) and then rely upon GIS to move to a larger scale the assessment of the aggregated effect of changes in land uses. This approach requires considering the characteristics (per hectare) of both the original ecosystems found (referring to natural categories of land cover) and the characteristics (per hectare) referring to categories of land use determined by human management.

Example #5 – large scale effect of ecological disruption due to excessive human pressure

Theoretical ecology can be used to develop quantitative indices of ecological impact at a large scale. In fact a method of accounting that can characterize the metabolic pattern of ecosystems exists using quantitative indices. This method is called *EMergy analysis* and shares many characteristics with the MuSIASEM approach. By using the approach based on EMergy it is possible to calculate the "natural EMergy" – i.e. the amount of embodied solar energy associated with the reproduction of ecological funds based on a natural recycling of nutrients powered by solar energy – in a given area. Then, the human interference with the natural metabolism of ecosystems can be assessed calculating the reduction of "natural EMergy" in a given area, that humans replace with technical inputs.

Another approach which would assess the impact on the integrity of ecosystems (especially for aquatic ecosystems) is the *Ascendency index*.

Both indices (EMergy analysis and Ascendency) can be easily related to the ability of natural ecosystem to preserve biodiversity and natural habitats in a given area (when considering a large scale).

CHAPTER 2

APPLICATION TO CASE STUDIES

The sole purpose of the case studies presented is to illustrate the potential of MuSIASEM to analyze the nexus between energy, food, and water flows in sustainability assessments of socioeconomic systems. These applications are a mere exercise and do not intend to actually guide policy development. A proper application of MuSIASEM demands the involvement of local actors and experts, a prerequisite that was not fulfilled in this project. Local actors are required in the pre-analytical choices of issue definition, that is, the choice of the narratives within which the quantitative analysis is to be developed. Input of local expertise is essential for:

(i) problem structuring – i.e. tailoring of the chosen grammars on the specific situations faced in the case study at a given point in space and time;

(ii) pertinent modeling – i.e. quality check on the plausibility of the assumptions; and

(iii) data quality – i.e. double-checking the robustness and reliability of data by triangulating across different data sources.

The three specific case studies, the Republic of Mauritius, the state of Punjab in the Republic of India, and the Republic of South Africa, were selected from among the countries studied by the larger nexus network given that they neatly suited the purposes of the study. The method of accounting is illustrated with practical examples (tables and GIS analysis) in relation to the application of the grammars presented in Chapter 1 to generate an integrated analysis of food, water and land use, when describing the case study of Mauritius. Examples of the application of the grammar for energy accounting are provided when discussing the case study of South Africa.

2.1. CASE STUDY - THE REPUBLIC OF MAURITIUS

2.1.1 Background, objectives and data

Since independence in 1968, Mauritius has developed from an agricultural based economy to a diversified economy by strongly expanding its financial and tourism sectors. In 2010, 78% of the agricultural lands of Mauritius were used for sugarcane plantations, producing for exports. Thus, Mauritius is using 78% of its agricultural land and 90% of its water for this single task. Yet, sugar exports contribute only 4% of Mauritius' Gross Value Added. The country presently imports most of its consumed food and energy.

The objective of this case study was to focus on possible changes in the agricultural sector of Mauritius by analyzing the energy, water, food, and monetary flows in relation to the requirement of human activity, power capacity and land use, considering the implications on imports and exports. To this purpose, a simulation was made to check the viability and feasibility of two policy options: (i) using actual sugar exports for internal production of biofuels to produce local energy carriers, thus reducing the dependency on energy imports, and (ii) moving to an alternative pattern of agricultural land use on the island to increase local food production, thus reducing the dependency on food imports.

Data for the analysis were mainly obtained from the Ministry of Finance and Economic Development, the Ministry of Agroindustries and Fisheries of the Republic of Mauritius, the Mauritius Sugar Industry Research Institute (MSIRI) as well as from FAO. All data refer to 2010 unless stated otherwise. A complete list of data sources consulted for this study is available in the appendix.

Mauritius is located in the Indian Ocean, at more than 800 km from Madagascar . Its surface covers 204,000 hectares (FAO), including the islands of Agalega, Cargados Carajos and Rodrigues, and its highest peak ranging at 828 metres above sea level. The island has a volcanic origin, so its geology is influenced by this fact, except for some coral formations of the reef and few alluvial areas.

The climate in Mauritius is humid, subtropical and maritime (Saddul 1995, Proag 1995), due to its tropical latitude, small size, low altitudes, and distance from continents. There are two main seasons: a warm and rainy season with 79% of the rainfall, and a more dry winter season from May to October. The temperature ranges from 16ºC to 28ºC, and humidity remains quite constant about 80% throughout the year. Rainfall varies into three main climatic zones (subhumid, humid and superhumid) according to the elevation, with an average annual precipitation of more than 2000 mm. Mauritius suffers occasionally from cyclones, affecting considerably the agricultural production (Proag 1995).

Half of the surface of Mauritius is used for agricultural production (FAO), and the urban area is quite extended, covering 15% of the island (MSIRI). The forests, shrubs, and rocky area represent 33% of the land (FAO and MSIRI). Sugarcane lands have lately slightly decreased, however, it remains by far the most important agricultural crop. The four major sugarcane varieties include R570, M 3035/66, M695/69 and 1658/78 (MSIRI). The rest of lands for other agricultural crops covers less than 12% of the harvested land, and the pastures cover around 10% of the land under production. The non-sugarcane crops are potatoes, few vegetables and fruits, tea and tobacco. An ad-hoc map of the main land covers of the island iwas created for this project starting from satellite imagery (see Fig. 9).

Since the geology in Mauritius is similar to the Hawaiian Islands, the soils are using the classification system of Hawaii, which is in relation to age and rainfall. A map with the soil types and distribution in the island is shown in Fig. 9. There are two main types of soils relevant for agriculture in Mauritius: the mature latosols and the immature latosolic soils.

Figure 8

Main land covers of Mauritius. Own elaboration from LandSat 7 imagery

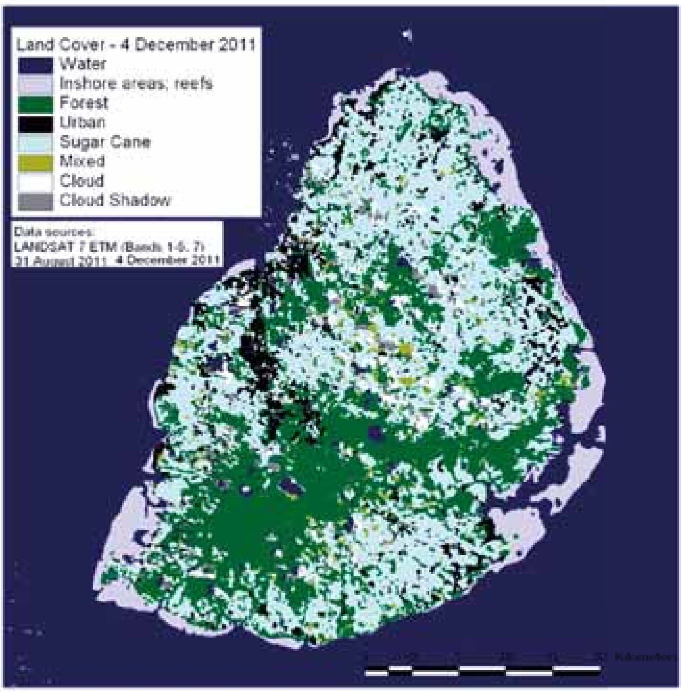
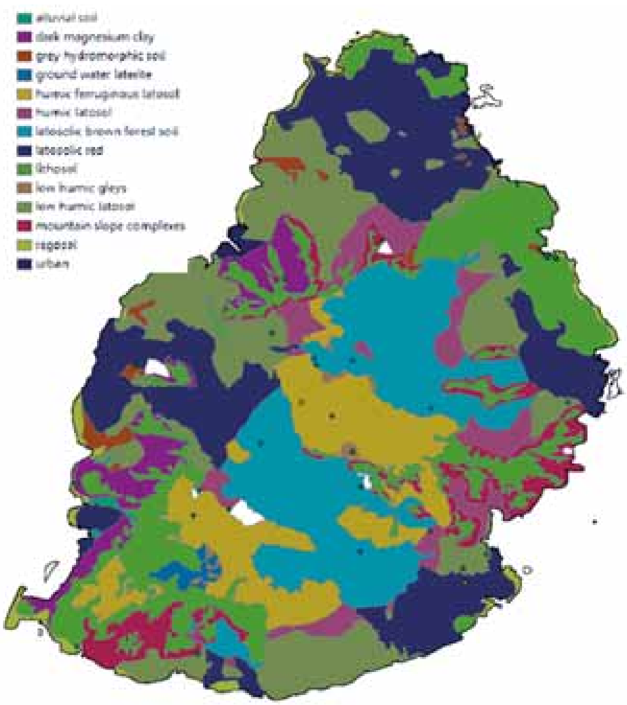


Figure 9

Soil types and distribution in Mauritius



The map has been generated using data from: Soil Map of Mauritius. D.O.S. (Misc) 317. Published by Directorate of Overseas Surveys. Base map prepared from Series Y682 published by D. Survey, War Office, And Air Ministry, 1957.

In the MuSIASEM approach, demographic variables such as populations size, demographic structure (dependency ratio), and other social variables such as employment, level of education work load for the employed are accounted for by looking at the profile of distribution of **Human Activity** over a given set of categories.

For this accounting data needed are:

- Total resident population, urban population, rural population, potentially active population, labour force, employment, unemployment and inactive population
- Employment by sector (in thousands of workers). Sectors are classified as follows:
  - Agriculture, forestry and fishing;
  - Sugarcane;
  - Tea;
  - Fishing;
  - Other primary sector;
  - Mining and quarrying;
  - Manufacturing;
  - Sugar;
  - Food, Textiles;
  - Other manufacturing;
  - Electricity, gas and water;
  - Construction;
  - Wholesale, retail trade, repair of vehicles;
  - Hotels and restaurants;
  - Transport, storage and communications;
  - Financial intermediation;
  - Real estate;
  - Public administration, defense;
  - Education;
  - Health and social work;
  - Other services;
- Hours of work per week (Sectors as above)
- Monthly wages (Sectors as above)

All these data have been taken from data from "Digest of Labour Statistics 2011" referring to the year 2010. Data on hours of work per week for the sectors Mining and quarrying, Manufacturing, Public administration and defence is taken from "Housing and Population Census 2011", Ministry of Finance and Economic Development, for the year 2011.

Human activity for each economic sector is calculated (in hours per year) as

HA = "people employed per sector" x "hours of work per week" x "52 weeks per year"

It is assumed that average hours of work per week as reported by national statistics take into account national holidays.

Data on **human activity of tourists** are taken from "Digest of International Travel and Tourism Statistics 2011". Data for 2010 refer to-"Number of overnights". The number of overnights of tourist makes it possible to calculate a number of "resident equivalent" as:

Tourist-resident equivalent = "Number of overnights" / 365 days per year

$HA_{tourists}$ = *"Number of overnights" x 24 hours per day*

The age structure of the resident population is taken from "Labour force, Employment and Unemployment based on the results of the Continuous Multi Purpose Household Survey - Year 2010". The data is aggregated in the categories used by the MuSIASEM protocol.

At level n (whole society), Total Human Activity (THA) is calculated as:

*THA = population * 8760 hours/year + HA tourists*

At level n-1, the two categories considered are Paid Work (PW) and Household (HH),

$$THA = HA_{HH} + HA_{PW}$$

When considering a hierarchical structure in which the sum of higher level compartment (e.g. THA at the level n) is the sum of lower level compartments (e.g. HA_{HH} and HA_{PW} at level n-1), Human Activity in Paid Work (the sum of hours of paid work in the economy) can be considered the sum of all the hours of paid work in the various sub-sectors of Paid Work:

$$HA_{PW} = \Sigma HA_i$$

Where the ***i*** sectors considered are all those appearing in the employment statistics. It is essential that the accounting across levels provides closure – i.e. the sum of the hours of work in the lower level must be equal to the hours of work in the upper level. As result of this assumption:

$$HA_{HH} = THA - HA_{PW}$$

Following this system of accounting, PW accounts for about 11% of THA and HH for the remaining 89%.

At level n-2, studying how the value of HA_{PW} splits among the lower level compartments, the definition of the economic sectors to be considered in the accounting depends on the focus of the case study. For example, in this case study focusing only on changes in the agricultural sector (moving its production to Energy and Mining with the production of biofuels), PW is divided into only three sectors: (i) agriculture (AG); (ii) Energy and Mining (EM); and (iii) the remaining economic activities (PW^*). Therefore, with this definition of compartments the MuSIASEM categories are derived from the categories found in national statistics as follows:

Table 2

Correspondence of categories used with national statistics categories

MuSIASEM categories	National Statistics categories
AG	Agriculture, forestry and fishing; Sugarcane; Tea; Other primary sector
EM	Mining and quarrying; Electricity, gas and water
PW*	Fishing; Manufacturing; Sugar; Food, Textiles; Other manufacturing; Construction; Transport, storage and communications; Wholesale, retail trade, repair of vehicles; Hotels and restaurants; Financial intermediation; Real estate; Public administration, defence; Education; Health and social work; Other services

In this accounting framework, AG accounts for 7% of the human activity (paid work) of PW, and EM only for 1%.

Since national statistics do not provide a lower level of disaggregation of the sector "Electricity, gas and water", values for "Electricity and gas" cannot be separated from values for "Water". The whole sector is attributed to EM in this analysis.

Data on **economic accounts**, taken from "National Accounts of Mauritius 2011", refer to the year 2010 and are reported in million Rupees. The report contains data on:

- Value added per economic sector (using the definition of Sectors as above);
- GDP at basic prices, Taxes on products, Subsidies, Compensation of employees, Final consumption expenditure, Current Account, Capital and Financial Account;
- Foreign trade statistics.

Data on the **agricultural sector**, taken from "Digest of Agricultural Statistics 2011", refer to the year 2010 and are reported in million Rupees. Data includes:

- Value added per product/service (Sectors: Industrial crops; Sugarcane; Tea; Tobacco leaf; Other industrial crops; Food crops; Fruits, flowers and forestry; Livestock and poultry products; Government services; Other agricultural services)
- Agricultural exports (Sectors: Sugar; Molasses; Tea; Fish; Vegetable and Fruits; Cut flowers and foliage; Other agricultural and food products).

Data on **household expenditure**, taken from "Household Budget Survey 2006/07", Ministry of Finance and Economic Development, Republic of Mauritius, refers to 2007, and includes:

- Expenditure of rural and urban households in: Food and non-alcoholic beverages; Alcoholic beverages and tobacco; Clothing and footwear; Housing, water, electricity, gas and other; Furnishing, household equipment and maintenance; Health; Transport; Communication; Recreation and culture; Education; Restaurants and hotels; Other goods and services;
- Average monthly income per capita of rural and urban population.

Therefore, all figures used in this study are reported in Rupees.

The data have been aggregated using the categories used by the MuSIASEM protocol.

At level n-1, the two categories considered are Paid Work (PW) and Household (HH). In the MuSIASEM accounting protocol the Value Added is attributed entirely to the PW sector:

$VA_{PW} = GVA$

$VA_{HH} = 0$

At level n-2, PW is subdivided into three sectors: agriculture (AG), Energy and Mining (EM), and other activities (PW^*). The MuSIASEM categories are derived from the categories found in national statistics following the same allocation as for HA. As a result, AG accounts for 4% of GVA, EM for 2%, with the remaining share of value added (94%) generated in the secondary and tertiary sectors. In particular, the financial sector and real estate sector of Mauritius together account for 23% of the country's GDP. In these sectors the creation of value added is not directly linked to the processing of resources but also from credit leverage, debt and speculations. As a matter of fact, Mauritius is listed as a "tax haven".

Gross Value Added in USD was obtained from the World Bank database for the year 2010. The exchange rate was derived for total GVA and applied to all economic sectors.

Economic Labour Productivity (ELP) is calculated as

ELP (USD/hour) = "GVA in USD" / HA

for each sector, as reported in the national statistics. The data are then re-aggregated following the MuSIASEM categories (as above), and calculated as weighted averages for the sectors comprising more than one category, referring to the GVA of each sector. For example:

$$ELP_{AG} = GVA_{AG}/HA_{AG}$$

where

$$ELP_{EM} = (GVA_{Mining\&quarrying} + GVA_{Electricity,\ gas\&water}) / (HA_{Mining\ \&quarrying} + HA_{Electricity,\ gas\&water})$$

2.1.2 Use as diagnostic tool: multi-scale integrated characterization of the existing situation

Land use

The general land use data are taken at country level from FAOSTAT (http://faostat.fao.org). For the detailed information about harvested land for every crop, data included in the tables of the Digest of Agricultural Statistics of the Ministry of Finance and Economic Development of Mauritius were used, as the same source was used for the analysis of food flows in the diagnosis phase. An important land use type for our approach is the urbanized land use, used to calculate the density of flows referring to those socioeconomic sectors different from agriculture (i.e. HH, and the other sectors - SG, EM, TR and BM – included all in the PW* sector). The urban area is not commonly reflected in land use statistics, so remote sensing data were used to get this information. In Mauritius the MSIRI assessed this area for 2010 (Chung Tze Cheong et al., 2010). It is important to underline that in most of cases it is very difficult to discriminate among different land uses belonging to residential, manufacturing, services or government categories (i.e. the land occupied by various buildings and other infrastructures associated with these sectors) through remote sensing. For the land analysis a common category of accounting was adopted, resulting from the sum of all land uses referring to all the economic sectors but agriculture (PW*), and the household sector (HH). Table 3 reports the main land uses for the diagnosis of Mauritius, and in Table 4 the summary of the harvested land for the main categories of agricultural uses in the island for 2010[5].

