Energy Policy 120 (2018) 110–120

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# Scarcity in abundance: The challenges of promoting energy access in the Southern African region

François Diaz-Maurin[a,b,*], Zivayi Chiguvare[c,d], Gideon Gope[e]

[a] Institut de Ciencia i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona (UAB), Edifici Z, Campus UAB, Bellaterra (Cerdanyola del Vallès), 08193 Barcelona, Spain
[b] Center for International Security and Cooperation (CISAC), Stanford University, Stanford, CA 94305, USA
[c] Namibia Energy Institute (NEI), Namibia University of Science and Technology (NUST), Private Bag 13388, Windhoek, Namibia
[d] Department of Physics, Faculty of Science, University of Namibia (UNAM), Private Bag 13301, Windhoek, Namibia
[e] Department of Electrical and Computer Engineering, Namibia University of Science and Technology (NUST), Private Bag 13388, Windhoek, Namibia

ARTICLE INFO

*Keywords:*
Integrated analysis
Energy modelling
Scenario assessment
MuSIASEM
Energy poverty
Development

ABSTRACT

The paper deals with the challenges of energy access, efficiency and security as essential conditions to improve people's living in the Southern African region. It supports energy policies by providing material for an integrated assessment of alternative energy systems at national level. Taking the example of Namibia, the paper applies the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach to assess the energy systems and scenarios. Using historical data from 2000 through 2013, the authors initially characterize energy supply and demand conditions of Namibia. Subsequently they conducted simulation analyses to find out a desirable energy policy to promote energy access in Namibia through 2030 under various environmental and societal constraints. The simulation results reveal that sustainable energy access in remote areas can be better achieved by small-scale distributed renewable energy systems rather than by large-scale energy technologies. Moreover, the study shows that energy policies should adopt a broader perspective to face the challenges of sustainable energy access in countries of the Southern African region by designing alternative development pathways rather than focusing on implementing new energy technologies.

## 1. Introduction: the challenges of energy access

The objective of this paper is to contribute to existing methodologies used to promote energy access in the Southern African region. In particular, it seeks to provide evidence of the importance of dealing with the issue of scales and dimensions in assessments. Lack of energy access affects most developing economies but mainly concerns countries of the Southern African region (Hailu, 2012). Many studies have explained the socio-economic factors that act as obstacles to improve electricity access in energy deprived countries (for a review, see (Magnani and Vaona, 2016)). These factors include the remoteness of communities, the low consumption level in remote areas due to low income and high costs of distribution, and the lack of availability of human capital and financial capital. However, most of the literature concern case studies for which there is no agreement on the method to use to assess energy access scenarios (Hailu, 2012). Moreover, it has been observed that many of the policy recommendations made these studies generally fail to address the urban-rural energy divide, which in some cases can lead to counter-productive recommendations (Khennas, 2012). This can be explained by the difficulty to describe the complex patterns of demand and supply of energy in societies.

Moreover, socio-economic factors alone cannot explain the systemic lack of energy access. To improve the understanding, these factors must be mapped against problems of availability and access to natural resources. Energy access is neither only a socio-economic problem, nor only a resources problem. It is both. Socio-economic factors prevent these countries from being able to improve the performance of their energy supply sector. Conversely, the difficulty in exploiting both renewable and non-renewable energy resources and even in securing energy imports prevent the same countries from improving the consumption of energy demand that would support economic development. Energy access is one further example of the complex relations between production and consumption of energy organizing human societies. This complexity calls for adopting a specific set of rules for the quantitative assessment of energy access scenarios.

Policy-relevant and technically-robust assessment from a complex systems approach cannot rely on the use of simple models, given that precise quantification cannot be achieved in the context of uncertainty

* Corresponding author at: Center for International Security and Cooperation (CISAC), Encina Hall, C228, 616 Serra St, Stanford University, Stanford, CA 94305-6055, USA.
*E-mail address:* fdm@stanford.edu (F. Diaz-Maurin).

https://doi.org/10.1016/j.enpol.2018.05.023
Received 9 December 2016; Received in revised form 8 May 2018; Accepted 9 May 2018
0301-4215/ 

(Saltelli and Funtowicz, 2014). However, it is possible to characterize patterns by combining approximate assessments of the structural and functional characteristics of the metabolic system*[1] with benchmarks* used to define the system's behaviour—*e.g.*, the amount of energy consumed per unit of land use*. In so doing, it is then possible to represent general trends and highlight the existence of incompatibilities with external constraints* and/or the emergence of internal constraints*. As complexity cannot be addressed by simply adding further quantification, a sound approach to energy access needs to embrace complexity to better deal with uncertainty.

Other applications of the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach have been conducted to address issues of energy access in urban setting, specifically in informal settlements (Kovacic and Giampietro, 2017; Kovacic et al., 2016). But there lacks an application that deals with both urban and rural settings at local levels and that can map these patterns to an assessment of energy access scenarios at national level.

The paper is structured as follows: Section 2 introduces the approach of multi-scale integrated analysis used to assess energy access at national level. Section 3 provides background information and details on the data used for the selected case study of Namibia. Section 4 presents and discusses the results of the application of the integrated approach to the scenario assessment in Namibia as well as its limitations. The concluding Section 5 points at the policy implications over energy access in countries of the Southern African region, of performing an integrated assessment of their energy systems.

## 2. Method

### 2.1. Standard definition of the MuSIASEM approach

MuSIASEM is an accounting approach for the assessment of sustainability (Giampietro et al., 2014). In the standard definition of MuSIASEM, a society can be described by a hierarchical structure of functional compartments (see Fig. 1). The five lower-level functional compartments are:

- *Households*, which ensures the reproduction and maintenance of the population (sleeping, eating, chores, children and elderlies, leisure, etc.);
- *Services and Government*, which ensures the reproduction and maintenance of institutions (education, health, military, government, etc.);
- *Building and Manufacturing*, which ensures the reproduction and maintenance of the infrastructures;
- *Agriculture and Fisheries*, which ensures the reproduction and maintenance of the flows of food;
- *Energy and Mining*, which ensures the reproduction and maintenance of the flows of energy.

These functional compartments are very helpful to understand how human societies have self-organized their activities over the ages leading to strong metabolic patterns (Giampietro et al., 2012). For instance, after the industrial revolution, the massive use of fossil energy (Smil, 2017) made possible for human societies to move as much as possible resources from the productive sectors – also called "hypercyclic compartments*" in Fig. 1 – to the non-productive sectors – "dissipative compartments*" in Fig. 1 – which comprise households, services and institutions. This phenomenon of a (temporary) emancipation from land (Mayumi, 1991) and from other resources – mainly labour and energy – for the productive activities explains why Western societies have been able to rapidly increase their standard of living. Quantifying the metabolic patterns of societies using these functional compartments

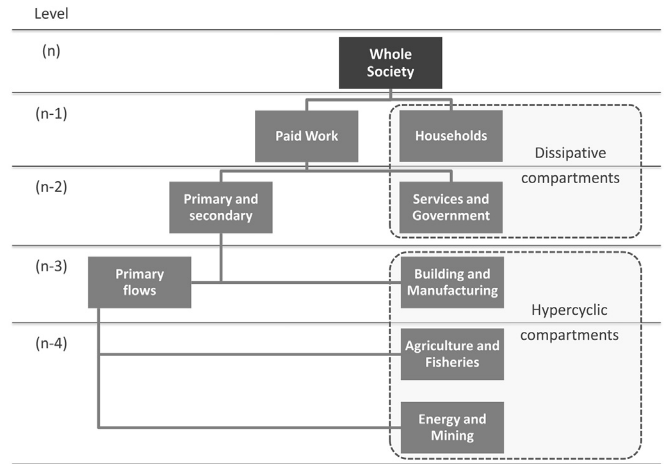


**Fig. 1.** The standard hierarchical structure of functional compartments of society used in MuSIASEM.
Source: own elaboration, based on (Giampietro and Bukkens, 2014b)

allows now to evaluate the possible constraints, for instance, on energy transitions and societal changes. Of particular interest for our paper, exploring the metabolic patterns of countries makes it possible to better understand the challenges of not having sufficient access to energy.

