56

ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER
ENVIRONMENT CLIMATE CHANGE [ENERGY] MONITORING AND ASSESSMENT

An Innovative Accounting Framework for the Food-Energy-Water Nexus

Application of the MuSIASEM approach to three case studies

56

ENVIRONMENT AND NATURAL RESOURCES MANAGEMENT WORKING PAPER

ENVIRONMENT CLIMATE CHANGE [ENERGY] MONITORING AND ASSESSMENT

An Innovative Accounting Framework for the Food-Energy-Water Nexus

Application of the MuSIASEM approach to three case studies

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*

* LIPHE[4]
** Climate, Energy and Tenure Division, FAO

Food and Agriculture Organization of the United Nations (FAO)
October 2013

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

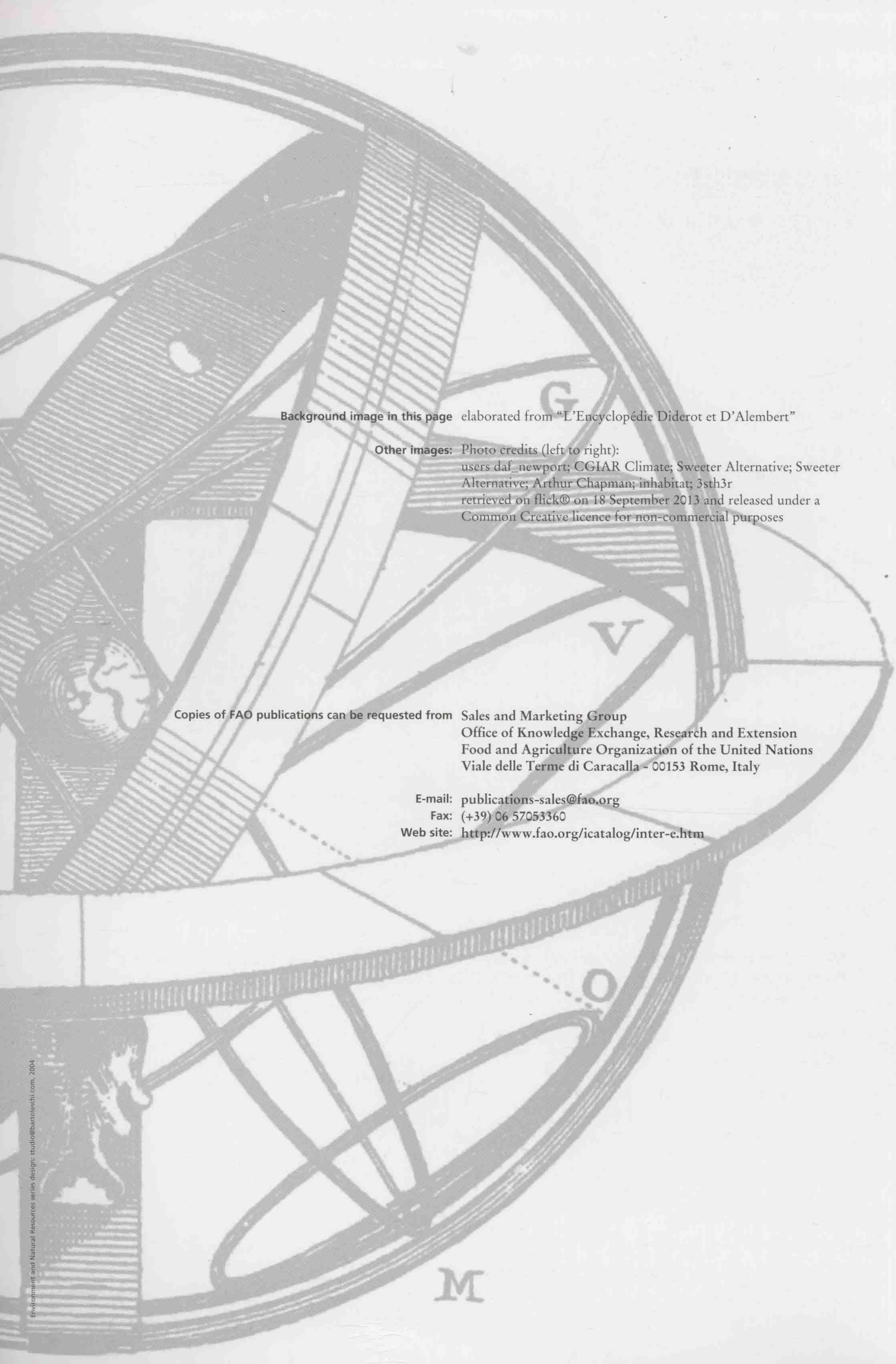
ISBN 978-92-5-107964-5 (print)
E-ISBN 978-92-5-107957-7 (PDF)