Table 3

Land uses of Mauritius for 2010

Category	Unit	Value	Source
Country area	hectares	204000	FAO
Land area	hectares	203000	FAO
Agricultural area	hectares	98000	FAO
Agricultural area irrigated	hectares	21000	FAO
Arable land	hectares	87000	FAO
Permanent crops	hectares	4000	FAO
Permanent meadows and pastures	hectares	7000	FAO
Forest area	hectares	34980	FAO
Other land	hectares	70020	FAO
Inland water	hectares	1000	FAO
Irrigated land	hectares	21500	FAO
Urban	hectares	28070	MSIRI

Table 4

Harvested land of the main groups of agricultural crops of Mauritius for 2010

indicator	Unit	Value	Source
Cereals and roots	Hectares	1881	Statistics Mauritius
Meat	Hectares	7000	FAO
Fruits & vegetables	Hectares	5683	Statistics Mauritius
Oils	Hectares	214	Statistics Mauritius
Stimulants	Hectares	698	Statistics Mauritius
Others	Hectares	310	Statistics Mauritius
Sugarcane	Hectares	58709	Statistics Mauritius
Total AG production	Hectares	74495	Statistics Mauritius

5 Harvested land is not reaching the value of the available agricultural land, as this data is excluding the harvesting losses and production not harvested for various reasons

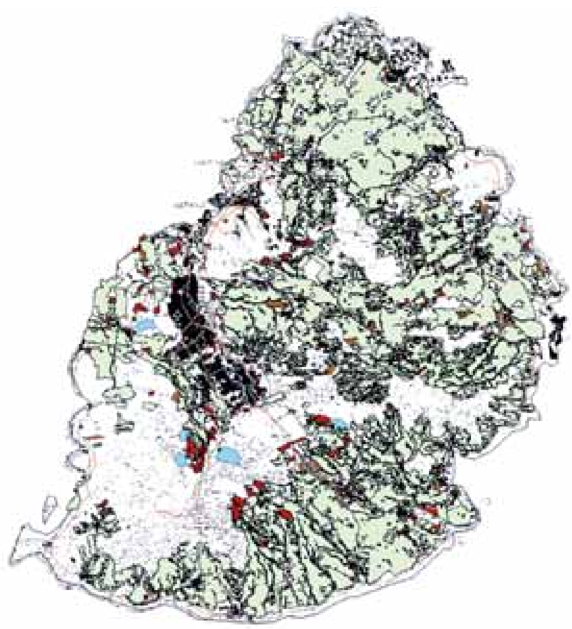
In relation to imports it is possible to make an estimation of the virtual land associated with imports according to the following protocol: (i) if the imported food is already being produced in Mauritius, then the land requirement for producing in the country the same amount of the different imported products is used6; (ii) if the imported food is not produced in the island, then an estimate of land requirement per ton of product is used considering as benchmark the land requirement of the country that provides the largest share of the imported product.

The use of geographic information in the diagnostic step

The geographic information on map layers was used in the case of Mauritius principally for two purposes: (1) for the calculation of water consumption for agriculture (e.g. in scenario b.1 illustrated hereafter); and (2) for the calculation of suitable land for an alternative pattern of agricultural production (e.g. scenario b.1). Geographic information makes it possible to check the option space for a different mix of agricultural crops. For this purpose, the information given by maps describing the current distribution of crops in the island were used/generated (figure 10), and areas with too much slope for agriculture (figure 11) and with non appropriate soil for the specific crops in the mix (figure 9) were discarded. The result of the combination of all this information is illustrated in figure 12.

Figure 10

Current land use for agriculture and urban uses in Mauritius

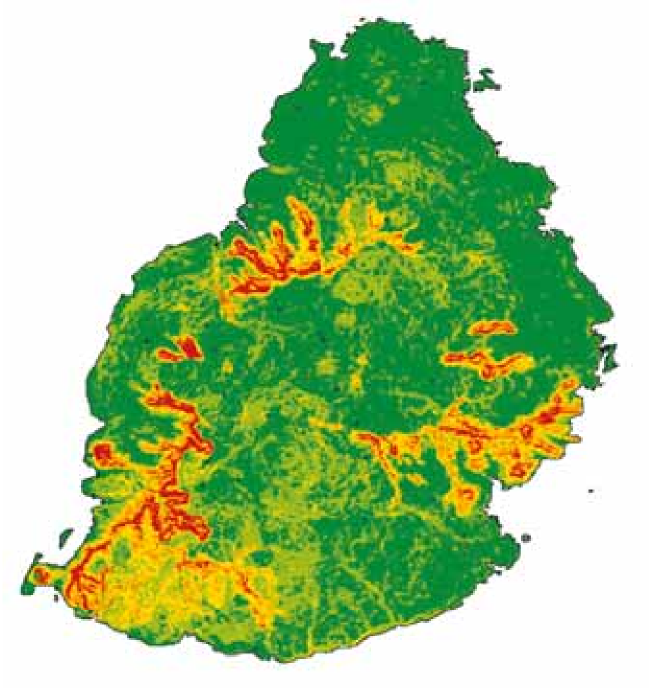


Source: Own elaboration with information from MSIRI and the Ministry of Housing & Lands of Mauritius

6 By looking at the yields of various crops or the land requirement associated to animal products (pasture plus the double conversion of feed into animal biomass)

Figure 11

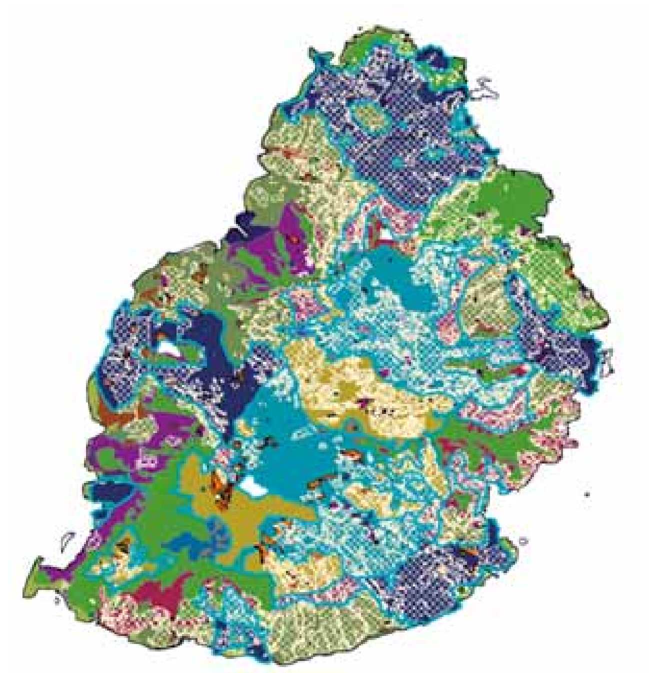
Slope map of Mauritius



Source: Elaborated from elevation data from Shuttle Radar Topographic Mapping Mission (2000)

Figure 12

Result of crossing the maps providing the information for the suitable land for the cultivation of a different crop mix in Mauritius



Land use and geographic information makes it possible to carry out an analysis of flow-fund ratios[7] (e.g. yields per hectare, or water evapotranspiration per hectare). These ratios can be calculated on categories of land use defined at low hierarchical levels, i.e. land uses referring to the production of individual crops are defined at a hierarchical level of analysis lower than the level of analysis of the whole agricultural sector, and can be scaled up across different levels of analysis (e.g. up to the whole Paid Work sector of the economy and the whole country level).

Analysis of the metabolic pattern of food: requirement, local production and supply

An overview of the flow of foodstuff is illustrated in Table 5.

Table 5

Foodstuffs flow in the Republic of Mauritius 2010

Category	Production (tonnes)	Imports (tonnes)	Changes in stock (tonnes)	Export (tonnes)	Re-export (tonnes)	Domestic Supply (tonnes)
Cereals, pulses and roots	26,312	379,688	1,233	43,393	43,393	361,374
Meat, milk and products, fish	71,439	147,336	2,946	**99,157**	**99,088**	**122,564**
Vegetables, fruits and products	110,460	52,900	0	**1,957**	**780**	**161,403**
Oil crops, oil and fats	5,484	33,188	30	**674**	**674**	**38,028**
Stimulants	1,477	2,426	0	**80**	**80**	**3,823**
Sugar crops	452,473	26,945	7,526	**435,105**	**26,945**	**36,787**
Others	2,784	32,401	938	**1,811**	**1,811**	**32,437**
TOTAL	670,428	674,884	6,720	**582,177**	**172,771**	**756,415**

Source: Ministry of Finance and Economic Development, 2012a; 2012b

Notes:

- *Some commodities have been rearranged into different categories to the original.*
- *Pulses include local production of beas and peas.*
- *Some processed commodities have been converted into their originating primary commodity equivalent. For instance, alcoholic beverages.*
- *Primary commodities equivalent of alcoholic beverages have been considered as imported products.*
- *Some commodities are not included because they are not considered relevants: offals, meat preparations, crustaceans and molluscs and products, other spices (anissed, cinnamon, vanilla, etc) and miscellaneous (infant food and beverages non-alcoholic as mineral water and others).*

In order to be able to check the coverage of dietary requirements of people living on the Islands provided by the supply of food products, the quantitative information had to be organized in a matrix making it possible to establish a dual reading of Gross Food Requirement: (i) the columns refers to values of food energy accounted according to categories of "nutrient carriers"[8]; (ii) the rows refers to values of food energy accounted according to categories of "primary nutrient[9] sources". Such double accounting is

7 When considering land use as fund
8 Classes of macronutrients such as carbohydrates, proteins, and fats required by humans
9 Primary nutrient sources are classes of food products that are source of nutrient carriers

reported in Table 6.

At this point it becomes possible to analyze the "level of openness" of the food system by typology of food. The level of openness characterizes how the gross requirement of nutrient carriers (quantity) is covered by a gross supply of primary nutrient sources. This analysis is provided in Table 7.

Table 6

Food Gross Requirement by type of food and energy carrier in Mauritius

Category	FGR - Carb (PJ)	FGR – Prot (PJ)	FGR - Fat (PJ)	FGR - Food Energy (PJ)
Cereals, pulses and roots	4.08	0.50	0.28	**4.86**
Meat, milk and products, fish	0.12	0.36	0.39	**0.86**
Vegetables, fruits and products	0.18	0.02	0.01	**0.21**
Oil crops, oil and fats	0.01	0.01	1.22	**1.24**
Stimulants, sugar crops and others	0.80	0.02	0.04	**0.86**
TOTAL	5.19	0.90	1.94	**8.03**

Table 7

Food self-sufficiency by type of food in Mauritius

Category	Local supply	Imports
Cereals, pulses and roots	2%	98%
Meat, milk and products, fish	43%	57%
Vegetables, fruits and products	56%	44%
Oil crops, oil and fats	10%	90%
Stimulants	7%	93%
Sugar crops	100%	0%
Others	9%	91%

In the same way it is possible to visualize and characterize the coverage of the energy dietetic requirement of local supply by typology of local production, against imports, as illustrated in Table 8.

Table 8

Food energy distribution between products in Mauritius

Category	Local supply	Imports
Cereals, pulses and roots	1.4%	59.1%
Meat, milk and products, fish	4.7%	6.1%
Vegetables, fruits and products	1.5%	1.2%
Oil crops, oil and fats	1.5%	13.8%
Stimulants	-	-
Sugar crops	7.1%	-
Others	0.3%	2.9%
TOTAL	16.5%	83.5%

The analysis of water metabolism

Using the grammar described in Fig. 5 it is possible to describe the metabolic pattern of water use. The quantitative information characterizing the water flows associated with the metabolic pattern can be organized using categories related to the external view - the interface ecosystems funds/society flows – based on the categories of water extraction and typologies of water flows (blue and green water) as illustrated in Table 9.

Table 9

The external view of water metabolism – multi-level matrix characterizing extraction per categories of sources and total use of the different compartments in Mauritius

Indicator/Compartment (societal function)	Extraction Total	EXT Blue-Surface	EXT Blue-Ground	EXT Green	USE Losses	USE Total
Whole (n)	1,706	555	432	718	108	1,599
% of USE						*100*
% of Extraction	*100*	*33*	*25*	*42*	*6*	*94*
HH (n-1)	98	74	24	0	14	84
HH-Urban (n-2)	41	31	10	0	0	35
HH-Rural (n-2)	57	43	14	0	0	49
PW (n-1)	1,608	481	408	718	94	1,515
PW-SG (n-2)	17	13	4	0	2	15
PW-TR (n-2)	1.72	1.30	0.42	0	0	1
PW-BM (n-2)	27	20	7	0	4	23
PW-EM (n-2)	262	255	7	0	4	258
PW-AG (n-2)	1,300	192	390	718	84	1,218
PW-AG-Sugar Cane (n-3)	1,110	164	333	680	71	1,106

The six columns describe: (i) total water extraction; that is divided in three categories (see column labels): (ii) Blue-Water from surface, (iii) Blue-Water from ground (under human control and requiring investment of production factors), (iv) Green water (not requiring human direct intervention), (v) losses, (vi) total use.

This information has to be complemented with an accounting based on categories related to the internal view – how the supply of water is used inside the various compartments of the society, as illustrated in Table 10.

The seven columns describe the end uses of water: (i) the total distributed water goes to: (ii) life water; (iii) citizen water; (iv) water used by the economy (but agriculture); (v) water used by agriculture for irrigation; (vi) evapotranspirated water (ET) that is not distributed. Non distributed water corresponds to the green water use of agriculture, which comes from the rain. Finally, there are two categories referring to the use for energy purposes: (vi) cooling; and (vii) hydropower, which both refer to "non extracted" water. Even though the water included in these two water uses, can be affected in its quality (e.g. temperature).

Table 10

The internal view of water metabolism – multi-level matrix characterizing consumption per categories of water use of the different compartments in Mauritius

Indicator/ Compartment (societal function)	Distributed-Total	Distributed-Life	Distributed-Citizenship	Distributed-Economy	Distributed-Irrigation	ETc- green	Energy-cooling	Energy-hydropower
Whole (n)	649	11	73	66	498	718	**4**	**228**
% of USE	***41***	***1***	***5***	***4***	***31***	*45*	*0*	*14*
% of Extraction	*38*	*1*	*4*	*4*	*29*	*42*	*0*	*13*
HH (n-1)	84	11	73	0	0	0	**0**	**0**
HH-Urban (n-2)	35	5	31	0	0	0	**0**	**0**
HH-Rural (n-2)	49	6	42	0	0	0	**0**	**0**
PW (n-1)	565	0	0	66	498	718	**4**	**228**
PW-SG (n-2)	15	0	0	15	0	0	**0**	**0**
PW-TR (n-2)	1	0	0	1	0	0	**0**	**0**
PW-BM (n-2)	23	0	0	23	0	0	**0**	**0**
PW-EM (n-2)	25	0	0	25	0	0	**4**	**228**
PW-AG (n-2)	500	0	0	2	498	718	**0**	**0**
PW-AG-Sugar Cane (n-3)	426	0	0	0	426	680	**0**	**0**

The information given in Table 9 is relevant to assess the environmental impact. The various categories of water extraction and appropriation by humans establish a link, depending on their source, with the stress on ecological funds[10] that the consumption of water within the society (described by the information in Table 10) implies: the total of water extraction is equal to the water required by wager uses plus the losses. Note that since the green water use is defined as the actual fraction of rain used, no losses are possible for this category and therefore green water use is equal by default to green water extraction.

It is possible to introduce new categories of accounting for both water flows and water funds in either the social or the environmental part, whenever it is needed. The Mauritius case study, which focuses on agriculture, has a larger number of categories and therefore in this case this accounting system is described[11].

The analysis of water metabolism can be tailored on specific compartments of the society using available statistical data. For example, both the water used by households and by industry is, in general, well covered by the national statistics together with decent estimates of losses. These data are available since these water used as guaranteed by economic agents handling water and keeping record of the relative volumes. When this is not possible, the estimation might become difficult[12]. When water use statistics are not available, the estimation can be based on benchmarks describing expected rate of

10 Here surface water refers to ecological funds such as rivers and lakes, while ground water refers to aquifers.

11 The Punjab case focuses on agriculture as well, but with a lower level or resolution. In that case study, only water sources were considered (to check environmental stress) for that case study and the categories of water use are not included. For the case of South Africa dealing only on an analysis of the energy sector, the most important categories are water uses for cooling and hydropower.

12 Such as in the Punjab case study.

consumption per typology of water uses (the specific Water Metabolic Rate – WMR), which depend on the type of industry and urban settlements.

The two categories "life water" and "citizen water" used to characterize the water metabolism of households should be used to clarify the level of access to water and sanitation services.

In the Mauritius and South Africa case studies, this issue becomes relevant mainly in rural places, but for the Punjab case the values of the assessments in these two categories are extremely important, as a high share of the population do not have covered those needs. The estimation of the amount of "life water" and "citizenship water" depends on the lifestyles. Life water is related to the human right of access to water and it can be related to a stable rate per person and day for all countries (about 20 litres per day according to UN). The citizenship water highly depends on the typology of settlements in urban areas as well as on the type of consumers. When data on the rural and urban population is available, as well as the employed population in each of them, the separation of the life and citizenship water use between rural and urban is possible, as shown in table 10.