The MuSIASEM framework can be used for diagnostic as well as for simulation purposes (Giampietro and Bukkens, 2014). The application of the MuSIASEM approach consists of three steps: (1) diagnostic analysis, (2) simulation, and (3) scenario assessment. As a diagnostic tool, MuSIASEM is used to characterize existing metabolic patterns of the socio-economic systems under analysis. It provides integrated information on population, labour force, land (defined as fund elements*) and on food, energy, water and money (defined as flow elements*). The funds (*e.g.*, human activity*, managed land*) provide the relevant structural elements serving as external referent to the metabolic analysis. They provide information about "what the system *is*". Conversely, flows (*e.g.*, energy, food, water, money) provide information about "what the system *does*". Relative distributional changes of funds are much slower than for flows (Diaz-Maurin, 2016). For this reason, funds are considered as more stable than flows in the time horizon of a metabolic analysis, hence can be considered as external referent. The use of external referents is essential to avoid relying only on the use of flows that cannot capture the metabolic characteristics of society. For instance, the aggregate indicator *economic energy intensity* (EEI) measuring the energy consumption per unit of gross domestic product (GDP) (a flow/flow ratio) is inadequate—even misleading—in metabolic analysis because economic and biophysical variables are often correlated and their value is determined by characteristics which can only be observed across different scales (Fiorito, 2013; Sorman and Giampietro, 2011). By combining the allocation profiles of flows and funds across the different functional compartments (*e.g.*, households, services and government, energy and mining), a series of flow/fund ratios can be obtained. The flow/fund ratios characterize the rate (per hour of human activity) and density (per hectare of managed land) of the 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.

In the MuSIASEM methodology, the societal compartments are linked through forced relations of congruence across scales formalized by the profiles of allocation of the flows and funds, whereas the dimensions of analysis (*e.g.*, energy, land, human activity) are linked together through the flow/fund ratios (Giampietro et al., 2014b). Allocation of flows and funds, and flow/fund ratios are presented in the form of a multi-dimensional multi-scale table (see Table 1). The use of a metabolic table illustrates the system closure at each level—the sum of

[1] A definition of each term followed by an asterisk (*) can be found in the Glossary.

**Table 1**
Example of allocation of flows and funds, as well as distribution of flow/fund ratios in a hypothetical society using MuSIASEM.
Source: own elaboration (minor differences in the numbers are due to rounding). Retrieved from http://beta.thesustainabilitysudoku.info/shrt/vrewh

| Societal compartments | | Flows | | Funds | | Flow/Fund | |
|---|---|---|---|---|---|---|---|
| Level n-1 | Level n-2 | Food (kg grain-equiv p.c.) | Energy (GJ-GER p.c.) | Human activity (hrs p.c.) | Land use (ha p.c.) | Energy metabolic rate (MJ/h) | Food metabolic density (kg grains-equiv/ha) |
| Consumption | Households | 200 | 63 | 7450 | negl. | 8.4 | n/a |
| | Services and government | 100 | 120 | 960 | negl. | 330 | n/a |
| | Building and manufacturing | 100 | 150 | 220 | negl. | 1840 | n/a |
| | Agriculture | 600 | 0.45 | 1.5 | 0.13 | 810 | n/a |
| | Energy and mining | n/a | 330 | 2380 | 89 | 370 | n/a |
| Supply | Domestic supply | 640 | 120 | 8760 | 0.08 | 14 | 8000 |
| | Imports | 360 | 530 | n/a | n/a | n/a | n/a |
| | Virtual imports | n/a | n/a | 2250 | 89 | n/a | n/a |
| Whole society (Level n) | | 1000 | 650 | 8760 | 0.08 | 74 | 12,500 |

ote: Values of flow and fund elements are expressed on a per capita per year basis.

the variable of the lower-level categories matches the variable of the upper-level category—that is an essential property of metabolic analysis of societies (Giampietro and Bukkens, 2014).

As a simulation tool, MuSIASEM is used to assess the environmental feasibility*, the economic viability*, and the social desirability* of proposed scenarios. The feasibility refers to the compatibility of the system's behaviour with the external biophysical constraints* both on the supply side (availability of natural resources) and sink side (impact of waste and pollution). The viability refers to the congruence between the demand and the supply of flows across different compartments of society. The desirability refers to the congruence of the resulting metabolic pattern (a set of flow/fund ratios) at the level of end uses to reference values (benchmarks*) describing known 'types' of socio-economic systems. The need for congruence implies a 'Sudoku effect'* in the multi-scale representation of the metabolic pattern (Giampietro and Bukkens, 2015; Giampietro et al., 2014b). If energy carriers*, labour and land are invested in production they cannot be invested in consumption. The concept of metabolic pattern implies that production factors are required not only for producing goods and services, but also for consumption.

We provide in the Supplementary Methodology more details on the role of scales in MuSIASEM and its use for scenario assessment. We also provide a detailed description of the energy accounting method—the focus of the analysis—followed in order to map the energy flows on the demand side and on the supply side, as well as the various methods of accounting, adopted for the other elements considered in the analysis: human activity*, managed land*, and GDP*. The numerical application of these accounting methods is presented in Section 4 and further detailed in the Supplementary Results. Specific assumptions considered in the analysis are listed as comments in the supporting calculation spread-sheet available as Supplementary Data.

### 2.2. Adaptation of the MuSIASEM framework to energy access issues

The MuSIASEM approach is a 'multi-purpose grammar' in which *semantic* categories can be tailored to different 'issue definitions' and contexts, allowing a selection of indicators *à la carte*. The use of the concept of grammar* highlights the importance of semantics and proper definition of issues before quantification is performed and decisions are made. As a result, the MuSIASEM approach can be appropriated and adapted as a general scheme, for any decision-making and evaluation process, for taming complexity in a comprehensive manner (Adigüzel, 2016).

This paper applies the MuSIASEM approach to assess scenarios aiming at improving energy access. For this, the methodology is tailored to the specific study of energy access issues at national level. The use of semantic categories, makes it possible for MuSIASEM to adapt to various issues and contexts. Moreover, MuSIASEM is capable of remaining quantitatively consistent when dealing with datasets composed by information referring to different dimensions and different scales of analysis (Giampietro et al., 2014, 2012, 2013). We detail below how the MuSIASEM approach has been adapted to address energy access issues.

#### 2.2.1. Pre-analytical definition of functional compartments

The adaptation of MuSIASEM to energy access issues first consists in accounting for the urban-rural energy divide that exists over energy demand in the concerned countries when defining the functional compartments (see Section 1). In this case, the "whole society" (WS, at level n) is now described from within as organized around two main compartments "urban" and "rural" (at level n-1) as shown in Fig. 2. Then, we proceed to the sub-level description of each functional compartments. The "urban" compartment is described using the same compartments as in the standard definition of MuSIASEM described in Section 2.1, distinguishing productive from dissipative compartments. It should be noted that the energy and mining (EM) sector requires to be further detailed at lower levels (not shown in Fig. 2) given the importance of the mining sector in Southern African countries (see "ECONOMIC" sheet of the Supplementary Data). The "rural" compartment is described separating consumption activities (CA)—through

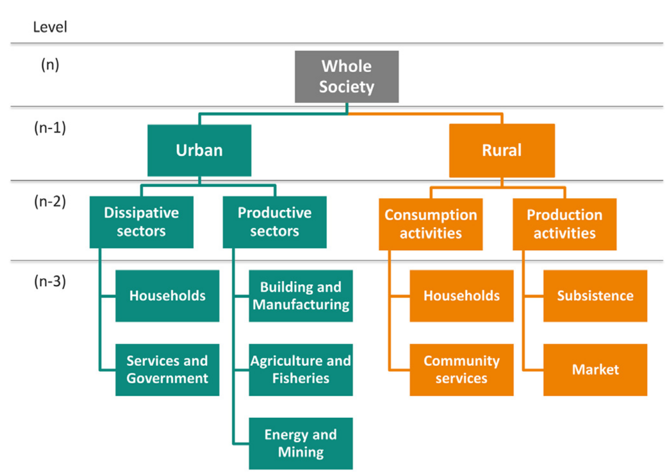


**Fig. 2.** Dendrogram of societal compartments for the metabolic analysis of Southern African countries.
Source: own elaboration.

"households" (HHr) and "community services" (CS)—from production activities (PA) through "subsistence" (SUB) and "market" (MKT) activities at level n-3.

This proposed definition of the societal compartments of Southern African countries serves the purpose of performing a metabolic analysis. Although there are interactions between the "sectors", the use of compartments helps to study the different *types* of activities and respond to the problems of joint-production (*e.g.*, the mining sector producing both energy and construction materials) and truncation (*e.g.*, how to define the "energy sector" of a developing country) found in energy analysis (Giampietro et al., 2013). The concept of functional compartment does not characterize where a sector is *spatially* located, but where its *end uses* are occurring, either within the urban or the rural population. For instance, the "agriculture and fisheries" sector concerns the food that is produced for the consumption by the urban population, although its processes are mainly located outside of urban areas. Consequently, the production of food (and energy) for the direct consumption of households within the rural population is accounted for in the "subsistence" compartment. On the other hand, the "market" and "community services" compartments within the rural compartment account for the productive activities and consumption activities, respectively, which occur outside of the households.