© FAO, 2013

FAO encourages the use, reproduction and dissemination of material in this information product. Except where otherwise indicated, material may be copied, downloaded and printed for private study, research and teaching purposes, or for use in non-commercial products or services, provided that appropriate acknowledgement of FAO as the source and copyright holder is given and that FAO's endorsement of users' views, products or services is not implied in any way.

All requests for translation and adaptation rights, and for resale and other commercial use rights should be made via www.fao.org/contact-us/licence-request or addressed to copyright@fao.org.

FAO information products are available on the FAO website (www.fao.org/publications) and can be purchased through publications-sales@fao.org.



Background image in this page elaborated from “L’Encyclopédie Diderot et D’Alembert”

Other images: Photo credits (left to right):
users daf_newport; CGIAR Climate; Sweeter Alternative; Sweeter Alternative; Arthur Chapman; inhabitat; 3sth3r
retrieved on flick® on 18 September 2013 and released under a Common Creative licence for non-commercial purposes

Copies of FAO publications can be requested from
Sales and Marketing Group
Office of Knowledge Exchange, Research and Extension
Food and Agriculture Organization of the United Nations
Viale delle Terme di Caracalla - 00153 Rome, Italy

E-mail: publications-sales@fao.org
Fax: (+39) 06 57053360
Web site: http://www.fao.org/icatalog/inter-e.htm

Environment and Natural Resources series design: studio@bartoleschi.com, 2004

ACKNOWLEDGEMENTS

This report was prepared under the overall supervision of Olivier Dubois, Senior Natural Resources Officer and Leader of the FAO Energy Team, and the technical supervision of Alessandro Flammini from the FAO Climate, Energy and Tenure Division (NRC).

The research was carried on by LIPHE[4], a non-profit scientific association gathering an international group of scholars in the field of sustainability science with the aim to promote research and educational activities related to sustainability science and science for governance, and FAO staff. The study team was led by Prof. Mario Giampietro from the *Universitat Autònoma de Barcelona*. The final technical editing was done by Alessandro Flammini. Author names are reported on page i.

The work was carried out in the context of the project "Application of the MuSIASEM approach to three cases in the agri-food sector" GCP/GLO/445/GER(GIZ), funded by the German Society for International Cooperation (GIZ).

An Innovative Accounting Framework for the Food-Energy-Water Nexus - Application of the MuSIASEM approach to three case studies

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

81 pages

Environment and Natural Resources Working Paper No.56 – FAO, Rome, 2013

Keywords: nexus, assessment, accounting, framework, energy, food, land, water, sustainability, musiasem, integrated assessment, societal metabolism, multi-scale

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

CONTENTS

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.

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 provides the conditions for life. The interconnections between these resources, what is now so 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 perspectives of resource use, and between social and economic aspects of society, highlight the complexities involved in addressing these challenges in ways that also enable effective use of the possible changes resulting from alternative policies or new technologies.

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 nexus 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 analysing 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 so far. 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 in analysing: (a) the desirability, viability and feasibility of the actual metabolism of socioeconomic systems (diagnostic); and (b) the feasibility of development scenarios and policy options (simulations) so as to generate a rich and 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.

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.