The category "economy water" refers to water used for generating economic benefit. Therefore, economy water includes also the water which is required to maintain the functioning of the energy sector, either for hydropower generation or cooling processes. However, as noted earlier, the water accounted in these two categories has a special status, since it is not water that is extracted from the fund (e.g. the river). Nevertheless is water somehow appropriated by the social system, which with its use, removes a certain quality from it (e.g. temperature or height).

Finally, there is the category of water used in agriculture, that requires a special treatment, since this compartment is, by far, the largest consumer of water in the metabolic pattern of societies. The consumption of water in agriculture depends on many factors like the type of crops cultivated in agriculture, the climatic conditions, soil a geo-morphological conditions. The estimations of water required by the agricultural sector can be performed at different levels. For example, one can estimate the overall requirement of water for the different primary sources of nutrients as illustrated in Tab. 11. This type of analysis establishes a link with the analysis of the metabolic pattern of food (Tables 6, 7 and 8).

Table 11

Water use in Agriculture in Mauritius

FOOD-related Compartimentalization	Production (ton)	Area harvested (ha)	Blue Water USE (hm^3)	Green Water USE (hm^3)
Group 1 - Cereals, Roots, and Pulses	24,772	1,880	0	6
Group 2 - Meat, Milk and Products	71,741	7,000	72	0
Group 3 - Vegetables, Fruits and products	91,561	5,683	0	22
Group 4 - Oil crops, oil and fats	2,083	214	0	1
Group 5 - Stimulants	7,380	698	0	7
Group 6 - Sugar crops	4,362,118	58,710	426	680
Group 7 - Others	2,784	310	0	1
Non-food	310	213	0	1
Total AG	4,562,749	74,707	498	718

Table 12

Analysis of water flows in the agricultural sector disaggregated by crop in Mauritius

Crop/Indicator	Area harv.	BCWR 1	GCWR 1	AREA 1	BCWR 2	GCWR 2	AREA 2	BCWR 3	GCWR 3	AREA 3	ETg-1	ETb-2	ETg-2	ETb -3	ETg -3	ET blue	ET Green	ET total
Unit	ha	mm (l/m²)	mm (l/m²)	ha	mm (l/m²)	mm (l/m²)	ha	mm (l/m²)	mm (l/m²)	ha	hm³	hm³	hm³	hm³	hm³	hm³	hm³	hm³
Group 1 - Cereals and Roots and pulses	**1,880**	**0**	**300**	**1,122**	**0**	**289**	**445**	**0**	**386**	**312**	**3**	**0**	**1**		**1**	**0**	**6**	**6**
Maize	335	0	278	200	0	273	79	0	418	56	1	0	0		0	0	1	1
Potatoes	1,072	0	320	640	0	316	254	0	478	178	2	0	1		1	0	4	4
Sweet potatoes	74	0	310	44	0	306	17	0	374	12	0	0	0		0	0	0	0
Cassava	38	0	290	23	0	286	9	0		6	0	0	0		0	0	0	0
Taro	36	0	329	21	0	324	9	0		6	0	0	0		0	0	0	0
Beans and Peas	326	0	269	194	0	227	77		275	54	1	0	0		0	0	1	1
Group 3 - Vegetables, Fruits and products	**5,683**	**0**	**411**	**3,393**	**0**	**399**	**1,346**	**9**	**496**	**943**	**13**	**0**	**5**		**4**	**0**	**22**	**22**
Beet remolacha	46	0	361	27	0	356	11	0	432	8	0	0	0		0	0	0	0
Cabbage	244	0	390	145	0	386	58	0	566	40	1	0	0		0	0	1	1
Carrots	370	0	449	221	0	443	88	0	538	61	1	0	0		0	0	2	2
Cauliflower	62	0	390	37	0	386	15	0	566	10	0	0	0		0	0	0	0
Cucumber	460	0	258	275	0	255	109	0	313	76	1	0	0		0	0	1	1
Lettuce	91	0	277	54	0	274	22	0	335	15	0	0	0		0	0	0	0
Onions, dry	287	0	465	171	0	459	68	0	523	48	1	0	0		0	0	1	1
Tomatoes	842	0	356	502	0	352	199	0	392	140	2	0	1		1	0	3	3
Leek	21	0	254	13	0	251	5	0	303	3	0	0	0		0	0	0	0
Pumpkin	512	0	264	306	0	260	121	0	320	85	1	0	0		0	0	1	1
Squash	90	0	420	54	0	414	21	127	480	15	0	0	0		0	0	0	0
Other vegetables	1,869	0	271	1,116	0	267	443	0	322	310	3	0	1		1	0	5	5
Banana	542	0	799	324	0	702	128	0	1,060	90	3	0	1		1	0	4	4
Pineapple	248	0	799	148	0	788	59	0	799	41	1	0	0		0	0	2	2
Group 4 - Oil crops, oil and fats	**214**	**0**	**300**	**128**	**0**	**295**	**51**	**0**	**362**	**36**	**0**	**0**	**0**		**0**	**0**	**1**	**1**
Groundnut (in shell or not)	214	0	300	128	0	295	51	0	362	36	0	0	0		0	0	1	1
Group 5 - Stimulants	**698**	**0**	**1,063**	**417**	**0**	**1,053**	**165**	**268**	**1,004**	**116**	**4**	**0**	**2**		**1**	**0**	**7**	**7**
Tea (green leaves)	698	0	1,063	417	0	1,053	165	268	1,004	116	4	0	2		1	0	7	7
Group 6 - Sugar - Sugar Cane	**58,710**	**0**	**1,092**	**34,902**	**80**	**1,433**	**13,979**	**342**	**1,004**	**9,829**	**381**	**0**	**200**		**99**	**28**	**680**	**708**
Group 7 - Others	**310**	**0**	**413**	**185**	**0**	**412**	**73**	**0**	**440**	**51**	**1**	**0**	**0**		**0**	**0**	**1**	**1**
Chillies	242	0	220	144	0	217	57	0	300	40	0	0	0		0	0	1	1
Garlic	6	0	470	3	0	470	1	0	470	1	0	0	0		0	0	0	0
Ginger	62	0	550	37	0	550	15	0	550	10	0	0	0		0	0	0	0
TOTAL AG FOOD	**67,494**	**0**	**13,433**	**40,146**	**80**	**13,502**	**16,061**	**1,014**	**14,486**	**11,287**	**403**	**0**	**209**		**106**	**28**	**718**	**746**
Tobacco-AG NON FOOD	**213**	**0**	**282**	**127**	**0**	**277**	**50**	**0**	**338**	**35**	**0**	**0**	**0**		**0**	**0**	**1**	**1**
TOTAL AGRICULTURE	**67,707**			**40,273**			**16,111**		**14,824**	**11,322**	**403**	**0**	**209**		**106**	**28**	**718**	**746**

However, if one wants to get to a lower level of analysis, associating the metabolic pattern of water use to the given crop mix, it is possible to provide a more detailed analysis, using a series of expected values of water use per hectare of typology of crop in production (according to available models). An example of this analysis is provided in Table 12.

For each one of the crops considered in the analysis, it is possible to calculate the evapotranspiration (ET) using FAO's Cropwat 8.0 with the Penman–Monteith method. This method uses climatic, soil and crop data to obtain the Crop Water Requirement (CWR) and effective rain. Green evapotranspiration is equal to the effective rain if this is lower than the CWR, and the CWR if the effective rain was higher. Blue water is the need for irrigation in the cases when the effective rain was much lower than the CWR.

In the case of Mauritius the estimations of blue water were really low. Table 12 summarizes the estimations of the green and blue ET per climatic zones. Note that the blue water ET estimations do not correspond to blue water use in Table 11. The estimations were too low as compared for the irrigation water registered in the national statistic service. A decision was made to take the water registered there and maintain the allocation on Table 12 for the assignation of that volume (498 hm^3, in table 11) to different crops. The green ET has been maintained as green water use.

Due to the problems of designing a GIS based estimation method that uses the Cropwat formula for the estimation of the ET on a grid, a discrete analysis was done on the basis of data from the FAO's ClimWat database. The three climatic zones were obtained from GIS assessments, necessary to select the suitable climatic station[13].

The same structure of the table was maintained for the estimation of virtual water imports and scenarios. For the virtual water imports the following was used: (i) the amount of water that would used by a virtual amount of land required for the production of the imported food, when the imported food could be produced on the island; and (ii) estimated the CWR of crops which are typically not produced in the Island, assuming that they were produced under the conditions of the other crops.

It should be noted that in relation to the water needed in the production of meat, a different procedure was followed. Table 13 shows an example of the relative calculations. For that case, coefficients of water use per capita of cattle are multiplied by times the heads. Water requirements (WR) per head obtained from *Mekonnen and Hoekstra 2010* include feed and maintenance water requirements[14]. Data of heads are from the Mauritius statistical service. The estimation of the water density of livestock production is not easy to separate by type of cattle as they share the land.

Finally, in order to generate quantitative information about water metabolism useful for environmental analysis, data was organized on the basis of natural divisions relevant for

13 The stations used to extract the climatic data are: Vascoas for the super-humid climate zone (Station 1), Flacq for the humid climate zone (Station 2) and Pampelmousses for the sub-humid climate zone (Station 3). The crop land under each climatic zone was assumed to keep the distribution of the area of the climatic zones.

14 In order to avoid double counting feed is not included in the estimations of agriculture above, as only the surface dedicated to other crops is included there.

the identification of water funds, such as river basins. However, in the case of Mauritius the quantitative analysis was organized in relation to existing identifications of "supply systems" for two reasons: the first one is that this division provides well documented information regarding water availability and population to be supplied; the second is that these supply systems are more or less defined following natural limits of water availability (where the water is taken from). The result of this multi-level analysis comparing the rate of water extraction with the availability determined by available water funds – divided by "supply systems" is illustrated in Table 14.

Table 13

Example of water need estimation for cattle

Animal	Water Req.	Production	Slaughtered	Carcass	Production	Production	TWT	Area
Units	l/head/day	Heads	Heads	Tonnes	Tonnes	Heads	hm^3-NWU	Ha
Cattle	24	1,180	9,700	203	2,515		129,985	7,000
Goats & Sheep	6	5,569	9,500	45	110		30,061	
Pig	18	11,106	11,383	785	800		74,408	
Chicken	0		46,200,000		46,200	46,200,000	4,553,010	
Rabbit	2				25			
Game meat	45		23,148		625	23,148		
TOTAL		17,855		1,032	50,275		4,787,464	7,000

Source: Data are referring to 2010 but data for Carcass of 2003

Table 14

Multilevel estimations of water extraction to estimate environmental impact

Indicator/ Compartment (Supply system)	Extraction	Surface	Ground	Rain	Water Renewable Resources (WRR)	Extraction as (%) WRR
Territorial System Covered (n+1)	1,492	550	428	513	2,834	53
Mare Aux Vacoas-Upper (n+1)	252	93	73	86	474	53
Mare Aux Vacoas-Lower (n+1)	193	96	75	22	122	158
Port-Louis (n+1)	291	85	66	140	775	38
North (n+1)	291	127	99	65	358	81
South (n+1)	247	85	66	96	528	47
East (n+1)	229	64	50	116	640	36
Uncovered (n+1)	214	5	4	205	1,130	19
TOTAL (n)	1,706	555	432	718	3,964	43

By using the MuSIASEM approach, even when data about the specific use of water per supply system was not available, inferences were made by considering the set of human activities carried out in the area and applying the expected flow per hectare of typology of land use that applies. As illustrated by Table 14, this type of analysis is very important, since it makes it possible to define two levels of analysis – the level of the whole system (country) and the level of individual "supply systems" – and highlight that, even if at the level n (the whole) there is no issue of overexploitation as the extraction is only 43% of the estimated maximum sustainable supply capacity. However overexploitation (i.e. extraction is higher than the recharge of the water funds for the system) might happen at lower levels, as in the case of Mare Aux Vacoas-Lower where the extraction rate is over 100% the pace of recharge of the relative funds.

The multilevel matrix of the metabolic pattern of Mauritius

At this point it is possible to provide an overview of the metabolic pattern of food, energy and water, of the Mauritius looking simultaneously at the internal view (i.e. how the flows are used inside the society) and the external view (i.e. how the flows are made available to society via local production and imports). The integrated characterization of the metabolic pattern of Mauritius is presented in Table 1. The accounting of energy flows within the metabolic pattern is not reported for this case study (see the South Africa case study for more information about energy accounting).

The upper (7 x 7) matrix characterizes the metabolic pattern according to the internal view, the required flows for end uses including the losses (gross and net flows). The 7 columns represent, respectively: (i) three flow elements, food, energy, and water; (ii) three fund elements, human activity, power capacity, and land use; plus (iii) an indication of monetary flows, whenever possible (e.g. gross added value in the various compartments and the economic values of imports and exports). The 7 rows represent the set of relevant compartments of society (6 lower level element - HH, PW*, AG, EM, plus two "special compartments" introduced for this specific case study plus a row for the whole society). This choice of definition of compartments make is possible to focus on the fund and flow elements allocated not only to express the standard internal functions of society, but also allocated to the generation of exports either in the agricultural sector (sugarcane and sugar production) or in the other economic sectors in PW*. For this case study, two additional compartments were added in the accounting framework (not previously described in Chapter 1 when presenting the approach in general terms), in order to be able to better characterize the effects of changes in the agricultural sectors when considering the proposed scenarios, in relation to both internal supply (e.g. increased local production of energy carriers or increased local production of food) and changes in the level of exports (e.g. how the changes assumed in the scenarios will affect the terms of trade). In biophysical terms, these two "extra compartments" associated with export "uses" production factors (fund and flows, such as labor, capital, land, energy, water) to generate products that are not consumed within the society under analysis. Therefore, they require production factors, but do not generate local supply. On the other hand, they can generate economic revenues and therefore they make it possible to use these revenues for imports. To better explore the trade-offs associated with exports level (in biophysical terms), exports are split into "agricultural exports" and "exports generated by the rest of the paid work sector" because agricultural exports use an enormous amount of water and land (when compared with the exports of the rest of the economy), while generating a lower economic return per unit of production factor, especially in relation to the requirement of labor.

The lower (3 x 7) matrix characterizes the pattern of sources. The 7 columns are the same as in the upper matrix and the 3 rows distinguish between: (i) the flows of the whole, (ii) local supply of the various flows; (iii) flows obtained by imports. Note that the two matrices have a row in common: the row characterizing the consumption of the whole society.

In the matrix illustrated in Table 1 it is possible to see how this method integrates different quantitative assessments referring to different levels of analysis and different views of the metabolic pattern. For example the food consumption in the household (5.9 PJ of food energy) are just a single value referring to the internal view, that is the net supply of nutrient carriers required for matching the dietary requirement of the population. By using the grammar illustrated in Fig. 4, losses and the internal investment of nutrients (seeds, eggs, and feed) consumed by the agricultural sector to produce food products are calculated. Then after having calculated the gross nutrient requirements consumed by the whole food sector, a relation (an interface) between the internal view (i.e. the gross and net nutrient requirement of the population) and the external view (i.e. the required supply of primary nutrient sources - the agricultural production) is established. This relation is illustrated in Table 6. The categories used to define the columns are linked to demographic characteristics[15], whereas the categories used to define the rows establish a link to agronomic variables and geographic characteristics. In fact, as noted in section 1.2.2 the analysis of agricultural production can be directly related to land uses. Thus, in this way, a relation is established between quantitative data on food flows and (i) dietary requirements of the population; (ii) supply of agricultural products; (iii) land use; (iv) technical coefficients (water, energy, labor and technical capital) to be invested in agricultural production.

This link makes it possible to perform simultaneously:

(1) a spatial analysis on the available dataset on food flows in relation to both the requirement side (size of the resident population) and the supply side (size of crop fields and yields of the various agricultural products); and

(2) an analysis based on the pace of the flows in relation to profiles of investments of human activity of the effects that metabolic pattern has on the socio-economic performance of the whole society. Are the monetary flows per hour (wages, profit generated in the different sectors, terms of trade determining gains and losses because of imports and exports) associated with biophysical flows determining a desirable metabolic pattern for Mauritius?

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15 In this accounting tourists are considered as a small number of "resident-equivalent" in relation to their food requirement

This integrated analysis makes it possible to apply the *Sudoku effect* to the multi-level representation based on vectors and matrices as illustrated in the next section when characterizing the feasibility and viability of scenarios.

2.1.3 Use as Simulator: multi-scale integrated characterization of scenarios

Scenario a: Using the present sugarcane output for local ethanol production

The first simulation illustrates the effects of the first scenario proposed for the study: all present sugarcane exports are used to produce biofuels (ethanol from sugarcane). This scenario implies that all production factors – the area planted to sugarcane for export purposes (72% of agricultural land) and the power capacity and human labour involved in its production as well as the relative input flows (water, energy, and food) presently allocated to the sector of agricultural export – are moved to the energy and mining sector to produce energy carriers for local use. In the matrix accounting system the simulation checks the viability and feasibility of this scenario by simply eliminating the vectors (flow and fund) of "end uses" that is moved in the compartment of "Export Agriculture" in Table 1, and summing the values of the various cells to the vector of "end uses" of the energy and mining (EM). This operation does not apply to the assessment of Added Value, but only to the biophysical accounting.

The net supply of energy carriers to society from the local production of biofuels is only 8 PJ. This contribution will reduce energy imports by only 30%, but it still would claim 90% of the water-use and 72% of agricultural land in Mauritius. A rough estimate of the level of economic productivity of labor for this option (obtained by comparing the flow of added value generated by an economic activity divided by the requirement of labor) generates serious doubts about the economic convenience of this solution. In fact, the average Economic Labor Productivity assessed at the level of the whole economy is 6.8 USD/hour. This average, however, hides a big difference between the average ELP of PW^* (all the economic sectors but agriculture) – that is 13.9 USD/hour – and the ELP of AG (agriculture) – that is 5.6 USD/hour. Coming to the ELP of biofuels production, the GVA of the production of ethanol is not calculated since reliable estimates of production costs are not available.