The choice of distinguishing urban and rural compartments is motivated by the fact that the energy metabolism of rural and urban populations is very different in Southern African countries, both on the supply side and on the demand side as shown in Section 4. An effective analysis of energy access therefore cannot be performed at aggregated national level, but rather requires separate characterization of both urban and rural metabolic patterns of demand and supply of energy.

#### *2.2.2. Assumptions and constraints*

The use of the proposed approach for studying energy access issues implies several assumptions and constraints. First, the formalization of the metabolic patterns requires the quantitative closure of the analysis. That is, if no information is available at some level (*e.g.*, the amount of electricity consumed in rural households), the analysis will need to infer this value by relations of congruence from the information obtained at other levels. Second, countries concerned by energy access issues are the most likely to have well-developed informal ("black market") and non-monetarized economic activities (subsistence and bargain). In this situation, any economic analysis would generate inconsistencies between monetarized and non-monetarized activities, especially between rural and urban areas. Energy access issues therefore require limiting the use of economic indicators in the analysis. Consequently, the simulation analysis and subsequent scenario assessment performed using the proposed approach are to be limited to a biophysical analysis (*e.g.*, energy, labour, land use) that can be used for describing both monetarized and non-monetarized economic activities. This type of biophysical analysis will be therefore unable neither to assess long-term scenarios using economic indicators (*e.g.*, GDP) nor to inform about the impact of a proposed scenario on, say, the price of electricity otherwise affected by an important number of variables. Specific assumptions and constraints considered for the case study are detailed in Section S.3.2 of the Supplementary Results.

## 3. Material and data

### *3.1. Background information on the energy situation in Namibia*

This paper uses the case of Namibia as a pilot country for the purpose of illustrating the proposed approach to energy access. This case study is part of the project "PARTICIPIA – Participatory Integrated Assessment of Energy Systems to Promote Energy Access and Efficiency" funded under the Cooperation Programme in Higher Education (EDULINK) of the African, Caribbean and Pacific Group of States (ACP), with the financial assistance of the European Union (EU). The project focused on the application of participatory integrated assessment of energy systems to promote energy access and energy efficiency in Southern Africa (Kiravu et al., 2017). Namibia is characterised by huge energy supply constraints. At the same time, the country's energy supply sector is relatively simple, with only very few types of local energy technology systems, and largely dependent on imports. This enables a relatively simple analysis that meets the objective of proposing a general scheme for the integrated assessment of energy access scenarios at national level.

The vast majority of the population in Namibia (2.4 million people) does not benefit from sustained access to modern energy (UN and World Bank, 2012). This concerns both rural and urban populations although unevenly affected—a phenomenon described as urban-rural energy divide (Khennas, 2012). In rural areas, where population is scattered over a large territory (Mendelsohn et al., 2002), communities are mainly relying on biomass fuelwood and paraffin uses for cooking and lighting, and have scarce access to imported gasoline for transportation. In addition, the vast majority of rural households are not connected to the electric grid, and access to renewable energy systems like photovoltaics (PV) systems remains marginal. In urban settings, although access to transportation fuels and services is much easier, about a third of the households do not have sustained access to electricity. About 70% of the urban population and about 18% of the rural population have access to electricity in Namibia, constituting a total access rate of about 40%. The rest of the total population of Namibia (60%) therefore still lacks access to electricity (SADC, 2010).

Rural populations also experience a relatively higher unemployment rate (30%) than urban population (26%) considering the economically active population in 2014 (NSA, 2015). In addition, the rural population has a higher dependency ratio than the urban population. Those socio-economic factors act as further constraints to development in rural areas. Consequently, like other countries in Southern Africa, rural population is rapidly declining as people move to urban areas where access to employment and basic needs seem more attractive—from 68% in 2000 to 54% in 2014 (NSA, 2014, 2015). If current trend is maintained, the urban population will represent the majority of the Namibia population by 2019. For the population still living in rural areas, subsistence remains the main source of livelihood.

Despite these issues, communities suffer from the paradoxical situation of scarcity in abundance that characterizes most countries of the Southern African region. Namibia's territory benefits from an abundance of resources, with one of the highest rates of annual solar radiation average on the planet exceeding 6 $kWh/m^2$ per day (von Oertzen and Bauer, 1998), high wind energy potential especially in the coastal areas, and one of the largest uranium deposits worldwide estimated at about 5.3% of the world's deposits (OECD and IAEA, 2010). Yet, Namibia faces many technical and societal challenges towards achieving sustainable energy access especially on the supply side. To explore those challenges, the paper will apply the methodology presented in Section 2.

### *3.2. Data*

The data used for the study presented here were collected from secondary data. Main data sources are from the Namibia government agencies, including the Namibia Statistics Agency (NSA), the National Planning Commission (NPC), the Ministry of Mines and Energy (MME), the Ministry of Lands and Resettlement (MLR), and the Ministry of Labour and Social Welfare (MLSW). Other main sources of information used to collect data include the Namibia Energy Institute (NEI, formerly the Renewable Energy and Energy Efficiency Institute, REEEI) of the Namibia University of Science and Technology (NUST, formerly the Polytechnic of Namibia), the VTT Technical Research Centre of Finland (VTT), the United Nations Development Programme (UNDP) in Namibia, the United Nations Food and Agriculture Organization (FAO), and the World Bank. Data collected for the diagnostic analysis cover the

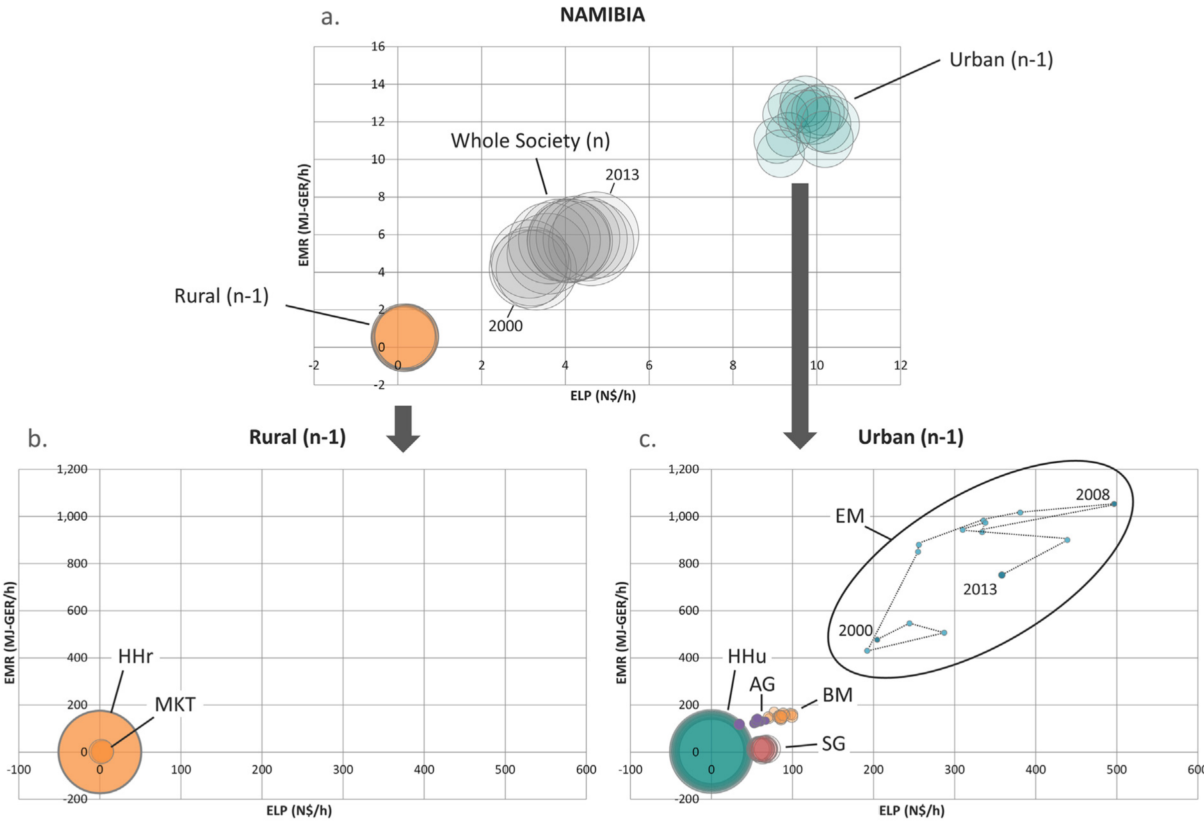


**Fig. 3.** Bubble chart of $EMR_i$ against $ELP_i$ across societal compartments in Namibia (Years 2000–2013). (a) Whole Society (level n); (b) Rural (n-1); (c) Urban (n-1). Note: Bubbles are scaled on the three charts relative to the size of HA in the compartment against the compartment of highest value (maximum values scaled to 100). Abbreviations used: AG, agriculture and fisheries; BM, building and manufacturing; ELEC, electricity (energy carrier); ELP, economic labour productivity; EM, energy and mining; EMR, energy metabolic rate; GER, gross energy requirement; HHr, households (rural); HHu, households (urban); h, hour; MJ, megajoule; MKT, market activities; SG, services and government.
Source: own elaboration.

period 2000–2013, although energy statistics for electricity generation are available until 2015.