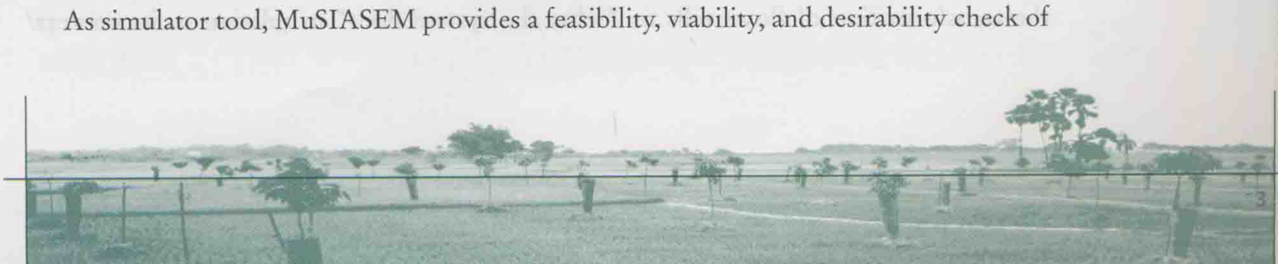
It can be used for diagnostic purposes or to simulate scenarios.

<u>As diagnostic tool</u>, 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

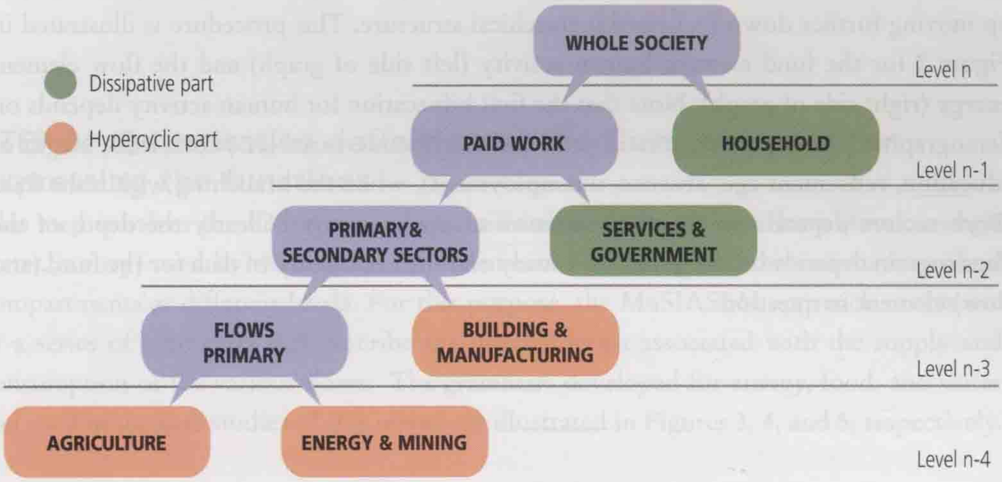
The approach involves the following six steps:

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

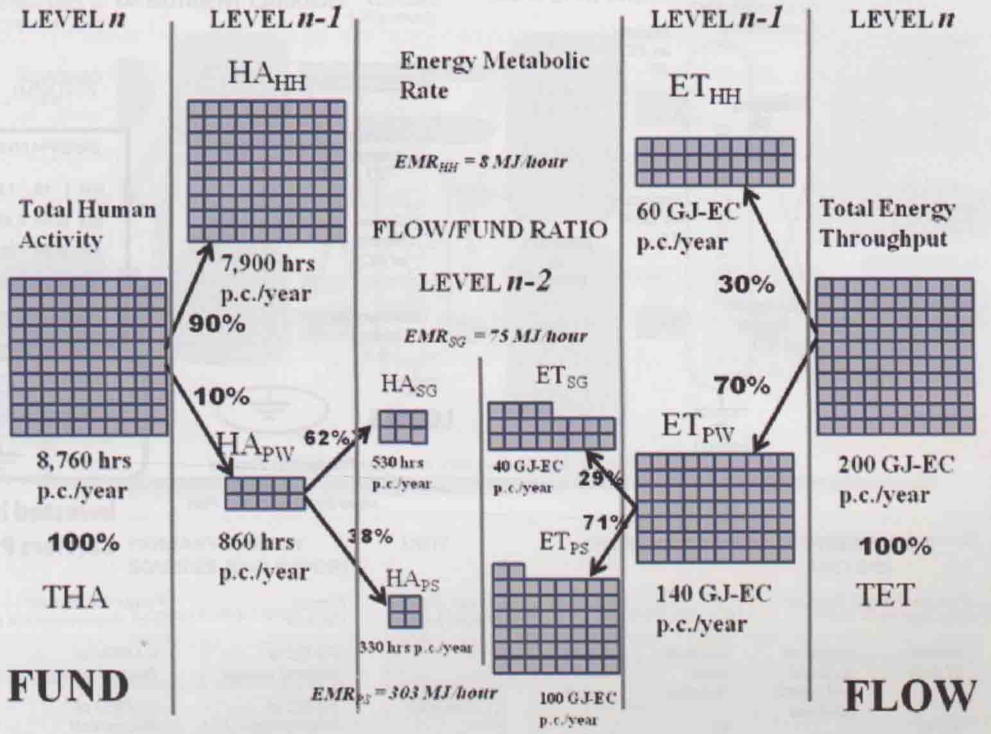
This step involves the selection of relevant fund elements and their quantification across the various functional compartments of the system (defined in the first step). In the case studies of this report, three fund elements are selected - human activity, power capacity, and managed land - and assess 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