However, it is possible to calculate a sort of "opportunity gain" of ethanol production by assessing the amount of money saved by reducing energy import thank to the ethanol produced. Then it is possible to calculate the economic saving per hour of labor that would be invested in ethanol production. This value is 5.5 USD/hour. Considering that this value does not include the economic costs of the production (that would reduce the resulting GVA), it is possible to conclude that, in economic terms and in relation to the possibility of generating well paid jobs, this activity is not attractive.

Scenario b.1: Replacing sugarcane with food crops cultivation to improve food self-sufficiency

The second simulation checks the feasibility (i.e. congruence with external constraints) and viability (i.e. congruence with internal constraints) of a scenario in which Mauritius is shifting the existing agricultural production of sugarcane monoculture to food and feed crop cultivation. All land devoted to sugarcane production would be converted to food crops. This policy has the goal of increasing the level of food self-sufficiency.

External constraints: land suitability for new crops

A large-scale shift from existing sugarcane plantations to food crop production for internal consumption is subject to geographic constraints, including soil type, slope, and hydrological characteristics. Using the existing crop characteristics and taking into account their limitations for expanding throughout the territory.

As explained in section 1.2.2 (Fig. 12), using GIS it is possible to estimate (with certain assumptions) that the new crop mix could only be expanded on 64.6% of the actual agricultural area. According to this simulation such a change in crop mix would anyway leave the country still in a situation of dependence from food imports. In fact, depending on the production system (assuming that this scenario were possible in relation to internal constraints) after saturating the internal demand of vegetables, the agriculture of Mauritius is called to produce either cereals or animal products, but looking at existing benchmarks, an internal supply of max 35% of actual gross requirement of food can be expected.

Internal constraint: labor shortage

The results of this simulation show that scenario b.1 is not viable because of shortage of labour on the island. In other words, when required production factors (including labor) are allocated in the sector of Agriculture, the '*Sudoku* approach' cannot be solved in relation to the fund element human activity. In this simulation, it can be assumed a constant mix of crops according to geographical constraints (such as climatic zones, slopes and soil). The simulation shows that with the new expansion of the crop mix, the labour requirement per hectare for cultivation would be much larger than the previous one for sugarcane. Therefore, such a switch to food crops would imply a substantial increase in the labour requirement in the agricultural sector, incongruent with the existing profile of allocation of labour in society.

Implementing this scenario would demand a major re-adjustment of the allocation profile of labour over the different economic sectors. Moreover, the ELP [= gross added value produced in a sector divided by the hours of human labour in that sector] of agriculture in the Mauritius does not encourage such re-adjustment. In fact, the ELP of agriculture is the lowest of all economic sectors in Mauritius (similarly to all the other modern economies). Therefore, a re-allocation of the work force in favor of agriculture not only is very unlikely (since workers get better jobs in the other sectors) but would also lead to a reduction in the overall added value generated in Mauritius.

Scenario b.2: Replacing sugarcane with food crop cultivation to improve food self-sufficiency

By maintaining the policy goal of improving food self-sufficiency, and after having checked that the land that is right now under sugarcane production cannot all be converted into local food supply it is possible to check the effect of an allocation of all available work supply (in the two sectors in which agriculture was split) at its present level (72 million hour in total) to the cultivation of food crops (rather than sugarcane). Sugarcane produced for export would be replaced with food crop cultivation to improve food self-sufficiency, by using all available Human Activity currently invested in the two sectors: "Agriculture internal supply" and "Agricultural exports".

By assuming the national average requirement of labor per hectare in local agricultural production, it was calculated that only 39,000 hectares of agricultural land can be cultivated. This means that, because of internal constraints, only half of the agricultural land presently under cultivation could be used (unless major changes in technology and in the structure of the costs take place). This is an example of internal constraint (shortage of labour) that would prevent making full use of available resources.

The situation could be overcome by increasing the biophysical labour productivity [food output/hour of labor] through increased and more efficient use of machinery; which would in turn increase the cost of production by requiring a larger investment of inputs per hectare for machinery and other inputs, and could also imply a negative impact on the ecological impact of this activity. This option could be considered only if the internal food supply is sold to tourists and residents at high prices. Such option would require e.g. marketing strategies to valorize the market value of the products (e.g. traditional delicacies, special local recipes, organic products).

Achieving economic viability for the internal production of crops is essential to justify the adoption of this scenario in the first place. Clearly this option cannot be fully addressed just in a theoretical exercise.

2.2. CASE STUDY - THE INDIAN STATE OF PUNJAB

2.2.1 Introduction

Being part of the Republic of India, the economy of the state of Punjab is subject to Indian regulations regarding water management, energy subsidies, food distribution and international trade. Punjab contributes about 45% of the wheat and 25% of the rice of India's central food pool. A program of procurement exists, delivering to the central government about 70% and 80% respectively of Punjab's local production of wheat and rice. These food flows play a key role in India's food security and are not only enforced by national law but also actively encouraged through high subsidies on electricity for groundwater pumping and a Minimum Support Price (MSP) for food grain purchases from farmers.

The objectives of this case study were to characterize (i) the actual performance of the metabolic pattern of the state of Punjab in relation to different criteria of local sustainability (feasibility, viability and desirability); and (ii) possible effects for Punjab due to existing trends in population and food prices growth, in relation to a possible future reduction of subsidies for electricity used in agriculture. For this reason, the multi-scale analysis has been carried out considering three distinct perspectives:

- the household level;
- the interface Punjab/India;
- the interface India/international market.

Data for this case study have been obtained from the Economic Adviser to the Government of Punjab; the Economic and Statistical Organization; the Department of Planning of the Government of Punjab; the International Labour Organization; the Ministry of Labour and Employment; the Ministry of Statistics and Planning; the Ministry of Agriculture; the Ministry of Water Resources and the Central Water Commission of the Government of India; the National Crime Records Bureau; the Reserve Bank of India; and the Census of India. Some data are from Bhullar and Sidhu (2007) and Dhawan (1993) and the maps are from the NGO DEEP[16] and the Soil Institute of India. All data refer to 2010 and, when this was not accessible, the closest year has been considered.

2.2.2 Diagnostic step: Checking internal and external constraints

An overview of the three levels of analysis

A summary of the characteristics of the metabolic pattern of Punjab is shown in Fig. 13.

In this figure the following flows are visualized: (i) the fraction of flows that is imported (in blue); (ii) the fraction of flows that is consumed by Punjab (in the green rectangle); (iii) the fraction of flows that is exported (in red). It is evident from the figure that the metabolic pattern of Punjab is closely tied to that of India, the larger socio-economic system of which Punjab is part. Indeed, when adopting the conceptualization of metabolism, Punjab can

16 Visit *defendersofpanjab.org* for more information

be considered a functional organ of India: around 95% of the energy consumed in Punjab is imported in the region (provided by India) and the vast majority of food produced in Punjab is bought by the Indian central pool (81% of the rice and 57% of wheat). As a consequence, a large part of the water use (63%) is used for production of food consumed in the rest of India.

Figure 13

Characterization of the openness of flows in the metabolic pattern of Punjab

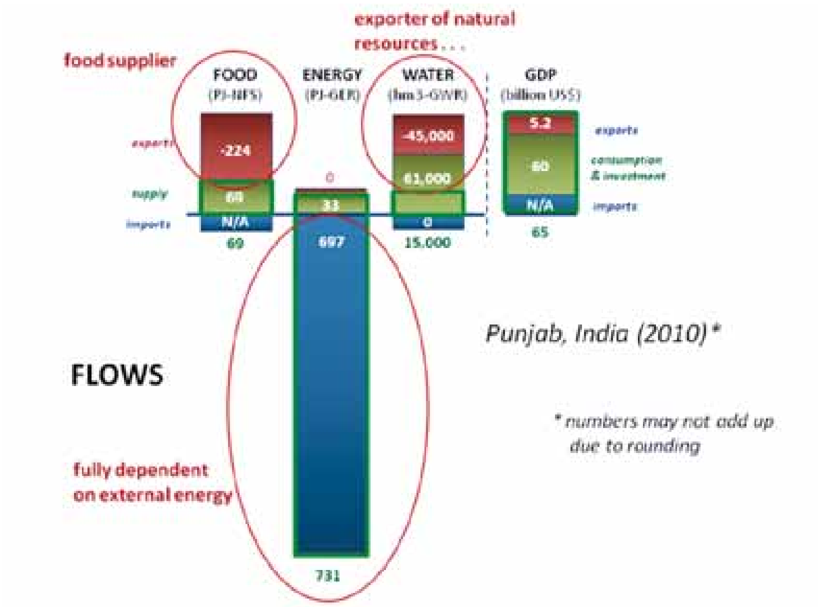
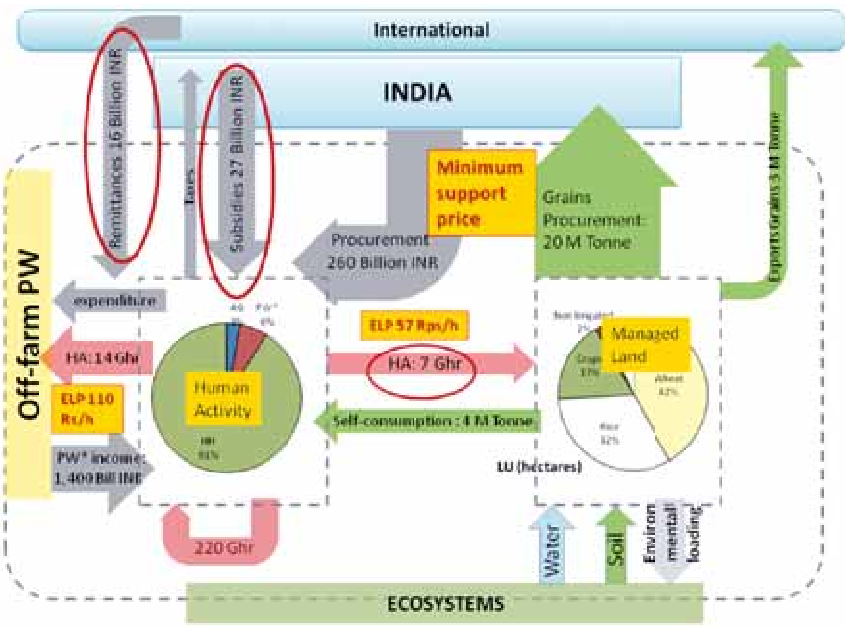


Figure 14

Overview of flows and funds in the metabolic pattern of rural Punjab



The relations between selected flow and fund elements in the economy of rural Punjab are illustrated in Fig. 14. This scheme highlights the internal and external constraints on the metabolic pattern of Punjab's agricultural sector from different perspectives (household, interface Punjab/India, interface India/international market). Flow elements considered in this representation of the system include monetary and food flows, represented by grey and green arrows respectively. The two pie charts in the centre of the figure represent the two fund elements:

(i) human activity (left), and

(ii) managed land (right).

The pies represent the total size of the funds, in terms of total hours of human activity per year and total hectares of managed land in Punjab, respectively. These two fund elements are divided into lower-level compartments (here the relevant sectors include: household sector HH, agriculture AG, and the rest of the economy PW*) and categories of land uses (i.e. rice, wheat and other crops), whose sizes are proportional to the relative allocation of the fund in question. Pink arrows represent the fund element human activity.

The centre of the figure deals with the rural community itself (i.e. labour supply for agriculture and food for self-consumption), while the bottom part of the graph shows the interface of the agricultural system with the ecological systems from which inputs are taken and where wastes are dumped. At the top, the interface with the market is illustrated, including export/import of agricultural commodities and monetary flows. On the left side the interaction of the rural community with the local economy (off-farm jobs) is visualized.

Analysis of internal constraints (viability)

In relation to the internal constraints, this case study focuses on the link between the flow of gross added value generated by the agricultural sector and the per capita income in the rural areas of Punjab. In this context, the MuSIASEM accounting system makes possible to individuate a criticality in the metabolic pattern of households in Punjab: in spite of the fact that the contribution of agriculture to the state GDP is relatively high (more than 30%) if compared with other Indian states (this is usually a bad sign for the vitality of the economy and for the income of rural households given that the ELP of the agricultural sector is less than half that of the average of other economic sectors) the average per capita income in Punjab is still medium-high when compared to other Indian states. This apparent anomaly can be explained by other sources of monetary flows entering the local economy. Indeed, three main monetary flows enter the Punjab economy:

(i) subsidies from India,

(ii) minimum support price guaranteed by India; and

(iii) remittances from abroad.

Of special importance is the role of remittances, which accounted for more than 10% of the Punjab GDP in the period 2000-2008; twice as high as for India as a whole.

Thus, paradoxically, at present remittances to Punjab are instrumental in guaranteeing the food security of India as they are essential for the viability of the metabolic pattern of rural Punjab at the household level. However, these remittances are gradually decreasing (8% of state GDP in 2010) probably due to the economic crisis in the countries of origin, and this is likely to cause a critical situation in Punjab (and the equilibrium of Indian society) in the near future.

Another key point identified by the analysis of internal constraints is the relation between subsidies for electricity from the central Indian government, which encourage the intensification of agricultural production, and the consequent impact on underground aquifers and soil in Punjab. This relation is well known (e.g. Bhullar and Sidhu, 2007) and the MuSIASEM approach allows to deepen the insight by linking the factors involved to the viability of the system at the different levels of analysis.

At the local level, the livelihood of rural households is mainly determined by the flow of money entering into the household sector from agricultural activities. With a monetary flow of 260 billion INR going into the grain production sector from the central (national) procurement of 20 million tonnes of grain, corresponding to around 7 billion labour hours in the sector (Fig. 14), a rough estimate of the ratio of monetary flow from MSP/hour of labor in agriculture can be estimated in 37 INR/hour.

This value is less than the ELP (= Gross Value Added of a sector/hours of paid work in the sector) of agriculture in Punjab, which is 57 INR/hour (about 3 USD/hour), since ELP includes also other monetary inflows. However it should be noted that the ELP in agriculture is much lower than the value of ELP in the other sectors of the economy (about 90 INR/hour) and the low value of ELP in agriculture (not helped by the monetary flows coming from MSP) translates into a low remuneration of labour, and it explains why remittances and subsidies are fundamental in order to maintain the economic viability of rural households. In particular, subsidies for electricity (making the pumping of underground water for irrigation economically feasible) can be considered a key factor in keeping high the biophysical productivity in grain production.

Looking at a historic view of water consumption in Punjab (surface versus underground water), it is evident that availability of water is not the only factor determining the level of its use. For example when heavy monsoons made plenty of water available in the region (e.g. in 1989/1990), the overall consumption of water for irrigation did not increase. On the contrary, the introduction of subsidies for the use of electricity for irrigation (in 1996/1997), alleviating the internal constraint represented by the excessive cost of electricity for farmers, generated an immediate shift from surface water to underground water utilization (because of the reduction of labour requirement in irrigation).

Analysis of external constraints (feasibility of the metabolic pattern)

The allocation of Punjab in 1947 between India and Pakistan left uncovered the issue of surface water share in the Indus River Basin. The Indian Punjab restructuration of 1966 foresaw a diversion of water that has resulted nowadays in having access to only 25% of Punjab surface water resources. Therefore, most part of the irrigation water is extracted from the aquifers with the support of electric pumps and has resulted in an overexploitation of 150% of renewable groundwater resources. Intensely irrigated agriculture covers about 80% of the land, against only 2% of rain-fed agriculture, and is a major responsible for the degradation of soil fertility.

The diagnostic analysis infers that the specialization of Punjab's agriculture in grain production is a consequence of food security policies imposed by the central government of India and not of the actual economic return that this activity provides to the state. This causes a lock-in of the system, preventing the economy of Punjabis from diversifying its economic activities (outside the agricultural sector) and the types of crops cultivated (within the agricultural sector). This situation is tolerated because a relatively high per capita income is achieved in the state (compared to other Indian states) thank to remittances and subsidies complementing the direct return of agricultural activities and a beneficial Minimum Support Price in relative terms. These two monetary flows entering Punjab from India and from abroad are essential for maintaining the rural system economically viable but, at the same time, they contribute to environmental degradation. This process makes agricultural production in Punjab "unfeasible" in the mid-term from an environmental point of view, eroding the resilience of the socio-ecological system.

As a consequence, Punjab's precarious equilibrium is becoming increasingly unstable. A significant decrease in subsidies and/or remittances is likely to have an important negative effect on the viability of the metabolic pattern of Punjab and, therefore, on Indian food security.

Exploring consequences of existing trends at the level of the household in relation to the interface Punjab/India

Trends in the contribution of remittances and population growth are discouraging. Moreover, the policy of heavy subsidies to electricity use in rural areas is increasingly unsustainable because of the negative side effects it is creating (Buhllar and Sidhu, 2007), and a future decrease also for this second source of monetary flow can be expected.

Looking at the factors determining the economic viability of rural households in Punjab (local level of analysis), the combination of decreasing remittances and a reduction in the subsidies for electricity in agriculture poses a serious risk to rural livelihood as, just to maintain the actual levels of agricultural production more and more electricity will have to be consumed to pump water from lower water tables. This additional consumption of electricity, if not compensated by subsidies, will further lower the (already low) economic labour productivity, while institutional settings prevent diversification of economic activities in rural Punjab.