In relation to the scenario analysis, data on the population projections were taken from NSA. Data on human activity was estimated by linearizing proportionally to the population projections and based on existing pattern of employment and other socio-economic characteristics. Data on land was also estimated by projecting the effects of the introduction of the new technologies on the existing allocation profiles. Monetary flows were not computed in the simulation because they can be significantly affected by domestic and international economic factors and policies. The simulation relies only on information referring to biophysical processes. Main data on the energy technologies collected for the scenarios come from pre-feasibility studies of the potential of concentrated solar power (CSP) (GESTO Energy Consulting, 2012) and biomass power from invader bush (WSP Environment and Energy, 2012), as well as information from the National Petroleum Corporation of Namibia on natural gas power (NAMCOR, 2013). For these alternative technologies, feasible targets have been considered in relation to resource requirement, but the feasibility of these targets in relation to the environmental loading on the sink side (waste and pollution) has been disregarded.

Collected projections and own estimates for the simulation cover the period 2014–2030, although projections on population are available until 2041. The choice of a time horizon of year 2030 for the simulation was made to capture the effects of the proposed changes in the energy supply technologies, while keeping the time horizon as short as possible given the rapid changes observed in the metabolism of developing countries, which may affect the accuracy of the analysis. The full dataset used in the analysis is available in the Supplementary Data.

## 4. Results and discussion

The study focuses on the challenges posed to the energy supply sector in Namibia with a focus on electricity generation. The study intends to support social deliberation and policies on energy access, efficiency and security, by providing an integrated assessment of alternative energy systems at national level. The integrated analysis of the energy metabolism in Namibia consists in performing (i) a diagnostic analysis characterizing the current energy mix both on the demand and supply sides, and the current metabolic pattern of Namibia by means of a set of flow/fund ratios; (ii) a simulation running scenarios of possible changes to the existing energy mix based on selected policy options considered by the Government of Namibia, and (iii) a scenario assessment of these selected options in relation to the three criteria of sustainability—feasibility, viability and desirability (Section 2.1).

### 4.1. Diagnostic analysis (2000–2013)

Societies are organized around patterns of production and consumption of resources, material goods and services. A diagnostic analysis seeks to measure these patterns in the form of a snapshot of the "current" situation. However, in rapidly changing economies like Namibia, a diagnostic analysis is better informed through the measurement of the evolution of the production and consumption over a significant time period. For this reason, we perform here a diagnostic analysis of Namibia for the period 2000–2013, in which we study the evolution of its patterns of production and consumption, as well as its population change over the same period. The diagnostic analysis aims at providing a robust assessment of how Namibia is "currently" organized around the production and use of resources, in particular energy, as well as its most recent trends. A diagnostic analysis from a societal metabolism perspective consists in quantifying the allocation of resources, opening up the energy supply matrix, and generating a series of indicators of energy use and demand that will serve as benchmarks for the scenario analysis. For reason of space, this section only presents these benchmarks. A detailed description of the results from the diagnostic analysis is provided in Section S3.1 of the Supplementary Results, including the allocation of funds and flows, a detailed analysis of the energy supply, and background information about the formalization of the flow/fund ratios used as indicators.

Fig. 3 summarizes the evolution of the metabolic patterns of Namibia over the period 2000–2013. The metabolic pattern is formalized in this figure by the use of two indicators: *economic labour productivity* ($ELP_i$) measuring the GDP generated per unit of human activity in compartment *i* (expressed in Namibian dollar per hour, N$/h)—on the X axis; and *energy metabolic rate* ($EMR_i$) measuring the amount of gross energy consumed per unit of human activity in compartment *i* (expressed in megajoule of gross energy requirement per hour, MJ-GER/h)—on the Y axis. Each one of these ratios provides a different piece of information that allows characterizing the metabolic pattern across the societal compartments and across the dimensions of analysis. The profile of $EMR_i$ is useful to characterize the level of access to energy. On that respect, the difference between the urban and rural categories is striking, with an average EMR of 12 MJ-GER/h against 0.52 MJ-GER/h, respectively, over the period of 2000–2013. Even comparing the two categories at the level of households (n-3), urban households exhibit an average EMR that is almost tenfold that of the rural households ($EMR_{HHu}$ = 3.0 MJ-GER/h against $EMR_{HHr}$ = 0.44 MJ-GER/h). This difference of energy access applies to both energy carriers, although access to electricity could not be characterised for community and subsistence activities of the rural category and has thus been considered as negligible in the analysis.

The profile of $ELP_i$ is useful to characterize the level of economic development. This indicator provides the same striking evidence that rural population generates much less economic value than urban population, with an average ELP of 0.17 N$/h against 9.7 N$/h, respectively. However, it should be mentioned that the ELP ratio does not capture the contribution of non-monetised activities which are a dominant source of livelihood in rural population. This illustrates the limits of using economic indicators in the study of developing countries that are not fully monetised, hence relying on ecological services for their survival. This makes the proposed characterization of societies using biophysical information in addition to monetary flows, very relevant (Giampietro et al., 2012). The existence of gradients in ELP between sectors—reflected by wages that are generally higher in the service sectors than in the productive sectors—helps to explain why with economic growth, job seekers tend to move from rural areas to urban areas, and then from the productive sectors to the service sectors. This continuous internal shift across sectors may result in shortages of labour in the productive sectors in the long run affecting the supply of food and energy to the population because the intensification of the productive sectors itself would be limited by a lack of energy supply. In the case of Namibia, though, the ELP in the services (SG) and productive sectors (AG and BM) are in the same range, with the exception of the EM sector. The EM sector indeed appears to be a total outlier in the metabolism of Namibia with average EMR and ELP values of, respectively, 803 MJ-GER/h and 316 N$/h (see Fig. S3.2 of the Supplementary Results).

Fig. 3 illustrates the significant differences that exist between the functional compartments with respect to energy consumption and economic labour productivity. This provides evidence for the validity of the pre-analytical definition of the societal compartments made for studying energy access issues (see Section 2.2). In the case of Namibia, results show that, for the whole society (at level n), both the EMR and ELP have significantly increased between 2000 and 2013—by 43% and 52%, respectively—at the same time population also rapidly increased by 22%, from 1.8 million to 2.2 million. This means that, overall, the energy consumption per hour (hence, "per capita") as well as the economic productivity have increased in Namibia between 2000 and 2013. Although the increase in energy consumption was made possible by an even larger dependence on imports, the increase in ELP translates to the fact that the whole economy has been able to increase its productivity by using this energy.

Fig. 3, however, provides striking evidence that the rural and urban compartments have very distinct metabolic patterns. This means that the improvements observed at the aggregated level between 2000 and 2013 are not equally distributed between the rural and urban compartments. Changes in the metabolic pattern of Namibia have been driven by the urban compartment, which in turn has been driven by the EM sector. The ability to observe distinct patterns represents the key advantage of a multi-scale analysis against an aggregated analysis (*e.g.*, macro-economic), which would not be able to "see" those distinctions because it does not address the problem of scales.