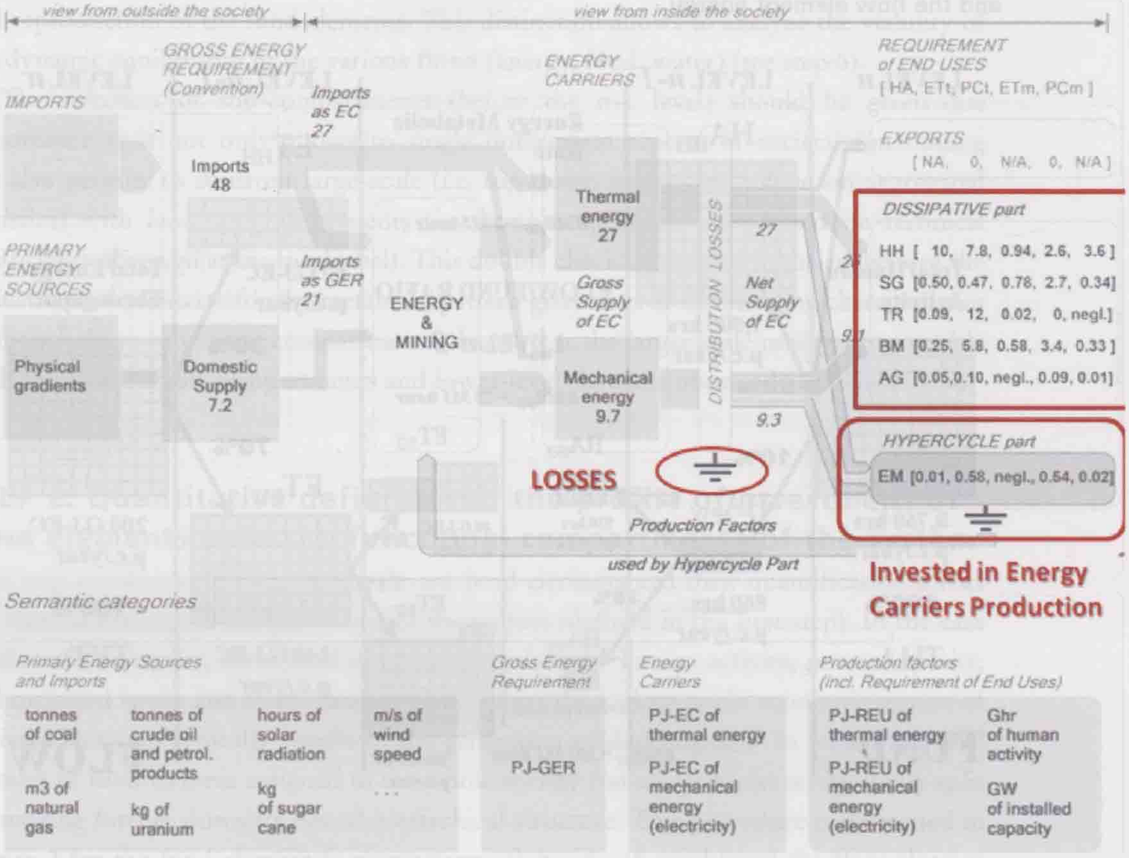


STEP 3: Quantitative definition of the flows required for expressing the functions

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.