2.2.5 Exploring consequences of existing trends at the level of India in relation to the interface India/international markets

Looking at the factors affecting the viability of the metabolic pattern of India as a whole (national level of analysis) other worrisome trends can be noted. In fact, a constant increase in the international price of energy can be expected and, as a consequence, in the international grain prices[17]. An increase in international grain prices would make it more difficult for India to import grains from abroad and as a consequence it is likely to increase pressure for a further intensification of grain production in Punjab. If the "fair price" of grain procurement from Punjab farmers by the central government is to be linked to changes in international prices, as claimed in official policies, India will have to accept a proportional increase in the cost of the internal supply of grain that will reflect, sooner or later, the increases in the international price.

An increase in international food prices coupled to an economic crisis of India, would force the country to: (i) reduce subsidies; (ii) adopt lower procurement prices; and (iii) prevent Punjab from exporting its food production abroad. In this case it would be reasonable to expect stronger stress and social tensions in the state of Punjab.

Exploring consequences of existing trends at the interface between societal metabolism and ecosystem metabolism

As regards the ecological compatibility of the metabolic pattern of rural Punjab, so far the socio-economic tensions within Punjab and between Punjab and India have been externalized to local ecosystems in the form of overexploitation of aquifers and soil degradation. An open question is for how long these tensions, which are expected to keep growing in the future, can be mitigated by further externalization to local ecosystems before a dramatic bad repercussion will cause a shock in the entire agricultural system.

17 Energy is needed at the local scale for irrigation and at the Indian scale for making fertilizers

E N E R G Y

2.3 CASE STUDY - SOUTH AFRICA

2.3.1 Introduction

In 2004, the South African government set a 100% electrification target by the end of 2012. However, given current electrification rates it recently had to push the universal electrification goal out to 2025. South Africa's energy system is heavily based on conventional non-renewable energy resources, as a consequence it is Africa's largest generator of GHG emissions and is among the top 10 countries with the worst "carbon footprint" in the world. In addition, current dependence of its food-supply on fossil energy (the food sector accounting for 30% of South Africa's total energy consumption) makes it vulnerable to fluctuating and rising fossil-fuel prices.

The objective of this case study was to check how MuSIASEM can be employed to generate an integrated assessment of the potential contribution (quantity) and convenience (quality) of concentrated solar power (CSP) and woody biomass as alternative sources for the production of electricity. For this task, plausible[18] quantitative results of published studies were used, providing quantitative characterizations of both "CSP" and "woody biomass" as input for the analysis. In particular such studies were used for the characterization of the demand of production factors per net supply of energy carrier (in this case: electricity for the two energy systems). This characterization includes technical aspects (plausible hypotheses and technical coefficients) and logistic problems (plausible locations). Thus, the goal of this case study is to illustrate the possibility of integrating a technical and a spatial analysis in a multi-level system of accounting capable of assessing the potential of alternative energy sources both in quantitative and qualitative terms.

Most part of the remaining data about energy flows in South Africa come from the International Energy Agency and refer to 2010, unless stated otherwise.

2.3.2 Diagnostic Analysis of the South African Energy Sector

As this case study focuses on the assessment of the quality of primary energy sources (PES) and the process of production of energy carriers (EC), the energy sector is singled out as the hypercyclic compartment of society in charge for the production of energy carriers (see the grammar for the analysis of the metabolic pattern of energy given in Fig. 3).

When adopting the internal view, the requirement of energy carriers in society are identified, looking at the metabolic flow from the consumption side, as determined by the sum of:

(i) the Net Supply of Energy Carriers: the specific consumption of energy carriers of the various compartments of the society (indicated by the vectors of end-uses) divided in a purely dissipative part (energy is used to express functions outside the energy sector); and hypercyclic part (the energy used in the energy sector);

(ii) the exports; and

18 i.e. quality studies published by reputable research centers

(iii) the losses.

When adopting the external view, the requirement of a gross supply that must be made available by using primary energy sources are defined as:

(i) the hypercyclic part (Energy & Mining): local production of energy carriers; plus

(ii) imports.

Quantitative analysis is undertaken based on the adoption of both the external and internal view. When checking the feasibility in relation to external constraints (i.e. the availability of enough primary energy sources) the required information can only be assessed using data referring to the external view. When checking the viability of the production of energy carriers in relation to internal constraints (i.e. the strength of the hypercycle generating more energy carriers of those used per unit of production factor) the required information can only be assessed using data referring to the internal view. This interface between the two views – the processes taking place within the energy and mining sector requiring the use of production factors - and the set of locally available primary energy sources exploited in the energy sector of South Africa is provided in Table 15.

Table 15

Profile of investment of production factors (categories defining columns) in the exploitation of different Primary Energy Sources in South African energy sector

Vectors of end uses required by the Hypercycle of Energy Carriers

	SUPPLY	HA (Mhr)	ET-t (PJ-NER)	PC-t (MW)	ET-m (PJ-NER)	PC-m (MW)	NSEC-t (PJ-EC)	NSEC-m (PJ-EC)
	EM (n-2)	460	100	2,600	4.2	130	5,600	850
Local Primary Energy Sources	***PHYSICAL GRADIENTS (n-3)***	***430***	***100***	***2,600***	***4.2***	***130***	***4,200***	***800***
	Fossil fuels (n-4)	150	37	370	2.6	84	3,600	750
	Nuclear (n-4)	12	3.2	32	1.5	48	-	42
	Biofuels (n-4)	270	60	2,200	negl.	negl.	600	3.4
	Others (n-4)	negl.	negl.	negl.	negl.	negl.	negl.	5.9
IMPORTS	***IMPORTS as GER (n-3)***	***35***	***0.85***	***9.2***	***0.03***	***0.8***	***1,200***	***7.2***
	Fossil fuels (n-4)	35	0.85	9.2	0.03	0.8	1,200	7.2
	IMPORTS as EC (n-3)	***negl.***	***negl.***	***negl.***	***negl.***	***negl.***	***260***	***40***
	Fossil fuels (n-4)	negl.	negl.	negl.	negl.	negl.	260	negl.
	Electricity (n-4)	negl.	negl.	negl.	negl.	negl.	-	40

Similarly to the analysis of the food system in Mauritius, the change of perspective, from the external to the internal view, implies switching in the quantitative representation from numbers organized in 'scalars' to numbers organized in 'vectors'. Gross Energy

Requirements are scalar quantities measured in $GER_{thermal\ joules}$ (e.g. tons of oil equivalent) whereas, if the use of Energy Carriers inside the society must be highlighted, vectors are to be used, describing different quantities of energy referring to different typologies of EC, all measured in joules – i.e. J of electricity (mechanical energy), J of fuels (chemical potential energy) and J of heat (thermal energy) (Giampietro et al. 2012).

According to the first and second laws of thermodynamics energy cannot be created. Therefore, by definition, primary energy sources must be favourable physical gradients provided by boundary conditions (by processes taking place outside human control) available to humans. These favourable boundary conditions enable the production of a net supply of energy carriers. This is what requires a check in relation to the external view. Moreover, thermodynamics also tells us that different energy forms do have different qualities and their conversion is subject to thermodynamic principles[19].

In the PES/EC supply matrix shown in Table 15, the following flows are illustrated:

(i) the relative contribution of each energy source in relation to the total net supply of energy carriers in the EM sector (on the last two columns on the right); and

(ii) the relative consumption of energy carriers (in the column ET_t and ET_m).

In this way, it becomes possible to establish a relation between the overall characteristics of the EM sector - using a vector: EM (n-2) - and the characteristics of its subparts - using a matrix: Physical Gradients (n-3). In particular, three main categories of energy products are distinguished:

(1) Physical gradients, which correspond to the domestic supply of primary energy sources (PES);

(2) Imports as $GER_{thermal}$, which correspond to the imported products used for making energy carriers (e.g. coal or fuel to power plants or refineries); and

(3) Imports as energy carrier (EC), which correspond to the import of energy products that are used directly as energy carriers (e.g. petroleum products or electricity with no conversion losses).

The energy supply matrix is useful to identify the profiles of use of production factors (labour and power capacity) and the requirement of energy carriers required for the exploitation of different types of primary energy sources. The combination of the characteristics of the various vectors of the matrix (determined by the relative contribution of each energy source) define the overall consumption of production factors and energy carriers that society has to invest in the energy&mining sector (EM) to generate its internal gross supply of energy carriers. On the basis of this representation of energy flows, the following two indicators are considered:

(1) Potential Supply of a given energy source – external view: this indicator is useful to perform a check on external constraints as it provides an assessment of the size (in extensive terms) of the Net Supply of Energy Carriers (NSEC) expressed in PJ-GER using the GER/NSEC equivalence ratios;

19 1 Joule of electricity cannot be summed to 1 joule of heat and conversion factors must be considered very carefully when accounting energy transformations within complex systems

(2) Energy Return On Investment (EROI) – internal view: within our approach, this indicator is defined as the amount of energy carriers that has to be invested in the exploitation of a Primary Energy Source in order to generate the net supply of energy carriers. EROI ratio is calculated for the production of electricity from different types of primary energy sources, from the vectors and matrices[20].

When information of the various EROI are aggregated using vectors and matrices into an assessment referring to the whole society (considering GSEC of the whole society as "the energy return" and the energy carriers consumed in the end-uses of the energy & mining sector as "the energy investment") an assessment of the so-called Strength of the Exosomatic Hypercycle (SEH) is obtained. This parameter is defined as the ratio of the overall size of the gross supply of energy carriers to the whole society (including both the dissipative and hypercyclic parts) to the energy throughput within the energy & mining sector (hypercycle part, when focusing on the metabolic pattern of energy).

Including the effect of imports, the strength of the exosomatic hypercycle is 60:1 for the South African energy sector. When the analysis is limited to the generation of electricity, it drops to 46:1 because the cost of production is generally higher for electricity than for thermal energy carriers.

2.3.3 The protocol of energy accounting used in this case study

This section presents how exosomatic energy flows are evaluated in line with the energy grammar presented in Fig. 3.

First, the entry points that are the typologies of data used for the all case studies are spelled out. Second, the logical framework of the energy analysis is provided by means of a set of steps presenting how the outputs are generated. For this purpose the South Africa case is used, but the same logic applies to the other cases. The logical framework makes it possible to understand the formalization of the analysis, and especially how to deal with non-equivalent forms of energy in just one integrated analysis.

Entry points

Three entry points are identified in the energy analysis, which correspond to data that can be measured:

- at the level of the End Uses, for the whole country and in each sector:
  - Energy statistics on imports and local supply: amount of fossil energy products either from imports or from domestic supply (in biophysical units, i.e. tonnes, m^3, etc.);
  - Energy statistics on electricity generation and consumption: consumption of

20 With this method of calculation, EROI values differ from those obtained with the conventional method developed by Charlie Hall (Hall and Klitgard, 2012). For example, in this accounting the EROI of imported energy carrier results infinite as no investments in the energy and mining sector are required for its generation.

electricity (in MWh) per economic activities (agriculture, transport, construction, manufacturing, services, household, etc.);

- at the level of the energy systems, for the most significant technologies:
  - Technical coefficients on energy systems: production factors required (consumption of energy carriers, human labor, land, etc.) and net supply of energy carrier.

These three items are examined one at the time below.

(i) Energy statistics on imports and local supply

Table 16 presents the energy statistics (excerpts) that have been used to generate the energy analysis in relation to the different energy products from imports or from local supply – expressed in physical units (tonnes, m³, etc.) or in thermal equivalent units (e.g. toe).

Table 16

Excerpts of energy statistics on imports and local production used for the energy analysis for South Africa in 2009

Product category	Product sub-category	Indicator	Value (ktoe)
Coal	Coal and Peat	Production	141,681
Crude Oil	-		150
Oil Products	-		0
Natural Gas	-		851
Nuclear	-		3,337
Renewables	Hydro		125
Renewables	Geothermal, Solar, etc.		64
Renewables	Biofuels and Waste		14,429
Energy carrier	Electricity		0
Energy carrier	Heat		0
Coal	Coal and Peat	Imports	1,354
Crude Oil	-		24,234
Oil Products	-		6,298
Natural Gas	-		2,858
Nuclear	-		0
Renewables	Hydro		0
Renewables	Geothermal, Solar, etc.		0
Renewables	Biofuels and Waste		0
Energy carrier	Electricity		1,057
Energy carrier	Heat		0
Coal	Coal and Peat	Exports	-45,234
Crude Oil	-		0
Oil Products	-		-2,701

Source: OECD/IEA 2011, http://www.iea.org/stats/balancetable.asp?COUNTRY_CODE=ZA

(ii) Energy statistics on electricity generation and consumption

Table 17 presents the energy statistics (excerpts) that have been used to generate the energy analysis in relation to the electricity generated per systems as well as the electricity consumption per sectors – expressed in Watt-hour (Wh).

Table 17

Excerpts of energy statistics on electricity production and consumption used for the energy analysis for South Africa in 2009

Indicator	Value	Unit
Electric power consumption	223,520,000,000	kWh
Electric power transmission and distribution losses	10	%
Electric power transmission and distribution losses	24,280,000,000	kWh
Electricity production	246,815,000,000	kWh
Electricity production from coal sources	94	%
Electricity production from coal sources	232,196,000,000	kWh
Electricity production from hydroelectric sources	1	%
Electricity production from hydroelectric sources	1,452,000,000	kWh
Electricity production from natural gas sources	0	%
Electricity production from natural gas sources	0	kWh
Electricity production from nuclear sources	5	%
Electricity production from nuclear sources	12,806,000,000	kWh
Electricity production from oil sources	0	%
Electricity production from oil sources	49,000,000	kWh
Electricity production from oil, gas and coal sources	94	%
Electricity production from renewable sources	1,764,000,000	kWh
Electricity production from renewable sources, excluding hydroelectric	0	%
Electricity production from renewable sources, excluding hydroelectric	312,000,000	kWh

Source: OECD/IEA 2011, http://www.iea.org/stats/balancetable.asp?COUNTRY_CODE=ZA

(iii) Technical coefficients on energy systems

The energy analysis requires information on the various technical coefficients characterizing the different energy systems (for the most significant energy technologies only) used in each case study, such as:

- net supply of energy carriers,
- average size of plants (unit's power capacity),
- average annual utilization factor (number of hours of use per year; and fraction of the total unit's capacity actually used),
- internal consumption of energy carriers (electricity and fuels),
- requirements of labor, land and water (either aggregate or per plant),
- significant types and quantities of waste/pollution generated,
- facilities' lifetime and construction time.

For example, in the South Africa case, the technical coefficients considered for the energy technologies are described in Table 18 and Table 19:

Table 18

Production factors used for the production of EC-MECHANICAL (electricity) for the most significant energy technologies in South Africa

PES / Imports Category	PES / Imports (using Eurostat nomenclature)	$ET_{THERMAL}$ (GJ-EC/GWh)	$ET_{MECHANICAL}$ (GJ-EC/GWh)	$PC_{THERMAL}$ (kW/GWh)	$PC_{MECHANICAL}$ (kW/GWh)	HA[(a)] (h/GWh)	WT[(a)] (m^3/GWh)	LU[(a)] (ha/GWh)
Solid Fuels	All	160	12	1.6	0.37	65	2,090	negligible
Nuclear	Nuclear Power [16_107030]	250	119	2.5	3.8	480	3,100	negligible

(a) Requires being cross-checked against economic, water and land-use analyses

Source: Diaz-Maurin and Giampietro, 2013; after EPRI, 2010

Table 19

Production factors used for the production of EC-THERMAL (fuels and heat) for the most significant energy technologies in South Africa

PES / Imports Category	PES / Imports (using Eurostat nomenclature)	$ET_{THERMAL}$ (GJ-EC/TJ)	$ET_{MECHANICAL}$ (GJ-EC/TJ)	$PC_{THERMAL}$ (kW/TJ)	$PC_{MECHANICAL}$ (kW/TJ)	HA[(a)] (h/TJ)	WT[(a)] (1000 m^3/TJ)	LU[(a)] (ha/TJ)
Petroleum products	All	0.5	negligible	0.005	negligible	negligible	negligible	negligible
Renewables	Biomass & Wastes [5540] - Biofuels (ethanol from sugarcane, Brazilian high input case)	370	negligible	4.0	negligible	231	150	7.5

(a) Requires being cross-checked against economic, water and land-use analyses

$ET_{THERMAL}$ corresponding to losses in oil refineries

Source: after Giampietro and Mayumi, 2009; after SASA, 2010

Logical framework

The logical framework used to generate the diagnostic analysis consists in a succession of logical steps dealing with different forms of energy:

STEP #1: PES/Imports category split

Step 1 consists in distinguishing the three categories of energy products: (1) imports as GER, that are used for generating electricity; (2) imports as EC, that are directly consumed in the different sectors of society (End Uses); and (3) Primary Energy Sources, that are coming from local supply. In addition, exports of EC are identified so as to equilibrate the energy balances.

In this case, only data on energy statistics on imports and local supply are used (tab. 20).