The specific evolution of the pattern of the EM sector between 2000 and 2013, observed in Fig. 3c, is explained as follows: EMR and ELP values for the EM sector over the period of the diagnostic analysis respectively ranged from 430 to 1053 MJ-GER/h and from 192 to 497 N$/h, implying high standard deviations and high standard errors (see Fig. S3.2 of the Supplementary Results). This very unstable pattern of the EM sector results from rapid changes in relation to international trade. Most of these changes observed have to do with the mining sector and not with the energy supply sector—the two sub-compartments making the EM sector. The energy supply sector is evolving more slowly and with a more stable pattern than what is observed for EM in Fig. 3c. For instance, the conversion ratio of gross energy requirement to energy carrier (GER/EC)—translating the efficiency of electricity generation in Namibia—has steadily increased by 35% between 2000 and 2013 (see "ENERGY-SUPPLY" sheet of the Supplementary Data), mainly due to the replacement of old technology and the installation of more efficient technologies.

Specifically, the values of ELP and EMR for the EM sector have been increasing (not in correlation though) between 2000 and 2008, when they started to decline following the same unstable pattern. The year 2008—corresponding to the maximum values of both ELP and EMR—represents a peak in the exports of mining products. Mining products exported from Namibia concern mainly unworked diamonds and uranium ores and concentrates. In 2008, Namibian exports of diamonds to the United Kingdom, and of uranium ores to Canada, the United States, China, and France peaked, reaching, respectively, 20% and 25% of the total revenues from exports outside the Southern Africa region (SACU, 2010). This translated into a high contribution of the mining activities to the national GDP (17.2%, see "data ECON" sheet of the Supplementary Data), with diamond mining and uranium mining contributing to 8.5% and 5.9%, respectively. This, in turn, led to a sharp increase of ELP as compared to 2007 as observed in Fig. 3c. However, the mining industry in Namibia has been immediately affected by the global financial crisis which started in 2008. In 2009, the country experienced a negative annual real GDP growth (−1.1% (OECD, 2014))—for the first time since it gained independence in 1990—which has been mainly due to a loss in revenues from mining exports, whose contribution to the GDP dropped to 10.9% in that year (see "data ECON" sheet of the Supplementary Data). During the same year, the Southern African region experienced a slightly less negative growth (−0.5%), whereas Africa remained with a positive growth of +6.5% (OECD, 2014). This demonstrates the high dependence on export revenues of the Southern African region, and of Namibia in particular, which adds to the problem of sovereignty given the issue of energy security (see Tab. S3.4 of the Supplementary Results). Namibia then experienced a reduction of its mining activities until 2011, which can be explained by the sustained global economic crisis and the very unstable commodity international markets.

### 4.2. Simulation (2014–2030)

Building upon the diagnostic analysis characterizing the metabolic patterns of Namibia, a simulation assessing the effects of proposed energy solutions on the metabolic pattern over the period 2014–2030 was conducted. The numerical application of the simulation mainly consists in updating the diagnostic analysis by introducing targets and projections in the energy supply matrix and in the metabolic table, in order to characterize the changes on the metabolic pattern of Namibia. The simulation is based on an energy scenario from the supply side with the objective of increasing energy security in Namibia. We investigate the potential of local energy supply from three alternative energy technologies: natural gas power from the Kudu gas field, CSP and biomass power from invader bush. These technologies respond to distinct energy needs. Natural gas power and CSP will be connected to the national electricity grid, thus, they will respond to the consumption of urban population. Biomass power will be connected both to the national grid and to mini-grids—through decentralised power stations connected to small isolated power line networks supplying several households, buildings or machinery—thus increasing energy access of the rural population. Other solutions to energy access in rural areas, such as energy shops, solar PV power and pumping (Schultz and Schumann, 2007) have not been considered in detail, although they are computed in the simulation. Clearly, other combination of energy technologies could be considered for building alternative scenarios. The main objective here is to see whether the methodology proposed can be applied to the assessment of energy access in countries of the Southern African region.

The increasing dependence on foreign imports of fuels and electricity, as shown in the diagnostic analysis (see Section 4.1), is the main driver behind the Strategic Plan 2012–2017 launched by the Ministry of Mines and Energy of Namibia (MME, 2012). This issue is even more strategic for the country given the prospects of possible constraints on the ability to secure imports of electricity from the Southern African Power Pool (SAPP) in the future due to the increasing consumption of South Africa (NamPower, 2014). For this reason, this simulation focused on the potential scenarios in relation to the supply of electricity. However, the expected demand of fuels based on the updated metabolism is also computed to complete the simulation from the energy-supply side.

The energy-supply scenario was built upon the following targets regarding the introduction of alternative energy technologies:

1. For gas-fired power generation, an 885 MW capacity Combined Cycle Gas Turbine (CCGT) power plant fuelled by natural gas from the Kudu field and starting operation in mid-2017 (after (NAMCOR, 2013; Rämä et al., 2013));
2. For CSP, 25 MW capacity installed per year starting in 2017, reaching a total installed capacity of 350 MW by 2030 (after (GESTO Energy Consulting, 2012; Rämä et al., 2013));
3. For biomass power generation from invader bush, 25 MW capacity installed per year in urban areas and 0.25 MW small scale capacity installed in rural areas per year, reaching a total installed capacity of about 350 MW by 2030 (after (DRFN, 2010; WSP Environment and Energy, 2012)).

Given it was still not clear at the time of writing this article how the Namibia government will pursue the development of these three alternative energy technologies, we considered them all in combination for building the simulation. Results of the energy-supply scenario are summarised in Table 2. We then performed the simulation of the metabolic table of end uses for the various compartments. Results of the simulation of end uses are provided in Table 3. We provide in Section S3.2 of the Supplementary Results a detailed description of the assumptions and constraints considered for conducting the simulation.

### 4.3. Scenario assessment (year 2030)

Based on the results from the simulation, we now perform the scenario assessment considering the three criteria of sustainability—feasibility, viability and desirability—as defined in Section 2.1. As the simulation is based on a scenario from the energy supply side, the feasibility of the resulting metabolism is therefore inherent, *i.e.*, the energy-supply scenario and associated end uses are compatible with the boundary conditions of the local environment. However, in relation to the consumption of fuels, although energy access has been increased, in particular in rural areas, the problem of energy security remains active in this simulation, with Namibia still largely dependent on imports of fossil fuels. According to the simulation, net imports of fuels are expected to increase by 70% compared to 2015, to reach a total of about 2300 metric kilotons (ktons) per year by 2030. In relation to supply of electricity, the simulation shows a surplus of electricity generated compared to the expected demand (45,500 terajoule of energy carrier (TJ-EC) vs. 26,100 TJ-EC in 2030, see Tables 2 and 3). This indicates that about 19,400 TJ-EC (5400 gigawatt hours (GWh)) of electricity would become available annually for export under the expected metabolism of year 2030. This corresponds to about 770 MW of the capacity of the Kudu power plant that would remain available for export, assuming the other alternative energy technologies are deployed as simulated in the scenario. In relation to land, the important changes observed in the land allocation between the compartments (Table 3) are due to the transfer of freehold land for agriculture and tourism activities to other types of "end uses" including government agriculture, resettlement, urban sprawling, deforestation and alternative energy sources. Overall, the total managed land[*] is expected to increase by 0.7% as compared to 2013, reaching 69.4 million hectares by 2030, out of the 82.4 million hectares of total land cover in Namibia.

In relation to viability constraints, the metabolic table of end uses was computed maintaining internal congruence among scales (compartments) and among dimensions (relative allocation of energy flows and human activity). In addition, the simulation of the updated internal requirements of human activity (labour) in the energy supply sector (51 million hours per year (Mhrs/y)) is compatible with the expected labour requirement in this sector from the demand side (60 Mhrs/y), despite the additional operating and maintenance labour required (11 Mhrs/y) after the introduction of alternative energy sources compared to 2013. The proposed scenario therefore can be considered as viable.

Last, as previously mentioned, this type of analysis cannot assess in absolute terms the desirability of a given scenario without the involvement of stakeholders and, from a larger perspective, society. Nevertheless, it is possible to compare the changes on the metabolic pattern against known benchmarks from other countries and/or previous patterns. From Table 3, we see that the flow/fund ratios—EMR, EMR-Fuels, and EMR-Elec—have increased by 18%, 17% and 20% respectively at the level of the whole society compared to the year 2013. These changes at the aggregated level are due to the important increase of those energy metabolic rates in the rural category (the slight reduction of the energy metabolic rates in the urban category is due to the rounding of flow and fund values considered in the flow/fund ratios). Yet, when comparing the simulated energy metabolic rates of Namibia for year 2030 to those of South Africa in year 2009 ((Diaz-Maurin, 2013; Diaz-Maurin et al., 2014)– see also "data SIMULATION" sheet of the Supplementary Data), Namibia will remain largely below its neighbour country (−60%, −70% and −46% respectively). This comparison indicates that energy access in Namibia is likely to remain a critical issue in the decades to come, despite attempts to develop—and eventually successfully implement—a strategic plan of alternative energy solutions.

**Table 2**
Simulated energy supply matrix of Namibia (Year 2030).

| Primary energy sources / Imports | | Gross energy requirement (GER) | | | | Gross supply of EC (GSEC) | | Input of EC (Hypercycle) | |
|---|---|---|---|---|---|---|---|---|---|
| **Level n-5** | **Level n-6** | **Natural resources (biophysical units)** | | **Primary energy (thermal equivalent)** | | **Fuels (TJ-EC)** | **Electricity (TJ-EC)** | **Fuels (TJ-EC)** | **Electricity (TJ-EC)** |
| **Local supply** | Hydro | 900 (+165%) | MW | 52,900 (+295%)* | TJ-GER | n/a | 14,400 (+213%) | negl. (n/a) | negl. (n/a) |
| | Biomass (wood charcoal) | 256 (+86%) | ktons | 7600 (+192%)* | TJ-GER | 7600 (+90%) | n/a | 500 (+85%) | negl. (n/a) |
| | On-grid wind | 44 (n/a) | MW | 351 (n/a) | TJ-GER | n/a | 96 (n/a) | negl. (n/a) | negl. (n/a) |
| | *On-grid solar (PV + CSP)* | *350 (n/a)* | *MW* | *160 (n/a)* | *TJ-GER* | *n/a* | *43 (n/a)* | *negl. (n/a)* | *negl. (n/a)* |
| | *Biopower (invader bush)* | *2800 (n/a)* | *MW* | *31,400 (n/a)* | *TJ-GER* | *n/a* | *8500 (n/a)* | *0.86 (n/a)* | *negl. (n/a)* |
| | *Natural gas (Kudu CCGT power plant)* | *1.3 (n/a)* | *Bcm* | *47,800 (n/a)* | *TJ-GER* | *n/a* | *22,300 (n/a)* | *3.1 (n/a)* | *0.10 (n/a)* |
| | Off-grid (wind + PV) | 12 (+102%) | MW | 40 (+146%)* | TJ-GER | n/a | 11 (+100%) | negl. (n/a) | negl. (n/a) |
| | **Sub-total** | **n/a** | | **140,200** (+776%)* | **TJ-GER** | **7600** (+90%) | **45,400** (+887%) | **510** (+89%) | **0.10** (n/a) |
| **Imports as GER (*i.e.* as primary energy)** | Fossil fuels (for electricity generation) | 3.3 (−55%) | ktons | 450 (−27%)* | TJ-GER | n/a | 120 (−43%) | 1.2 (−52%) | negl. (n/a) |
| **Imports as EC (*i.e.* as secondary energy)** | Fossil fuels | 2300 (+209%) | ktons | 71,600 (+190%)* | TJ-GER | 71,600 (+88%) | n/a | n/a | n/a |
| | Electricity (from SAPP) | n/a | | 0 (−100%)* | TJ-GER | n/a | 0 (−100%) | n/a | n/a |
| | **Sub-total** | **n/a** | | **71,600** (+30%)* | **TJ-GER** | **71,600** (+88%) | **0** (−100%) | **n/a** | **n/a** |
| **Whole energy sector (n-4)** | | **n/a** | | **212,200** (+196%)* | **TJ-GER** | **79,100** (+88%) | **45,500** (+199%) | **510** (+89%) | **0.10** (n/a) |

Note: New alternative energy sources are emphasized. Percentage changes against the reference year (2013) are indicated between brackets. “n/a” indicates that the comparison is not possible either because the value for the reference year was null or negligible. (*): Values related to primary energy for the reference year were corrected applying the same GER/EC-Elec ratio of 2.92 for year 2030, translating a higher efficiency in electricity generation. See Supplementary data.

**Table 3**
Simulated metabolic table of allocation of funds, flows and energy metabolic rates in the various societal compartments of Namibia (Year 2030).

| Societal compartments | | | Flows | | | Funds | | Flow/fund ratios | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Level n-1** | **Level n-2** | **Level n-3** | **Gross energy (TJ-GER)** | **Fuels (TJ-EC)** | **Electricity (TJ-EC)** | **Human activity (Mhrs)** | **Land uses (1000 ha)** | **EMR (MJ-GER/h)** | **EMR-Fuels (MJ-EC/h)** | **EMR-Elec (MJ-EC/h)** |
| **Urban** | **Dissipative sectors** | Households | 28,600 (+82%)* | 13,100 (+83%) | 5300 (+82%) | 13,580 (+84%) | 1800 (+82%) | 2.1 (negl.)* | 1.0 (negl.) | 0.4 (negl.) |
| | | Services and government | 11,700 (+58%)* | 1800 (+54%) | 3400 (+60%) | 1300 (+58%) | 1400 (+4%) | 9.1 (negl.)* | 1.4 (negl.) | 2.6 (negl.) |
| | **Productive sectors** | Building and manufacturing | 34,800 (+61%)* | 19,300 (+62%) | 5300 (+61%) | 290 (+61%) | 38 (+60%) | 120 (negl.)* | 66 (negl.) | 18 (negl.) |
| | | Agriculture and fishery | 20,500 (+51%)* | 19,000 (+50%) | 500 (+56%) | 180 (+50%) | 7100 (−71%) | 114 (negl.)* | 106 (negl.) | 2.7 (negl.) |
| | | Energy and mining | 33,400 (+50%)* | 11,200 (+50%) | 7600 (+51%) | 60 (+50%) | 3400 (+36%) | 557 (negl.)* | 186 (negl.) | 126 (negl.) |
| | **Sub-total** | | **129,000** (+60%)* | **64,400** (+59%) | **22,100** (+61%) | **15,400** (+79%) | **13,700** (−53%) | **8.4** (−10%)* | **4.2** (−11%) | **1.4** (−10%) |
| **Rural** | **Consumption activities** | Households | 10,600 (+141%)* | 10,300 (+136%) | 95 (n/a) | 11,000 (+18%) | 32,400 (+10%) | 1.0 (+104%)* | 0.9 (+100%) | 0.0087 (n/a) |
| | | Community services | incl. in HHr | incl. in HHr | incl. in HHr | 320 | incl. in HHr | – | – | – |
| | **Production activities** | Subsistence | incl. in HHr | incl. in HHr | incl. in HHr | 110 (negl.) | 760 (−6%) | – | – | – |
| | | Market | 4400 (+120%)* | 4400 (+121%) | incl. in HHr | 920 (+10%) | 22,500 (+145%) | 4.8 (+101%)* | 4.7 (+100%) | – |
| | **Sub-total** | | **15,000** (+134%)* | **14,700** (+130%) | **95** (n/a) | **12,300** (+17%) | **55,700** (+41%) | **1.2** (+100%)* | **1.2** (+96%) | **0.0078** (n/a) |
| Losses (Level n) | | | 11,400 (+200%)* | negl. | 3900 (+202%) | n/a | n/a | n/a | n/a | n/a |
| **Whole society (Level n)** | | | **155,400** (+72%)* | **79,100** (+69%) | **26,100** (+74%) | **27,700** (+45%) | **69,400** (+0.7%) | **5.6** (+18%)* | **2.9** (+17%) | **0.9** (+20%) |

Note: Percentage changes against the reference year (2013) are indicated between brackets. "n/a" indicates that the comparison is not possible either because the value for the reference year was null or negligible. (*): Values related to primary energy and EMR for the reference year were corrected applying the same GER/EC-Elec ratio of 2.92 for year 2030, translating a higher efficiency in electricity generation. See Supplementary Data.

### 4.4. Limitations

The use of the MuSIASEM framework presents several limitations both general to the methodology and specific to its application to energy access issues (see also Section 2.2 on the constraints and assumptions). First, given MuSIASEM includes a semantic framing of the situation, it requires to be conducted on a case-specific approach. As a result, the framework does not allow a full generalization of the approach to address an issue from a global perspective. Second, MuSIASEM, which is not a model, requires bringing together analysts able to apply the approach and experts in the issues under study. This requires a genuine commitment to holistic analysis and interdisciplinarity in the practice of science for policy advice (Kiravu et al., 2017). Moreover, the application of MuSIASEM is relatively data intensive and requires ensuring quantitative closure across scales of analysis.