Table 20

Distinction of imports and PES

PES/Imports Category	PES/Imports (using Eurostat nomenclature)	Total PES/ Imports (ktoe)	PES (ktoe)	Imports as GER (ktoe)	Imports as EC (ktoe)	Assumptions	Exports (ktoe)	Assumptions
Petroleum products	Crude Oil [3105]	24,384	150	24,234	as GER only	Input to Refineries	0	exports as THERMAL
	Feedstocks and other hydrocarbons [3190]	-	-	-	-			
	All petroleum products [3200]	6,298	as EC only	as EC only	6,298		-2,701	exports as THERMAL
	LPG [3220]	see [3200]	-	-	-	see [3200]		
	Motor spirit [3230]	see [3200]	-	-	-	see [3200]		
	Kerosenes - Jet Fuels [3240]	see [3200]	-	-	-	see [3200]		
	Naphta [3250]	see [3200]	-	-	-	see [3200]		
	Gas/Diesel oil [3260]	see [3200]	-	-	-	see [3200]		
	Residual Fuel Oil [3270A]	see [3200]	-	-	-	see [3200]		
	Other petroleum products [3280]	see [3200]	-	-	-	see [3200]		
Solid Fuels	All solid fuels [2000]	143,602	142,248	1,354	-		-45,234	exports as THERMAL
	Hard Coal and Patent Fuels [2112-2118]	see [2000]	-	-	-	see [2000]		
	Coke [2120]	see [2000]	-	-	-	see [2000]		
	Lignite and Deriv. [2200]	see [2000]	-	-	-	see [2000]		
Gas	Natural Gas [4100]	3,709	851	2,858	-			
	Derived Gas [4200]	-	-	-	-			
Nuclear	Nuclear Power [16_107030]	3,337	3,337	-	-	Assuming all uranium from domestic supply		
Renewables	Hydro Power [16_107034]	125	125	-	-			
	All renewables, excl. Hydro	-	-	-	-			
	Wind Energy [5520]	-	-	-	-			
	Solar Energy [5530]	-	-	-	-			
	Solar Heat [5532]	-	-	-	-			
	Photovoltaic Power [5534]	-	-	-	-			
	Biomass & Wastes [5540] - Biofuels	14,429	14,429	-	-		-267	exports as THERMAL
	Geothermal Energy [5550]	64	64	-	-			
Energy Carriers	Electricity	1,057	as EC only	as EC only	1,057		-1,208	exports as MECHANICAL

Table 21

Energy carrier split using a convention on GER per energy products

PES/Imports Category	PES/Imports (using Eurostat nomenclature)	Total PES/ Imports used to make MECHANICAL energy (ktoe)	Total PES/ Imports used to make THERMAL energy (ktoe)	Total GSEC-MECHANICAL (GWh)	GER (convention) as THERMAL energy (PJ-GER)	GER (convention) as MECHANICAL energy (PJ-GER)[a]	x_t (thermal)	x_m (mechanical)
Petroleum products	Crude Oil [3105]	-	24,384	-	1,021	-	**1.00**	0.00
	Feedstocks and other hydrocarbons [3190]	-	-	-	-	-	-	-
	All petroleum products [3200]	12	6,286	49	263	0.46	1.00	0.00
	LPG [3220]	see [3200]	see [3200]	see [3200]	-	-	-	-
	Motor spirit [3230]	see [3200]	see [3200]	see [3200]	-	-	-	-
	Kerosenes - Jet Fuels [3240]	see [3200]	see [3200]	see [3200]	-	-	-	-
	Naphta [3250]	see [3200]	see [3200]	see [3200]	-	-	-	-
	Gas/Diesel oil [3260]	see [3200]	see [3200]	see [3200]	-	-	-	-
	Residual Fuel Oil [3270A]	see [3200]	see [3200]	see [3200]	-	-	-	-
	Other petroleum products [3280]	see [3200]	see [3200]	see [3200]	-	-	-	-
Solid Fuels	All solid fuels [2000]	58,866	84,736	232,196	3,548	2,171	0.62	0.38
	Hard Coal and Patent Fuels [2112-2118]	see [2000]	see [2000]	see [2000]	-	-	-	-
	Coke [2120]	see [2000]	see [2000]	see [2000]	-	-	-	-
	Lignite and Deriv. [2200]	see [2000]	**SEE [2000]**	see [2000]	-	-	-	-
Gas	Natural Gas [4100]	-	3,709	0	155	0	1.00	**0.00**
	Derived Gas [4200]	-	-	-	-	-	-	-
Nuclear	Nuclear Power [16_107030]	-	-	12,806	-	120	-	1.00
Renewables	Hydro Power [16_107034]	125	0	1,452	0	14	0.00	1.00
	All renewables, excl. Hydro	-	-	312	-	2.9	-	1.00
	Wind Energy [5520]	-	-	(see above)	-	-	-	-
	Solar Energy [5530]	-	-	(see above)	-	-	-	-
	Solar Heat [5532]	-	-	(see above)	-	-	-	-
	Photovoltaic Power [5534]	-	-	(see above)	-	-	-	-
	Biomass & Wastes [5540] - Biofuels	89	14,340	1,035	600	9.7	0.98	0.02
	Geothermal Energy [5550]	5	59	58	2.5	0.54	0.82	0.18
Energy Carriers	Electricity	1,057	-	12,293	-	115	-	1.00

(a) Using Partial Substitution Method for PES/Imports used to generate mechanical energy (after Sorman, 2011)

STEP #2: GER (convention) and EC-split

Step 2 consists in evaluating the Gross Energy Requirement (GER) of each energy product as well as on obtaining the distribution between the different EC generated. For this purpose, the different energy products (PES and Imports) used to generate are tracked (thermal or mechanical energy carriers).

In doing so, since non-equivalent forms of energy are considered (GER and EC; and thermal and mechanical), the formal evaluation of GER results from a conventional equivalence between GER/GSEC. Using data from Sorman (2011) it is possible to assume[21]:

GER/GSEC THERMAL = 1.00
GER/GSEC MECHANICAL = 2.60 (= 1 / 0.385)

For this step, data on energy statistics on imports and local supply (Tab. 16) are use for thermal energy, and data on energy statistics on electricity generation and consumption for mechanical energy (Tab. 17). GER-convention values can be expressed per each energy product following the PES/Imports split made in step 1 as illustrated in Tab. 22.

21 In strict terms, the GER/GSEC ratios can be evaluated only after the End Uses have been characterized, which in turn requires a GER/GSEC equivalent ratio (impredicativity of energy analysis). Only these ratios are used to provide an adequate split of EC as illustrated in Table 21. The final evaluation of GER uses the iterated GER/GSEC (after the EU are characterized) as shown in tab. 24.

Table 22

GER (convention) per PES/Imports categories

PES/Imports Category	PES/Imports (using Eurostat nomenclature)	Total PES/Imports (PJ-GER)	PES (PJ-GER)	Imports as GER (PJ-GER)	Imports as EC (PJ-GER)
Petroleum products	Crude Oil [3105]	1,021	6	1,015	0
	Feedstocks and other hydrocarbons [3190]	-	-	-	-
	All petroleum products [3200]	264	0	0	264
	LPG [3220]	-	-	-	-
	Motor spirit [3230]	-	-	-	-
	Kerosenes - Jet Fuels [3240]	-	-	-	-
	Naphta [3250]	-	-	-	-
	Gas/Diesel oil [3260]	-	-	-	-
	Residual Fuel Oil [3270A]	-	-	-	-
	Other petroleum products [3280]	-	-	-	-
Solid Fuels	All solid fuels [2000]	5,719	5,665	54	0
	Hard Coal and Patent Fuels [2112-2118]	-	-	-	-
	Coke [2120]	-	-	-	-
	Lignite and Deriv. [2200]	-	-	-	-
Gas	Natural Gas [4100]	155	36	120	0
	Derived Gas [4200]	-	-	-	-
Nuclear	Nuclear Power [16_107030]	120	120	0	0
Renewables	Hydro Power [16_107034]	14	14	0	0
	All renewables, excl. Hydro	2.9	2.9	0	0
	Wind Energy [5520]	-	-	-	-
	Solar Energy [5530]	-	-	-	-
	Solar Heat [5532]	-	-	-	-
	Photovoltaic Power [5534]	-	-	-	-
	Biomass & Wastes [5540] - Biofuels	610	610	0	0
	Geothermal Energy [5550]	3.0	3.0	0	0
Energy Carriers	Electricity	115	0	0	115
TOTAL		**8,023**	**6,456**	**1,188**	**379**
share of total GER		**1.00**	**0.80**	**0.15**	**0.05**

Table 23

GSEC and LOSSES per PES/Imports category

PES/Imports Category	PES (using Eurostat nomenclature)	GSEC		DISTRIBUTION LOSSES		Assumptions
		THERMAL (PJ-EC)	MECHANICAL (PJ-EC)	THERMAL (PJ-EC)	MECHANICAL (PJ-EC)[(a)]	
PHYSICAL GRADIENTS		**4,159**	**884**	**0**	**87**	
Petroleum products	All petroleum products [3200]	6.3	negligible	negligible	negligible	assuming no THERMAL LOSSES
Solid Fuels	All solid fuels [2000]	3,514	828	negligible	81	assuming no THERMAL LOSSES; TJ-EC for MECHANICAL is the joule-equivalent of Wh
Gas	Natural Gas [4100]	36	-	negligible	-	assuming no THERMAL LOSSES
Nuclear	Nuclear Power [16_107030]	-	46	-	4.5	TJ-EC for MECHANICAL is the joule-equivalent of Wh
Renewables	Hydro Power [16_107034]	-	5.2	-	0.51	TJ-EC for MECHANICAL is the joule-equivalent of Wh
	All renewables, excl. Hydro	-	1.1	-	0.11	TJ-EC for MECHANICAL is the joule-equivalent of Wh
	Biomass & Wastes [5540] - Biofuels	600	3.7	negligible	0.37	assuming no THERMAL LOSSES; TJ-EC for MECHANICAL is the joule-equivalent of Wh
	Geothermal Energy [5550]	2.5	0.21	negligible	negligible	assuming no THERMAL LOSSES; TJ-EC for MECHANICAL is the joule-equivalent of Wh
IMPORTS AS GER		**1,167**	**8**	**0**	**0.8**	
Petroleum products	All petroleum products [3200]	1,014	0.14	negligible	negligible	assuming no THERMAL LOSSES; TJ-EC for MECHANICAL is the joule-equivalent of Wh
Solid Fuels	All solid fuels [2000]	33	7.9	negligible	0.8	assuming no THERMAL LOSSES; TJ-EC for MECHANICAL is the joule-equivalent of Wh
Gas	Natural Gas [4100]	120	-	negligible	-	assuming no THERMAL LOSSES
IMPORTS AS EC		**264**	**44**	**0**	**4.4**	
Petroleum products	All petroleum products [3200]	264	0.04	negligible	negligible	assuming no THERMAL LOSSES; TJ-EC for MECHANICAL is the joule-equivalent of Wh
Energy Carriers	Electricity	-	44	-	4.4	TJ-EC for MECHANICAL is the joule-equivalent of Wh
TOTAL		**5,590**	**937**	**0**	**92**	

(a) Assuming 10% of distribution losses in grid for MECHANICAL energy only (Source: OECD/IEA, 2011)

STEP #3: GSEC and LOSSES

Step 3 consists in evaluating the Gross Supply of Energy Carriers (GEC) as thermal and mechanical, as well as the losses of distribution (considered as negligible for thermal energy) for each energy product. In this way, it becomes possible to evaluate the Net Supply of Energy Carriers (NSEC) generated by each PES/Import category (Table 23).

Table 24

Characterization of the End Uses for South Africa in 2009

PES/Imports Category	PES/Imports (using Eurostat nomenclature)	NSEC		HYPERCYCLE (EM sector)		EXPORTS		DISSIPATIVE part (EU)		Assumptions
		THERM. (PJ-EC)	MECH. (PJ-EC)	ET-THERM. (PJ-NER)	ET-MECH. (PJ-NER)	THERM. (PJ-NER)	MECH. (PJ-NER)	ET-THERM. (PJ-NER)	MECH. (PJ-NER)	
PHYSICAL GRADIENTS		**4,159**	**797**	**100**	**4.2**	**-1,119**	**-47**	**2,944**	**746**	
Petroleum products	All petroleum products [3200]	6.3	negligible	negligible	negligible	-0.6	negligible	5.7	negligible	
Solid Fuels	All solid fuels [2000]	3,514	747	37	2.6	-1,107	-45	2,371	699	Exports of electricity spread over all MECHANICAL energy production systems
Gas	Natural Gas [4100]	36	-	negligible	-	-	-	36	-	
Nuclear	Nuclear Power [16_107030]	-	42	3.2	1.5	-	-2.5	-	38	Exports of electricity spread over all MECHANICAL energy production systems
Renewables	Hydro Power [16_107034]	-	4.7	-	negligible	-	-0.28	-	4.4	Exports of electricity spread over all MECHANICAL energy production systems
	All renewables, excl. Hydro	-	1.0	-	negligible	-	negligible	-	1.0	
	Biomass & Wastes [5540] - Biofuels	600	3.4	60	negligible	-11	negligible	529	3.4	assuming output/input of 10:1
	Geothermal Energy [5550]	2.5	0.21	negligible	negligible	-	negligible	2	0.2	
IMPORTS AS GER		**1,167**	**7.2**	**0.85**	**0.03**	**-100**	**-0.4**	**1,067**	**6.8**	
Petroleum products	All petroleum products [3200]	1,014	0.14	0.50	negligible	-89	negligible	925	0.14	
Solid Fuels	All solid fuels [2000]	33	7.1	0.35	0.03	-11	-0.4	23	6.7	Exports of electricity spread over all MECHANICAL energy production systems
Gas	Natural Gas [4100]	120	-	negligible	-	-	-	120	-	
IMPORTS AS EC		**264**	**40**	**0**	**0**	**-23**	**-2.4**	**240**	**37.5**	
Petroleum products	All petroleum products [3200]	264	0.04	imports as EC	-23	negligible	240	0.04		
Energy Carriers	Electricity	-	40	imports as EC	-	-2.4	-	37.5		Exports of electricity spread over all MECHANICAL energy production systems
TOTAL		**5,590**	**845**	**101**	**4.2**	**-1,242**	**-50**	**4,251**	**790**	

STEP #4: NSEC-EU bifurcation

Step 4 consists in characterizing the End Uses (EU) allocated to each PES/Imports category based on the evaluation of NSEC derived from step 3 (Table 24).

In the example of the South Africa case, the EU can be characterized as the Dissipative part (all sectors except the EM sector) once both EC consumed by the Hypercycle (EM sector) and Exports are known.

Step #5: Consumption of EC and PC (DISSIPATIVE vs. HYPERCYCLE)

Step 5 summarizes the energy carriers (Tab. 25) and power capacity (Tab. 26) consumed by the different parts of the system.

Table 25

Consumption of EC in the different compartments of the system for South Africa in 2009

Part	Demand-side Sectors	EU-THERMAL (PJ-EC/y)	EU-MECHANICAL (PJ-EC/Y)
TOTAL	-	**4,352**	**886**
DISSIPATIVE	All compartments excl. EM	4,251	790
HYPERCYCLE	EM sector (from Tab. 24)	101	4.2
LOSSES	-	0	92
EXPORTS	-	**-1,242**	**-50**

Table 26

Consumption of PC in the different compartments of the system for South Africa in 2009

Part	Demand-side Sectors	η (%)	CL (%)	OL (%)	UF (%)	PC (GW)
DISSIPATIVE-thermal[(a)]	All compartments excl. EM	25%	100%	10%	10%	337
DISSIPATIVE-mechanical [(a)]	All compartments excl. EM	80%	100%	5%	5%	448
HYPERCYCLE-thermal [(a)]	EM sector	25%	100%	20%	20%	see Tab. 27
HYPERCYCLE-mechanical [(a)]	EM sector	80%	100%	20%	20%	see Tab. 27

(a) Using PC evaluation method based on FLOWS; assuming 25% efficiency for THERMAL-based

The consumption of the power capacity (PC) in the EM sector comes from a bottom-up assessment presented in Tab. 27.

Table 27

Production factors consumed and net supply of EC in the Energy & Mining (EM) sector for South Africa in 2009

Level	PES/Imports (using Eurostat nomenclature)	Consumption					Supply	
		HA (Mhr)(a)	$ET_{THERMAL}$ (PJ-NER)	$ET_{MECHANICAL}$ (PJ-NER)	$PC_{THERMAL}$ (MW)	$PC_{MECHANICAL}$ (MW)	$NSEC_{THERMAL}$ (PJ-EC)	$NSEC_{MECHANICAL}$ (PJ-EC)
Level n-2	**EM**	**463**	**101**	**4.20**	**2,607**	**133**	**5,590**	**845**
Level n-3	**PHYSICAL GRADIENTS**	**428**	**100**	**4.2**	**2,598**	**132**	**4,159**	**797**
Level n-4	All petroleum products [3200]	negligible	negligible	negligible	negligible	negligible	6.3	negligible
Level n-4	All solid fuels [2000]	150	37	2.6	365	84	3,514	747
Level n-4	Natural Gas [4100]	negligible	negligible	-	negligible	negligible	36	-
Level n-4	Nuclear Power [16_107030]	12	3.2	1.5	32	48	-	42
Level n-4	Hydro Power [16_107034]	negligible	-	negligible	negligible	negligible	-	4.7
Level n-4	All renewables, excl. Hydro	negligible	-	negligible	negligible	negligible	-	1.0
Level n-4	Biomass & Wastes [5540] - Biofuels	266	60	negligible	2,201	negligible	600	3.4
Level n-4	Geothermal Energy [5550]	negligible	negligible	negligible	negligible	negligible	2.5	0.21
Level n-3	**IMPORTS AS GER**	**35**	**0.85**	**0.03**	**9.2**	**0.8**	**1,167**	**7.2**
Level n-4	All petroleum products [3200]	35	0.50	negligible	5.0	negligible	1,014	0.14
Level n-4	All solid fuels [2000]	negligible	0.35	0.03	3.6	0.8	33	7.1
Level n-4	Natural Gas [4100]	negligible	negligible	-	0.6		120	-
Level n-3	**IMPORTS AS GER**	**0**	**0**	**0**	**0**	**0**	**264**	**40**
Level n-4	All petroleum products [3200]	negligible	imports as EC	negligible	negligible	264	0.04	
Level n-4	Electricity	negligible	imports as EC	negligible	negligible	-	40	negligible

(a) Including statistical differences as overheads

STEP #6: TOTAL GER (whole incl. losses) per PES/Imports categories

Step 6 consists in formal evaluation of the total GER of each PES/Imports categories (result presented in Tab. 29). For this purpose, the GER/GSEC ratio is used which derives from the characterization of the End Uses, hence different from the one used in step 2 as it is country- and year-specific (Tab. 28).