As far as the limitations specific to this application of MuSIASEM to issues of energy access, the approach assumes fixed-proportion technologies. Fixed-proportion is valid at national level of analysis but may generate problems at lower level of analysis, due to possible changes in the relative use of resources. That is, the evolution of the flow/fund ratios observed between 2000 and 2013 (Section 4.1) could occur also in the long run as resources move from less productive sectors to more productive sectors, or from productive sectors to services and households. Besides, the relative "quality" of funds is ignored in the analysis. Urban and rural population may present different labour productivities. Similarly, the amount of human-made capitals used on urban land would be different than on rural area. In a more formal analysis, it may be necessary to distinguish between urban and rural lands.

## 5. Conclusion and policy implications

Reducing 'energy poverty' in developing countries has become one of the most pressing priorities at international level, to the extent that it has been recognised as the "missing development goal" by the Food and Agriculture Organization of the United Nations (FAO, 2012). The issue of energy access has received increasing scrutiny at energy policy level (Srivastava and Sokona, 2012) and its consequences have been discussed under the concept of energy (in)justice (Jenkins et al., 2016; Magnani and Vaona, 2016; Sovacool and Dworkin, 2015). This issue concerns all countries of the Southern African region, although they are very unequally affected (Hailu, 2012). To address this problem, a number of Southern African States have set aside optimistic, individual country- and regional-level energy access targets, with a number of them putting forth 100% access targets in electrification, modern fuels and/or mechanical power (IRENA, 2015).

Aggressive targets on energy access imply a situation of forced energy transition in Southern African countries. However, conventional energy technologies and deployment approaches are said to be insufficient to eliminate energy poverty in Africa (Agbemabiese et al., 2012). Moreover, the development of renewable energy technologies in Southern Africa does not necessarily guarantee that these resources would be properly used to develop energy systems that are accessible equally to all social actors involved and that would offer an endogenous development pathway to the communities concerned. Many of these technologies may remain as costly propositions and systems, and which would remain unused in the day-to-day lives of the people they intend to help. For this reason, it is essential that societies undergoing an energy transition have available effective methods of energy analysis, energy planning and procedures of governance.

Energy policies become more relevant where Southern African states have adopted energy access targets because it is possible to measure and monitor progress towards these goals (Hailu, 2012). But conventional indicators or metrics are not able, *per se*, to capture progress on energy access since this analysis would require simultaneous consideration of multiple dimensions (Bhanot and Jha, 2012). Yet, efforts towards developing more effective integrated analysis have not been made (Hailu, 2012). It is therefore crucial to develop coherent and holistic assessment methods and governance procedures, across different scales, for policy support in the Southern Africa region.

The integrated analysis presented in this paper illustrates how to properly account for internal and external constraints in energy scenarios. The study shows that the development of alternative energy sources is limited by economic costs, spatial constraints, resources availabilities and/or insufficient institutional establishments. In addition, the study reveals that it is not only the supply of large-scale energy technologies that can lead to sustainable energy access in Namibia. Rather, small-scale distributed renewable energy systems offer considerable potential which should be assessed, especially so for energy access in remote areas in Namibia and elsewhere. Consequently, rather than just focusing on alternative energy systems, this study claims that energy policies should also pay attention to alternative development pathways. This requires revisiting the conventional paradigms of clean energy and community development which are typically adopted by governmental and international institutions. Responding to the challenges of sustainable energy access in the Southern African region calls for more holistic approaches, as proposed in this paper.

## Acknowledgments

We wish to thank Mathias Moyo from the Electricity Control Board of Namibia and Lindroos Tomi from VTT Technical Research Centre of Finland for providing data and additional information on energy statistics in Namibia. We also thank Samuel Nakale from the National Planning Commission, Noddy Hipangelwa from the Ministry of Mines and Energy, and Sydney Pretorius and Deon Smith from the Big & Bold Company for providing valuable information on the national energy setting in Namibia during a workshop with local stakeholders in Windhoek on 5 February 2015. We thank the three anonymous reviewers for their valuable comments and suggestions that helped to clarify the paper's scope, approach and findings.

The paper was revised when F.D.M. was already at Stanford University. Although the paper received no specific funding from those institutions, F.D.M. acknowledges the support of the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 739850, as well as the MacArthur Foundation under the Nuclear Security Fellowship program of the Center for International Security and Cooperation (CISAC) at Stanford University.

The contents of this publication are the sole responsibility of the authors and can in no way be taken to reflect the views of the persons mentioned, the ACP Group of States, the European Union, or Stanford University.

## Author contributions

F.D.M. conceived the analysis, collected the data, performed the analysis, interpreted the results, and wrote the manuscript. Z.C. and G.G. provided input for the analysis, and comments and complementary information for the manuscript.

## Funding

The research leading to these results was supported by the project "PARTICIPIA – Participatory Integrated Assessment of Energy Systems to Promote Energy Access and Efficiency" coordinated by the Universitat Autònoma de Barcelona (UAB) in Spain and funded under the ACP-EU Cooperation Programme in Higher Education (EDULINK); a Programme of the ACP Group of States, with the financial assistance of the European Union, under grant agreement no. DCI-AFS/2013/320–333.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2018.05.023.

## References


Adigüzel, Y., 2016. Historical and critical review on biophysical economics. Biophys. Rev. Lett. 11 (02), 63–86. http://dx.doi.org/10.1142/S1793048016300012.

Agbemabiese, L., Nkomo, J., Sokona, Y., 2012. Enabling innovations in energy access: an African perspective. Energy Policy 47 (Suppl. 1), S38–S47. http://dx.doi.org/10.1016/j.enpol.2012.03.051.

Bhanot, J., Jha, V., 2012. Moving towards tangible decision-making tools for policy makers: Measuring and monitoring energy access provision. Energy Policy 47 (Suppl. 1), S64–S70. http://dx.doi.org/10.1016/j.enpol.2012.03.039.

Diaz-Maurin, F., 2013. The Viability and Desirability of Alternative Energy Sources: Exploring the Controversy over Nuclear Power. Universitat Autònoma de Barcelona, Spain. Retrieved from ⟨https://www.educacion.gob.es/teseo/mostrarRef.do?Ref=1052415⟩.

Diaz-Maurin, F., 2016. Power capacity: a key element in sustainability assessment. Ecol. Indic. 66 (C), 467–480. http://dx.doi.org/10.1016/j.ecolind.2016.01.044.

Diaz-Maurin, F., Cadillo Benalcazar, J., Kovacic, Z., Madrid, C., Serrano-Tovar, T., Giampietro, M., Bukkens, S.G.F., 2014. The Republic of South Africa. Chapter 14. In: Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F. (eds.), Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use (pp. 194–213). Routledge. (ISBN: 978-0-415-72059-5) ⟨http://www.routledge.com/books/details/9780415720595/⟩.

DRFN, 2010. Combating Bush Encroachment for Namibia's Development (CBEND) Project 2007–2010. Desert Research Foundation of Namibia (Retrieved from). ⟨http://drfn.org.na/projects/energy/cbend/⟩.

FAO, 2012. Press Release: Energy-Smart Food Systems Needed to Address Energy and Food Security in a Sustainable Way. Natural Resources and Environment Department, Food and Agriculture Organization of the United Nations, Rome, Italy (Retrieved from). ⟨http://www.fao.org/uploads/media/2012_January_pr_en.pdf⟩.

Fiorito, G., 2013. Can we use the energy intensity indicator to study "decoupling" in modern economies? J. Clean. Product. 47, 465–473. http://dx.doi.org/10.1016/j.jclepro.2012.12.031.

GESTO Energy Consulting, 2012. Pre-Feasibility Study for Establishment of a Pre-Commercial Concentrated Solar Power Plant in Namibia (Energy and Environment Partnership No. NA.2012.A.002.0) (p. 385). Ministry of Mines and Energy, Namibia. Retrieved from ⟨http://nei.nust.na/sites/default/files/projects/NA.2012.R.005.2.pdf⟩.

Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F. (eds.), 2014a. Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use. Routledge. (ISBN: 978-0-415-72059-5) ⟨http://www.routledge.com/books/details/9780415720595/⟩.

Giampietro, M., Bukkens, S.G.F., 2014. The multi-scale integrated analysis of societal and ecosystem metabolism. Chapter 2. In: Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F. (eds.), Resource Accounting for Sustainability Assessment: The Nexus Between Energy, Food, Water and Land Use (pp. 11–21). Routledge. (ISBN: 978-0-415-72059-5) ⟨http://www.routledge.com/books/details/9780415720595/⟩.

Giampietro, M., Bukkens, S.G.F., 2015. Analogy between Sudoku and the multi-scale integrated analysis of societal metabolism. Ecol. Inform. 26 (Part1), 18–28. http://dx.doi.org/10.1016/j.ecoinf.2014.07.007.

Giampietro, M., Bukkens, S.G.F., Aspinall, R.J., Ramos-Martin, J., 2014b. The Sudoku effect within MuSIASEM. Chapter 11. In: Giampietro, M., Aspinall, R.J., Ramos-Martin, J., Bukkens, S.G.F. (eds.), Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use (pp. 147–160). Routledge. (ISBN: 978-0-415-72059-5) ⟨http://www.routledge.com/books/details/9780415720595/⟩.

Giampietro, M., Mayumi, K., Sorman, A.H., 2012. The Metabolic Pattern of Societies: Where Economists Fall Short. Routledge. (ISBN: 978-0-415-58953-6) ⟨http://www.routledge.com/books/details/9780415589536/⟩.

Giampietro, M., Mayumi, K., Sorman, A.H., 2013. Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism. Routledge. (ISBN: 978-0-415-53966-1) ⟨http://www.routledge.com/books/details/9780415539661/⟩.

Hailu, Y.G., 2012. Measuring and monitoring energy access: decision-support tools for policymakers in Africa. Energy Policy 47 (Suppl. 1), S56–S63. http://dx.doi.org/10.1016/j.enpol.2012.03.065.

IRENA, 2015. Africa 2030: Roadmap for a Renewable Energy Future. International Renewable Energy Agency, Abu Dhabi (Retrieved from). ⟨http://www.irena.org/DocumentDownloads/Publications/IRENA_Africa_2030_REmap_2015_low-res.pdf⟩.

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016. Energy justice: a conceptual review. Energy Res. Soc. Sci. 11 (Supplement C), 174–182. http://dx.doi.org/10.1016/j.erss.2015.10.004.

Khennas, S., 2012. Understanding the political economy and key drivers of energy access in addressing national energy access priorities and policies: African perspective. Energy Policy 47 (Suppl. 1), S21–S26. http://dx.doi.org/10.1016/j.enpol.2012.04.003.

Kiravu, C., Diaz-Maurin, F., Giampietro, M., Brent, A.C., Bukkens, S.G.F., Chiguvare, Z., Yunta Mezquita, F., 2018. Proposing a master's programme on participatory integrated assessment of energy systems to promote energy access and energy efficiency in Southern Africa. Int. J. Sustain. High. Educ. 19 (3), 622–641. http://dx.doi.org/10.1108/IJSHE-04-2017-0048.

Kovacic, Z., Giampietro, M., 2017. Between theory and quantification: an integrated analysis of metabolic patterns of informal urban settlements. Energy Policy 100 (Suppl. C), S377–S386. http://dx.doi.org/10.1016/j.enpol.2016.06.047.

Kovacic, Z., Smit, S., Musango, J.K., Brent, A.C., Giampietro, M., 2016. Probing uncertainty levels of electrification in informal urban settlements: a case from South Africa. Habitat Int. 56, 212–221. http://dx.doi.org/10.1016/j.habitatint.2016.06.002.

Magnani, N., Vaona, A., 2016. Access to electricity and socio-economic characteristics: panel data evidence at the country level. Energy 103 (Suppl. C), S447–S455. http://dx.doi.org/10.1016/j.energy.2016.02.106.

Mayumi, K., 1991. Temporary emancipation from land: from the industrial revolution to the present time. Ecol. Econ. 4 (1), 35–56. http://dx.doi.org/10.1016/0921-8009(91)90004-X.

Mendelsohn, J., Jarvis, A., Roberts, C., Robertson, T., 2002. Atlas of Namibia: A Portrait of the Land and Its People. David Philip Publishers, Cape Town, South Africa (Retrieved from). ⟨http://www.uni-koeln.de/sfb389/e/e1/download/atlas_namibia/index_e.htm⟩.

MME, 2012. Strategic Plan 2012/13–2016/17. Ministry of Mines and Energy, Namibia (Retrieved from). ⟨http://www.mme.gov.na/files/pdf/mme-strategic-plan-2012_17.pdf⟩.

NAMCOR, 2013. Kudu Gas to Power Project. National Petroleum Corporation of Namibia. Retrieved from ⟨https://www.namcor.com.na/kudu-gas⟩.

NamPower, 2014. NamPower Annual Report 2014. NamPower, Namibia, pp. 140. (Retrieved from). ⟨http://www.nampower.com.na/public/docs/annual-reports/Nampower%20Annual%20Report%202014.pdf⟩.

NSA, 2014. Namibia Population Projections, 2011–2041. Namibia Statistics Agency, pp. 68. (Retrieved from). ⟨http://cms.my.na/assets/documents/p19dn4fhgp14t5ns24g4p6r1c401.pdf⟩.

NSA, 2015. Namibia Labour Force Survey 2014. Namibia Statistics Agency, pp. 102. (Retrieved from). ⟨http://cms.my.na/assets/documents/9b8e77842e3dec459407c2a76b9d79ab.pdf⟩.

OECD [dataset] African Economic Outlook 2014 – Namibia 2014 OECD Development Centre.

OECD and IAEA, 2010. Uranium 2009: Resources, Production and Demand (No. OECD NEA Publication No. 6891). OECD Nuclear Energy Agency and the International Atomic Energy Agency. Retrieved from ⟨https://www.oecd-nea.org/ndd/pubs/2010/6891-uranium-2009.pdf⟩.

Rämä, M., Pursiheimo, E., Lindroos, T., Koponen, K., 2013. Development of Namibian Energy Sector (No. VTT-R-07599-13). VTT Technical Research Centre of Finland, Espoo, Finland (Retrieved from). ⟨http://www.vtt.fi/inf/julkaisut/muut/2013/vtt-r-07599-13.pdf⟩.

SACU, 2010. Namibia Merchandise Trade Statistics Profile (2007–2009). Southern African Customs Union (Retrieved from). ⟨http://stats.sacu.int/v2CountryProfile.php⟩.

SADC, 2010. SADC Regional Energy Access Strategy and Action Plan (p. 178). SADC Energy Programme, with the support of EUEI. Southern African Development Community. Retrieved from ⟨http://www.euei-pdf.org/sites/default/files/field_publication_file/EUEI_PDF_SADC_Regional_Energy_Access_Strategy_Mar_2010_EN.pdf⟩.

Saltelli, A., Funtowicz, S., 2014. When all models are wrong. Issues Sci. Technol. 30 (2), 79–85. ⟨http://issues.org/30-2/andrea/⟩.

Schultz, R., Schumann, C., 2007. Off-Grid Energisation Master Plan for Namibia. Ministry of Mines and Energy, Namibia (Retrieved from). ⟨http://www.mme.gov.na/files/publications/541_off-grid-masterplan.pdf⟩.

Smil, V., 2017. Energy and Civilization: A History. MIT Press, Cambridge, MA (ISBN: 978-0-262-03577-4). ⟨https://mitpress.mit.edu/books/energy-and-civilization⟩.

Sorman, A.H., Giampietro, M., 2011. Generating better energy indicators: addressing the existence of multiple scales and multiple dimensions. Ecol. Model. 223 (1), 41–53. http://dx.doi.org/10.1016/j.ecolmodel.2011.10.014.

Sovacool, B.K., Dworkin, M.H., 2015. Energy justice: Conceptual insights and practical applications. Appl. Energy 142 (Suppl. C), S435–S444. http://dx.doi.org/10.1016/j.apenergy.2015.01.002.

Srivastava, L., Sokona, Y., 2012. Special Issue "Universal access to energy: Getting the framework right. Energy Policy 47 (Suppl. 1), 1–94. ⟨http://www.sciencedirect.com/science/journal/03014215/47/supp/S1⟩.

UN and World Bank, 2012. NAMIBIA: Rapid Assessment and Gap Analysis (Sustainable Energy for All (SE4ALL)) (p. 29). United Nations and World Bank. Retrieved from ⟨http://www.se4all.org/sites/default/files/Namibia_RAGA_EN_Released.pdf⟩.

D. von Oertzen R. Bauer Assessment of Solar and Wind Resources in Namibia (No. REEE1/98)1998 Ministry of Mines and Energy Namibia.

WSP Environment & Energy, 2012. Reports on Prefeasibility study for biomass power plant, Namibia. NamPower Partnership. Retrieved from ⟨http://www.nampower.com.na/Page.aspx?P=382⟩.