Table 28

GER/GSEC ratio per EC-type for South Africa in 2009

	GER/GSEC-THERMAL	GER/GSEC-MECHANICAL
GER/GSEC ratio[(a)]	1.02	2.90

(a) Excluding IMPORTS as EC; NER excl. HYPERCYCLE (EM sector) but incl. EXPORTS

Table 29

TOTAL GER ("WHOLE" incl. LOSSES) per PES/Imports categories for South Africa in 2009

PES/Imports Category	PES/Imports (using Eurostat nomenclature)	"WHOLE"		DISTRIBUTION LOSSES		TOTAL GER
		THERM. (PJ-GER)	MECH. (PJ-GER)	THERM. (PJ-GER)	MECH. (PJ-GER)	TOTAL (PJ-GER)
PHYSICAL GRADIENTS		**3,099**	**2,172**	**0**	**252**	**5,523**
Petroleum products	All petroleum products [3200]	5.8	negligible	negligible	negligible	6
Solid Fuels	All solid fuels [2000]	2,454	2,032	negligible	236	4,722
Gas	Natural Gas [4100]	36	-	negligible	-	36
Nuclear	Nuclear Power [16_107030]	-	113	-	13	126
Renewables	Hydro Power [16_107034]	-	13	-	1.5	14
	All renewables, excl. Hydro	-	2.9	-	0.32	3.3
	Biomass & Wastes [5540] - Biofuels	601	10	negligible	1.1	611
	Geothermal Energy [5550]	2.5	0.61	negligible	negligible	3
IMPORTS AS GER		**1,088**	**20**	**0**	**2.2**	**1,110**
Petroleum products	All petroleum products [3200]	943	0.40	negligible	negligible	943
Solid Fuels	All solid fuels [2000]	23	19.3	negligible	2.2	45
Gas	Natural Gas [4100]	122	-	negligible	-	122
IMPORTS AS EC		**245**	**109**	**0**	**13**	**366**
Petroleum products	All petroleum products [3200]	245	0.10	negligible	negligible	**245**
Energy Carriers	Electricity	-	109	-	13	121
TOTAL		**4,432**	**2,300**	**0**	**267**	6,999

STEP #7: DIAGNOSTIC of the energetic metabolism

Finally, step 7 provides the formal characterization of the diagnostic of the energetic metabolism of the system. This formalization makes it possible to summarize information about the energetic metabolism for the purpose of a nexus assessment linking it to other dimensions (money, food, water, land). However it maintains the possibility of "opening the box" by looking at the set of vectors of production factors behind each number shown in Table 30.

Table 30

Diagnostic of the energetic metabolism for South Africa in 2009

BENCHMARKS[(a)]	ENERGY (PJ-GER)	PC (GW)
TOTAL (WHOLE incl. LOSSES)	7,000	780
IMPORTS	1,500	
DOMESTIC SUPPLY	5,500	
EXPORTS	-1,400	

(a) Numbers may not add up due to rounding

2.3.4 Integrated assessment of the potential of CSP and woody biomass for electricity production

In this simulation only two options are considered for generating electricity with alternative primary energy sources that can potentially replace fossil energy sources:

- Concentrated Solar Power (CSP): a power tower systems similar to the one considered for the 50 MW Bokpoort CSP power plant in South Africa under the UN's CDM programme (UNFCCC 2012). For this scenario, data referring to the similar 20MW Gemasolar plant in Spain with molten salt storage and wet cooling were considered (Torresol Energy 2011).
- Woody biomass for electricity production: dry woodchips production from forestry residue in South Africa. For this scenario, data from the literature (Torresol Energy 2011; Larrain and Escobar 2012 (CSP); Pimentel et al. 2002; Buhholz et al. 2012) and from the Centre for Renewable and Sustainable Energy Studies (CRSES) of Stellenbosch University (*www.crses.sun.ac.za/*) were used.

The EROI values of the hypercycle for the two alternative primary energy sources are: 12-20:1 for CSP and 7-11:1 for woody biomass for electricity. Thus, both alternatives have a significantly lower EROI of the hypercycle compared to the present electricity production in South Africa (46:1). Hence, a significant deployment of these two alternative primary energy sources would reduce the overall strength of the South African exosomatic hypercycle (SEH) in relation to electricity production. As a consequence, a larger share of the production factors available to South Africa would have to be invested in generating electricity since the requirement of production factors per unit of energy carrier supplied is larger than the average of the hypercycle allocated to the production of electricity, rather than using the same production factors for producing and consuming goods and services.

Once the relation between the requirement of primary energy sources and the net supply of energy carriers to society are defined, it is possible to characterize the two alternative energy sources in relation to external constraints (in this case, spatial constraints).

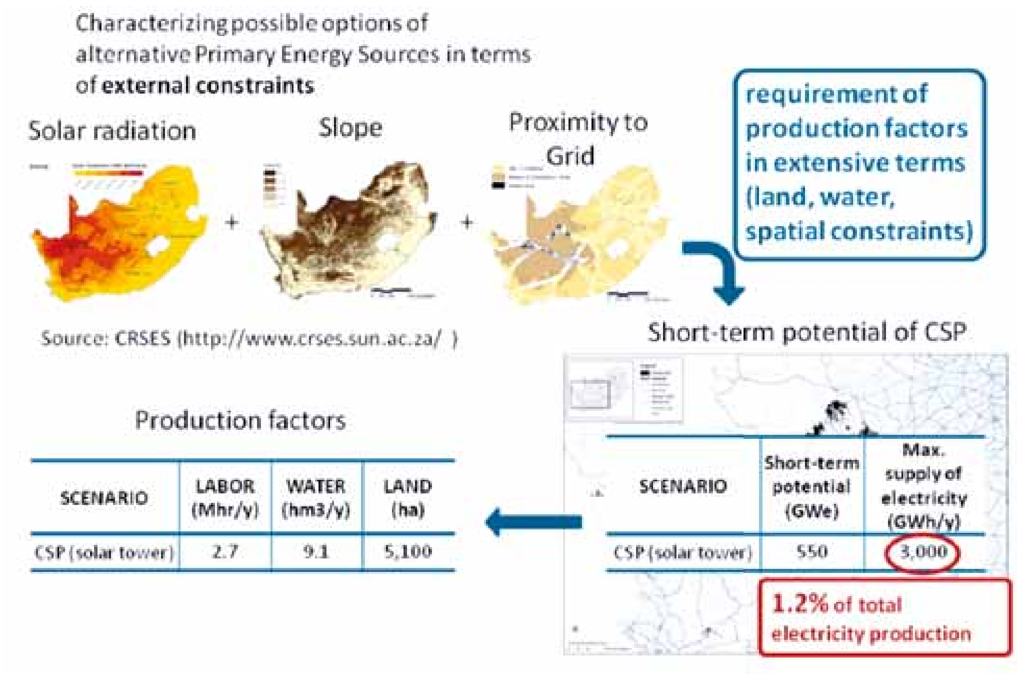
As regards CSP, the spatial constraints and plausible exclusion criteria are determined by:

- The availability of direct normal solar irradiation (DNI superior to 7.0 kWh/m^2);
- The slope (inferior to 2%);
- The distance to the existing transmission grid (inferior to 20 km).

A spatial analysis of these external constraints and the resulting potential net supply of electricity for South Africa is illustrated in Fig. 15.

Figure 15

Characterization of the performance of concentrated solar power for electricity supply for South Africa



In this case this alternative energy source in the short-term can supply only a tiny fraction of the electricity consumed in South Africa.

As regards woody biomass, spatial constraints and plausible exclusion criteria are determined by:

- Availability of biomass resources (forests, excluding protected areas);
- The biomass land productivity;
- Logistics for transportation.

A spatial analysis of these external constraints and the resulting potential net supply of electricity for South Africa is illustrated in Fig. 16.

The data in Figs. 15 and 16 show that the short-term potential of electricity production from CSP and woody biomass in South Africa is 1.2% and 2.3%, respectively of the total annual amount of electricity production. Given these short-term potentials, the requirement of production factors that would have to be invested in the Energy and Mining Sector to generate this amount of electricity (all together 3.5% of the total) can be assessed. The requirements of production factors associated with the CSP and the woody biomass scenarios[22] are shown in Tab. 31. The assessments refer to the production

22 Data for CSP come from Larrain and Escobar, 2012; data for woody biomass from Forestry come from *South Africa, 2010.*

factors required only by CSP and woody biomass for generating their "maximum short-term potential" equal to 3,000 GWh (1.2% of total electricity production) and 5,900 GWh (2.3%) respectively.

Figure 16

Characterization of the performance of woody biomass (residues) for electricity supply for South Africa

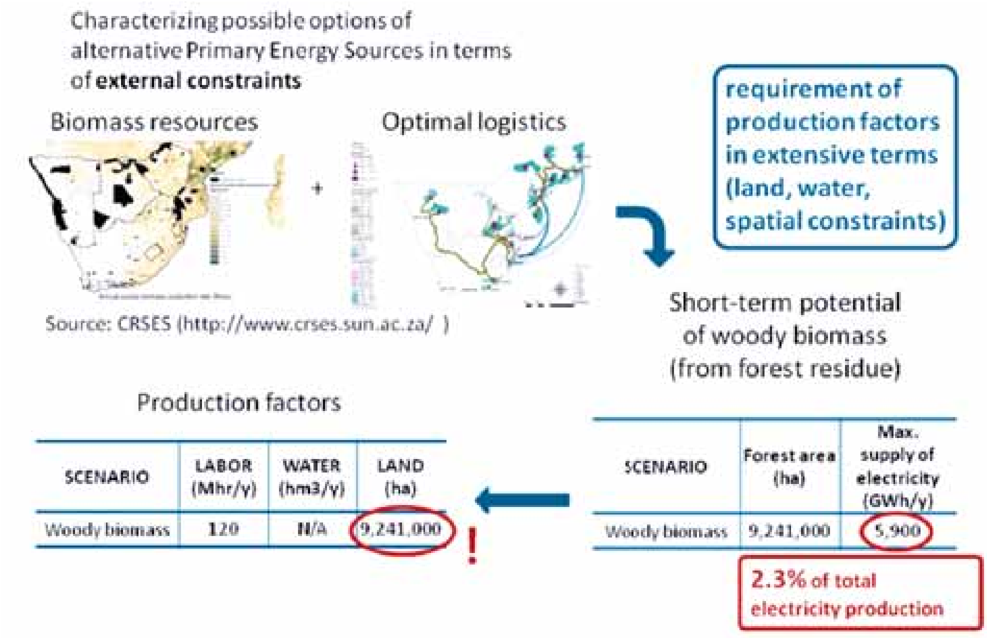


Table 31

Requirement of production factors in the scenario of CSP and Woody Biomass based electricity for South Africa

Scenario	Labor (Mh/y)	Water (hm^3/y)	Land (ha)
CSP (solar tower)	2.7	9.1	5,100
Woody biomass	120	n/a	9,241,000

This allows a check of the trade-offs associated with increasing the net supply of electricity relying on these two alternative energy sources.

In this case, what appears highly relevant is that these alternative energy sources, when compared with fossil energy and import do imply a significantly larger demand of production factors in order to cover only a tiny fraction of the consumed electricity.

CHAPTER 3

LESSONS LEARNED

3.1. ADDED VALUE OF THE APPROACH

The added value of the MuSIASEM approach for the analysis of the energy-food-water nexus lies in the following aspects:

- The philosophy of accounting of MuSIASEM guarantees coherence in the necessarily heterogeneous dataset needed for a quantitative multi-criteria and multi-scale sustainability analysis. MuSIASEM is able to develop an integrated characterization of the existing situation and of the option spaces across different dimensions and different scales of analysis. This holistic perception of the issue of sustainability enables the simultaneous consideration of most relevant aspects of the problem that are observable only on different scales of analysis and using different dimensions. Conventional quantitative methods, based on the traditional rationale of reductionism in which quantitative analysis is developed at one scale and one dimension at the time, lacks this holistic view.
- The three conceptual tools used (multi-purpose grammars, Sudoku effect, impredicative loop analysis) constitute an accounting method that is semantically open and therefore adaptable to specific situations. They provide a pre-analytical meta-structuring of the analysis that is tailored to specific instances when implementing the analysis. Therefore, the final protocols of accounting may differ among the socio-ecological systems under investigation. However, the quantitative representation of large-scale characteristics remains sufficiently robust to allow cross-system comparison.
- The simultaneous use of non-equivalent perceptions to describe the metabolic pattern, and in particular the interfacing of the external and internal view on society, creates a certain redundancy in the system of matrices and vectors. This redundancy is extremely useful to check the congruence of the quantitative assessments (of flows, funds, flow-fund ratios, fund-fund ratios) across the various levels and dimensions of the accounting scheme (thank to the Sudoku effect). Indeed, it allows to:
  (i) Check the data quality by confronting top-down assessments based on aggregate statistical data with bottom-up assessments based on empirical data on technical coefficients of local plants and processes;
  (ii) Infer missing information in case of data gaps given that the organization of the quantitative information is subject to the rules of inference typical of Sudoku games;

(iii) Generate robust scenarios as the system of vectors and matrices clearly indentifies the set of "external referents".

In this way, the plausibility of scenarios can be checked simultaneously across all the elements of society from the macro to the micro. Whenever a scenario implies values in specific vectors that are too distant from known benchmarks, the changes in the metabolic pattern considered are most likely unfeasible.

- Applications can be developed and used within participatory frameworks and processes (e.g. sustainable livelihoods, ecosystem approach, social multi-criteria evaluation). The MuSIASEM approach allows focusing on plausible scenarios only, by eliminating those hypotheses that are inconsistent with the constraints of feasibility, viability and desirability, and it can also help to identify and generate integrated packages of indicators, chosen ad-hoc by the users of the analysis, to structure and facilitate an informed process of deliberation.
- The approach can link traditional variables used in socio-economic sciences with GIS-based data used in spatial analysis, thus establishing a much needed bridge between the socio-economic and ecological dimension. GIS-based data enable the handling of information at multiple spatial scales (local, regional, national) and establish a bridge between representations of environmental impacts and land use (at various scales, depending on the type of land use) and representation of the associated socio-economic processes.
- The complexity of the approach is in line with reality, as it recognizes:
  (i) fuzziness and uncertainty (it is impossible to have a clear-cut representation of the situation or completely eliminate uncertainty from scenario assessments);
  (ii) that there is no optimal solution. The best the approach does is to identify the trade-offs resulting from using different dimensions and scales of analysis.

3.2. PROBLEMATIC POINTS OF THE APPROACH

The problematic points of applying MuSIASEM to the goal of analyzing the nexus between energy, food, and water security can be summarized as follows:

- The holistic approach generates a large output of information, which is not easy to interpret and summarize. The multi-dimensional and multi-level accounting is based on vectors and matrices, the elements of which are all interrelated. The structure of the expected relations (i.e. the construction of the matrices) is fairly simple, but the resulting set of simultaneous representations of the socio-economic system and its context across different dimensions and scales proves more difficult to handle.
- The transdisciplinar character of the approach presents a major challenge for the team members involved in the endeavor. MuSIASEM goes beyond exchanging information among specialists; team members not only contribute their unique expertise but strive to understand the complexities of the whole system, rather than one part of it, and build a common protocol of accounting that defines the observed

system across all its hierarchical levels, scales and dimensions. It requires team members to transcend their own disciplines to inform one another's work, capture complexity, and create new intellectual spaces.

- The accounting scheme can be operated with official statistics, but requires a preliminary processing of datasets (especially energy statistics) to "fit" the grammars as the categories of accounting are not entirely compatible. Given that today datasets are very detailed and organized in digital format, the processing of the data input (re-shuffling data among categories) does not represent a major obstacle, but it does require a minimum of expertise.

  The calculation of virtual flows, that is, the flow elements embodied in imports, can be approached with different logical assumptions:

  (i) In the present MuSIASEM accounting scheme, virtual flows are calculated from the amount of resources that would be required if the flows were produced within the importing society. For example in the Mauritius case study, the "virtual water" embodied in food imports by the country is calculated by assessing the water that would be used in local agriculture if the imported food were produced on the island. This method has limitations when the imported commodities cannot be produced in the importing country.

  (ii) In an alternative accounting scheme, virtual flows could be calculated from the amount of resources actually required to produce the flows in the exporting societies. For example in the Mauritius case study, the water used by the agricultural sectors of the countries exporting food products to Mauritius could be calculated. Also this method has its limitations because imported commodities often come from several different countries and it is not always easy to track the origin of the imports.

  (iii) Yet another approach would be to calculate virtual flows from the standard average amount of resources needed to produce the flows (e.g. the world average water use in agriculture for defined commodities). The drawback here is that world average estimates can differ substantially from local assessments and if one can track the sources of the imports this would introduce an unnecessary inaccuracy in the assessment. Thus, each of these solutions does have pros and cons, and the final choice must depend on the goal of the study and data availability.

- The Sudoku effect requires data closure. Hence, before getting the benefits of the "Sudoku effect" it is necessary to obtain a certain amount of information (a threshold) associated with a mix of data across levels and dimensions in relation to the various flow and fund elements of the various compartments. Like for the Sudoku game, a lot of information can be inferred from the available input, but the available input must provide the necessary information to generate the Sudoku effect. After having reached the threshold of required data, gaps in the data can be handled by re-adjusting the definition of compartments and the choice of categories, but this solution requires expertise.

- The link between biophysical and economic flows is not always easy to establish and it is important to have a good environmental economist in the team who can relate economic concepts and data to biophysical flows. In this context, the analysis of credit and debt presents a major challenge.

REFERENCES

Ablim, A. (2011). Indicadores de la cadena de valor de la Sidra.Available at <http://www.alimentosargentinos.gov.ar/contenido/sectores/bebidas/productos/Sidra_2011_09Sep.pdf> Revised [14-12-2012]

Agencia Española de Seguridad Alimentaria y Nutrición AESAN (2012). Tabla de composición de los alimentos. Red BEDCA. Available at <http://www.aesan.msc.es/AESAN/web/notas_prensa/red_bedca.shtml> revised [13-12-12]

Aranda, A.; Zabalza, I.; Scarpellini, S. (sd). Análisis del ciclo de vida de la elaboración del vino. Reflexiones y propuestas para lograr un producto ecoeficiente. Available at <http://wine.uab.cat/ponencies%20i%20comunicacions/21%20p%20alfonso%20aranda.pdf> Revised [4-1-2013]

Bhullar, A.S. and Sidhu, R.S. (2007). Integrated Land and Water Use: A Case Study of Punjab. Economic & Political Weekly, vol. 41 (no. 52), 5353–5357

Buchholz T., et al. (2012). Modeling the profitability of power production from short-rotation woody crops in Sub-Saharan Africa. *Biomass and Bioenergy*. Available online 23 December 2012. In Press

CASTLE MALTING (2010), Presentation Quality malt for quality beer since 1868

Central water Comission. Government of India (2007). Water Data Complete Book 2005. http://www.cwc.gov.in/main/downloads/Water_Data_Complete_Book_2005.pdf

Centre for Renewable and Sustainable Energy Studies (2013). Renewable Energy Research and Education at Stellenbosch University. Presentation by W. van Niekerk and A. Brent. Stellenbosch University, 20 February 2013. (personal correspondence)

Chapagain A, Hoekstra AY (2003)Virtual water flows between nations in relation to trade in livestock and livestock products.http://www.waterfootprint.org/Reports/Report13.pdf

CIA (2012). The World Factbook, South Africa. https://www.cia.gov/library/publications/the-world-factbook/geos/sf.html

CIEL Group (2012) Consolidated Energy Co. Ltd. Power Generation Statistics. http://www.cielgroup.com/agro/sugar_mauritius.aspx (accessed 15 November 2012)

Defenders of Panjab (2013). Water issues. http://www.defendersofpanjab.org/#/water/4529547648

Dhawan, B.D., 1993. Ground Water Depletion in Punjab. Econ. Polit. Wkly. 28, 2397–2401

Diaz-Maurin F, Giampietro M (2013). A "grammar" for assessing the performance of power-supply systems: comparing nuclear energy to fossil energy. Energy 49:162–177

Economic Adviser to Government of Punjab (2011). Disaggregated Estimates of Gross State Domestic Product Handbook Punjab. Publication No. 935. http://pbplanning.gov.in/pdf/Disaggregated%20Estimates%20of%20Gross%20State%20Domestic%20Product%20-%20Punjab.pdf

Economic Adviser to Government of Punjab (2011). State Domestic Product of Punjab 2004-05 to 2009-10. Publication No. 931. http://pbplanning.gov.in/pdf/State%20income%20punjab%20pub_GSDP.pdf

Economic and Statistical Organisation, Government of Punjab (2011). Economic Survey 2011-2012. http://pbplanning.gov.in/pdf/economicsurvey%202011-12.pdf

Economic and Statistical Organisation, Government of Punjab (2011). Statistical Abstract of Punjab 2011. Publication No. 930. http://punjab.gov.in/General/Abstract/default1.asp

Electric Power Research Institute (2010). Power Generation Technology Data for Integrated Resource Plan of South Africa. http://www.energy.gov.za/IRP/irp%20files/Tech_Data_for_Integ_Plan_of_South_Africa_July_08_2010_Final.pdf (accessed 19 March 2013)

FAO (1995) 'World livestock production system', FAO, Rome, Italy. http://www.fao.org/ag/AGA/LSPA/Paper127/Metho.htm, 14 Nov. 2002

FAO (2001) Food Balance Sheet, a handbook, FAO, Rome, Italy. Available at <http://www.fao.org/docrep/003/X9892E/X9892E00.HTM>

FAO (2009) Agribussines Handbook. Barley, Malt and Beer. Available at <http://www.fao.org/fileadmin/user_upload/tci/docs/AH3_BarleyMaltBeer.pdf> Revised [10-01-2013]

FAO (2010) Pesticides (incl. Fungicides/Bactericides, Herbicides and Insecticides) in Mauritus. Food and Agriculture Organization, United Nations. http://faostat3.fao.org/home/index.html (accessed 15 November 2012)

FAO (2013) Agricultural Statistic, <http://faostat.fao.org/>. Food and Agriculture Organization, United Nations. Revised [22-12-12]

FAO (2013b) Technical Coversion Factors for Agricultural Commodities. Available at <http://www.fao.org/economic/the-statistics-division-ess/methodology/methodology-systems/technical-conversion-factors-for-agricultural-commodities/ar/> Food and Agriculture Organization, United Nations. Revised [22-12-12]

FAO (2013c). CROPWAT 8.0. http://www.fao.org/nr/water/infores_databases_cropwat.html

Fluri, T.P. (2009). The potential of concentrating solar power in South Africa. Energy Policy 37: 5075–5080

Forestry South Africa (2010). The South African Forestry and Forest Products Industry 2009. http://www.forestry.co.za/uploads/File/home/facts/SA_Forestry_Industry_2010_colour.ppt (accessed 19 March 2013)

Frederica M. Bunge (1983). Indian Ocean, five island countries. American University (Washington, D.C.). Foreign Area Studies, United States. Dept. of the Army

Cheeroo-Nayamutha F.C, M.J Robertsonb, M.K Wegenerc, A.R.H Nayamutha (2000). Using a simulation model to assess potential and attainable sugar cane yield in Mauritius. Field Crops Research, 66 (3):225-243

Georgescu-Roegen, N. (1971). The Entropy Law and the Economic Process. Cambridge, Harvard Unversity Press

Giampietro, M., Mayumi, K. and Sorman A.H. (2012). The Metabolic Pattern of Societies – Where economists fall short. Routledge.

Giampietro M and Mayumi K (2009). The Biofuel Delusion: The fallacy of large-scale agro-biofuel production. Earthscan

Giampietro, M., Mayumi, K. and Sorman A.H. (2013) Energy Analysis for a Sustainable Future: the Multi-Scale Integrated Analysis of Societal and Ecosystems Metabolism. Routledge

Government of Punjab (2013). Statistical abstract of Punjab 2010. http://punjab.gov.in/General/Abstract/default1.asp

Gustavsson J., Cederberg C., Sonesson U., Otterdijk R., Meybeck A., (2011) Global food losses and food waste. Extent, causes and prevention. Study conducted for the International Congress SAVE FOOD! at Interpack 2011. Düsseldorf, Germany. FAO, Rome, Italy. Available at http://www.fao.org/docrep/014/mb060e/mb060e00.pdf

Hall, C.A.S. and Klitgaard, K.A. (2012). Energy and the Wealth of Nations. Springer

ILO (2013). Hours of work, by economic activity. http://laborsta.ilo.org/STP/guest Accessed on: 18/12/2012.

International Energy Agency (2005). Energy statistics manual. http://www.iea.org/stats/docs/statistics_manual.pdf (accessed 19 March 2013)

International Renewable Energy Agency (2013). Concentrating Solar Power Technology Brief. http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E10%20Concentrating%20Solar%20Power.pdf (accessed 19 March 2013)

Istituto Nazionale di Ricerca per gli Aglimenti e la Nutrizione INRA, (2000). Tabelle di Compozicione degli Alimenti. Aggiornamento 2000

Larrain T. and Escobar R. (2012). Net energy analysis for concentrated solar power plants in northern Chile. Renewable Energy, vol. 41, May 2012, pp. 123–133

Mekonnen M and Hoekstra AY (2011). National Water Footprint Account.The green, blue and grey water footprint of production and consumption. Research resport series, 50. Vols I and II. UNESCO-IHE

Ministry of Agroindustry and fisheries (2008). A sustainable diversified agri-food sector strategy for Mauritius 2008 - 2015. http://www.gov.mu/portal/goc/moa/file/bprintagriju08.pdf

Ministry of Finance and Economic Development (2012a). Digest of Agricultural Statistics 2011. http://www.gov.mu/portal/goc/cso/file/DigestAgric2011.pdf

Ministry of Finance and Economic Development (2012b). Digest of Statistics on Rodrigues 2011. http://www.gov.mu/portal/goc/cso/file/DigestStatisticsRod2011.pdf

Ministry of Finance and Economic Development (2012c). Digest of Labour Statistics 2011. http://www.gov.mu/portal/goc/cso/file/DigestLabour2011.pdf

Ministry of Finance and Economic Development (2012d). Digest of International Travel and Tourism Statistics 2011. http://www.gov.mu/portal/goc/cso/file/DigestTravel2011.pdf

Ministry of Finance and Economic Development (2012e). Housing and Population Census 2011, Volume V: Economic Characteristics. http://www.gov.mu/portal/goc/cso/report2013/2011PCVOLV.pdf

Ministry of Finance and Economic Development (2012f). National Accounts of Mauritius 2011. http://www.gov.mu/portal/goc/cso/file/nationalaccts.pdf

Ministry of Finance and Economic Development (2010). Continuous Multi Purpose Household Survey. Economic and Social Indicators. Labour Force Employment and Unemployment Year 2010. http://www.gov.mu/portal/goc/cso/ei896/cmphs.pdf

Ministry of Finance and Economic Empowerment (2007). Household Budget Survey 2006/07, Analytical Report. http://www.gov.mu/portal/goc/cso/report/natacc/hbs0607/hbs.pdf

Ministry of Environment and Forests, Government of India (2013). Envis center in Punjab. Status of environmental and related issues. http://www.punenvis.nic.in/water/technologies9.htm

Ministry of Home Affairs. Government of India. (2011). Census of India. http://www.censusindia.gov.in/

Ministry of Labour and Employment, Government of India (2011). Report on Employment and Unemployment 2011-12. Volume I. http://pbplanning.gov.in/pdf/Second%20Annual%20EUS%20 Report-Volume-I.pdf

Ministry of Labour and Employment, Government of India (2011). Report on Employment and Unemployment 2011-12. Volume II. http://pbplanning.gov.in/pdf/Second%20Annual%20EUS%20 Report-Volume-II.pdf

Ministry of Petroleum & Natural Gas of India (2013). Indian Petroleum & Natural Gas Statistics 2010-11. http://petroleum.nic.in/pngstat.pdf (accessed 11 January 2013)

Ministry of Renewable Energy and Public Utilities of Mauritius (2010) Digest of Energy & Water Statistics 2010. http://www.gov.mu/portal/goc/cso/report/natacc/energy10/energy.pdf (accessed 15 November 2012)

Ministry of Statistics and Planning Government of India .Implementation of India (2012). Energy Statistics 2012 (reporting year 2010). http://mospi.nic.in/mospi_new/upload/Energy_ Statistics_2012_28mar.pdf?status=1&menu_id=201 (accessed 11 January 2013)

Ministry of Statistics and Planning Government of India .Compendium of environmental statistics 2011. http://mospi.nic.in/mospi_new/upload/compendium_2011_30dec11.htm

Ministry of Water Resources. Government of India.(2012). National Water Mission Vl II Under National Action Plan on Climate Change. http://wrmin.nic.in/index2.asp?sublinkid=579&langid=1& slid=794

National Crime Records Bureau (2010). Accidental Deaths and Suicides in India 2010. http://ncrb.gov.in/ Accessed on: 08/01/2013

National Statistics Organisation, Government of India (2011). Key Indicators of Household Consumer Expenditure in India 2009-2010. http://mospi.nic.in/Mospi_New/upload/Key_Indicators-HCE_66th_Rd-Report.pdf

Panagos P., Jones A., Bosco C., Senthil Kumar P.S. European digital archive on soil maps (EuDASM): Preserving important soil data for public free access (2011) International Journal of Digital Earth, 4 (5), pp. 434-443

Pimentel, D. et al. (2002). Renewable energy: current and potential issues. Bioscience 52 (12): 1111-20

Protermosolar (2011) Macroeconomic impact of STE sector in Spain in 2011. http://www.protermosolar.com/saladeprensa/sites/default/files/comunicados/Macroeconomic%20Impact%20STE%20 sector%202011.pdf (accessed 19 March 2013)

Punjab State Transmission Corporation Ltd., State Load Dispatch Center (SLDC) (reporting year 2010-11) http://www.punjabsldc.org (accessed 11 January 2013)

Punjab State Planning Board (2012). Environmental Statistics of Punjab 2011. http://pbplanning.gov.in/pdf/environmentReport_final.pdf

Ramjeawon T. (2008) Life cycle assessment of electricity generation from bagasse in Mauritius. *Journal of Cleaner Production* 16: 1727-1734

Reserve Bank of India (2013). Appendix III: Capital Receipts of States and Union Territories with Legislature. http://rbidocs.rbi.org.in/rdocs/Publications/PDFs/03_A3SF280311.pdf

Singh, S. and Mittal, J. P. (1992). Energy in Production Agriculture. Mittal Publications

Sorman A.H. 2011 The energetic Metabolicm of Societies Ph.D. Dissertation - ICTA (Institute of Environmental Science and Technology), Universitat Autonoma Barcelona, Bellaterra, Spain

Statistics South Africa (2001). A Survey of Time Use. http://unstats.un.org/unsd/demographic/sconcerns/tuse/Country/SouthAfrica/sourcezaf00c.pdf

Statistics South Africa (2009). Labour Force Survey, Historical Revision, September Series - September 2001 to September 2007. http://www.statssa.gov.za/Publications/P0210/P0210September2000,2001,2002,2003,2004,2005,2006,2007.pdf

Statistics South Africa (2009). Mining Industry 2009. Report No. 20-01-02. http://www.statssa.gov.za/publications/Report-20-01-02/Report-20-01-022009.pdf

Statistics South Africa (2012) Census 2011. Statistical release – P0301.4. http://www.statssa.gov.za/publications/P03014/P030142011.pdf

Statistics South Africa (2012). Electricity, gas and water supply 2010. Report No. 41-01-02. http://www.statssa.gov.za/publications/Report-41-01-02/Report-41-01-022010.pdf

Statistics South Africa (2012). Gross domestic product, Annual estimates 2002 – 2011, Regional estimates 2002 – 2011, Third quarter 2012. http://www.statssa.gov.za/publications/P0441/P04413rdQuarter2012.pdf

Statistics South Africa (2012). Labour market dynamics in South Africa, 2011. http://www.statssa.gov.za/Publications/Report-02-11-02/Report-02-11-022011.pdf

Statistics South Africa (2012). Tourism satellite account for South Africa, Provisional 2010. Report No. 04-05-07. http://www.statssa.gov.za/publications/Report-04-05-07/Report-04-05-072010.pdf

Statistics of South Africa (2012). Transport and Storage industry 2010. Report No. 71-02-01. http://www.statssa.gov.za/publications/Report-71-02-01/Report-71-02-012010.pdf

South African Reserve Bank (2010). Annual Economic Report 2010. http://www.resbank.co.za/Lists/News%20and%20Publications/Attachments/3614/aer2010.pdf

Torresol Energy (2011) Gemasolar power plant. http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en (accessed 22 March 2013)

United Nations Framework Convention on Climate Change (2012) "Project 7841 : Bokpoort CSP (Concentrating Solar Power) Project, South Africa". http://cdm.unfccc.int/Projects/DB/CarbonCheck_Cert1350990641.93/view (accessed 22 March 2013)

United States Departament of Agriculture (2012). National Nutrient Database for Standard Reference. Available at <http://ndb.nal.usda.gov/ndb/foods/list> Revised [2-12-2012]

von Blottnitz, H. (2006) Alternative Biofuel Crops in South Africa: What to Look for from a Life Cycle Perspective? University of Cape Town. http://www.corpoica.org.co/sitioweb/Documento/JatrophaContrataciones/ALTERNATIVEBIOFUELSCROPSINSOUTHAFRICA-LCA.pdf (accessed 19 March 2013)

World Bank (2009) Statistics on Electric power consumption (kWh) in South Africa (reporting year 2009). http://data.worldbank.org/indicator/EG.USE.ELEC.KH (accessed 19 March 2013)

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Human wellbeing relies upon the availability and wise management of food, energy and water. The interconnections between these resources make clear that the management of each of them cannot be considered in isolation but in an integrated and holistic way. Inter-linkages should be considered also among different scales, between local and global processes of resources use, and between social and economic aspects of a society, in order to properly assess the impacts of new policies or interventions.

This report presents the results of the application of an integrated analysis approach, the Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism to three case studies: (i) an analysis of the option to produce biofuel from sugarcane in the Republic of Mauritius; (ii) an exploration of the future of grain production in the Indian state of Punjab; (iii) an assessment of two alternative energy sources to produce electricity in the Republic of South Africa.

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