Applied Energy 107 (2013) 329–337

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Life cycle modeling of energy matrix scenarios, Belgian power and partial heat mixes as case study

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HIGHLIGHTS

- ▶ An LCA modeling approach is proposed for energy systems.
- ▶ A simplified Belgian energy system with and without nuclear power is optimized.
- ▶ A sustainability pathway is obtained from successive scenario optimizations.
- ▶ Reduction of GWP without nuclear power is limited under modeled conditions.
- ▶ Biomass potential implies an increase of toxicity and land occupation indicators.

ARTICLE INFO

Article history:
Received 6 July 2012
Received in revised form 16 February 2013
Accepted 19 February 2013
Available online 19 March 2013

Keywords:
LCA
Energy sustainability
Energy model
Exergy

ABSTRACT

The present paper introduces a life cycle modeling approach for representing actual demand of energy or energy intensive products delivered within a system (electricity, heat, etc.) for optimization of the energy mix, according to some of the available life cycle impact assessments (LCIAs). Unlike classical LCA modeling approach, the real amount of several energy products leaving the system and the interactions due to the presence of multi-output processes are considered within the present approach. As a case study, future scenarios are obtained for the Belgian electricity mix production and the heat mix potentially substituted by CHP or biomass, switching between abandoning or not power from nuclear energy. The possibility of using natural gas, biomass for cogeneration, wind power and solar photovoltaic energy are considered within the availability ranges of these resources. Finally, results are presented from successive optimizations according to the sustainability potential defined in a previous paper. A pathway to a more sustainable Belgian energy system is obtained. Finally it is concluded that under the modeling conditions and without nuclear energy it is not possible to obtain a reduction of GHGs and despite diminishing of non-renewable resource consumption, a rising of toxicity is obtained.

1. Introduction

1.1. Energy-economic models' limitations

Different kinds of energy-economic models have been proposed in the last 30 years. For top-down models the energy system is modeled from aggregated macroeconomic variables, and in the bottom-up models the energy system is modeled from the technologies and their relationship [1,2]. The MESSAGE energy model, a bottom-up kind, was developed in the 1970s and it was later linked with the MACRO model, which is a top-down macroeconomic approach [3,4]. MARKAL/TIME is similar to MESSAGE-MACRO and it was developed in Europe. Many other modeling approaches have been developed for different specific purposes like EnergyPlan, MARKAL-LITE, and eTransport, but all of them are still just economically driven [5–7].

It is the author's opinion that a functional environmental sustainability criterion should be included in such models. The classical economic approach is also affected by the variability of prices, market speculation and country's monetary and fiscal policies.

Alternatively, a life cycle approach provides a different perspective based on material accounting of flow exchange between techno-sphere and nature. Material accounting does not ignore economic issues. In fact monetary accounting could be used as constraint in the same way as environmental concern does in econometric models.

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http://dx.doi.org/10.1016/j.apenergy.2013.02.052

1.2. Life cycle analysis potential

Life cycle analysis (LCA) supplies the necessary framework for a resource and emission based accounting which underlies in most of sustainability quantification theories [8]. LCA goes as deep as possible in the production tree of the assessed process, inventorying all natural resources taken out from nature and all polluting substances emitted to the nature to run the process [9,10]. Life cycle inventories (LCIs) obtained are then used to calculate indicators like global warming potential (GWP), ecological foot print (EFP), Ecoindicator99 [11] and cumulative exergy demand (CExD) [12].

Life cycle analysis has been used in several researches to evaluate alternative energy transforming processes [13–15]. In such processes it is possible to assess natural resources consumption and pollution to compare them [16]. System perturbation analysis (SPA) [17], a life cycle based approach, focuses also on the variation of intermediate products and emphasizes the potential of by products to substitute parallel-generated products.

Comparing life cycle inventories of two or more equivalent products is meaningful only when small perturbations are considered so the mix of those products in the real life system can be supposed unaltered. Consequently significant penetration of any production method can alter its own life cycle performance. This issue is not significant in the case of products that are not consumed downstream in the model, but in the case of energy products or services it does is significant since energy is always consumed downstream in energy models.

This problem has been addressed by extrapolating on time technological improvements and predicting variation on energy mixes [18,19].

Another option is to take the life cycle analysis to a *meso* level by considering groups of related products and technologies or baskets of commodities [20]. In the case of energy it would be possible to model the energy system by means of aggregated technologies supplying energy intensive products. In this way it would be possible to consider downstream interactions in a meaningful way. However the computational structure of LCA does not consider multiple system outputs [21].

The present article will introduce a LC energy matrix modeling procedure derived from the matrix approach used for LCA model solving.

The issue of modeling multi-output technologies is approached in such a way that allocation could be avoided by considering co-products as part of produced energy mixes. This modeling feature implies substitution of similar products in the mix it is part of however, in contrast to environmental LCA, this substitution will occur according to the response of the model to the life cycle indicator used as objective function.

The primary goal is to model an energy matrix in its real dimension using average LCA data of energy technologies so it would be possible to optimize the system according to some of the LC environmental indicators. This LC energy modeling approach will contribute with a more realistic image of new technologies environmental suitability and its sustainability.

The proposed modeling approach is tested by modeling Belgium's energy matrix using LCA information and optimizing scenarios according to three LCA indicators: global warming potential (GWP), indirect cumulative exergy demand ($CExD_{ind}$) and the sustainability potential (S). The last two are defined by Rubio Rodríguez et al. [22]. The main idea is to obtain alternative scenarios to those generated by pure econometric models, and to assess the differences when optimization is driven by those three different indicators. This LCA model takes into account real amount of energy products generated by the system (heat and power in this case), thus it would be possible to obtain a picture of the LCIA variation, including the influence of co-product generation on the co-product mix.

2. Life cycle modeling for assessing energy matrix scenarios

The procedure that is presented within this section uses LCA data from the Ecoinvent database v2.0 [23]. The Ecoinvent database comprises consistent and coherent LCA datasets in a unified and generic form called EcoSpold [11].

Fig. 1 represents a simplified but quite comprehensive life cycle energy model where a demand of $\boldsymbol{P_1}$ (electricity mix) and $\boldsymbol{P_2}$ (heat mix) are satisfied. Table 1 lists the names and units of all processes in Fig. 1. In the figure, $\boldsymbol{P_i}$ (kg/year, tkm/year, kW h/year) designates the products or services (from now on only the term product will be used) generated in the processes $\boldsymbol{i}$ (UP $\boldsymbol{i}$, MN $\boldsymbol{i}$, MUP $\boldsymbol{i}$, LCI $\boldsymbol{i}$ and V $\boldsymbol{i}$). UP refers to unit processes where products are consumed (P), elementary flows are exchanged with nature (I^{in}) and a single product goes out. MN refers to virtual nodes where products of the same kind are mixed to form one single stream of its kind; no exchange with the environment occurs. MUP refers to processes with the same definition of UP except for the fact that it produces more than one output. LCI serves as virtual node containing life cycle inventory of the product it is associated (I^{out}) and are coming from outside the system under assessment. V is a virtual node introduce in this work to handle MUP but avoiding allocation by acting as substitute of an equivalent product mix.

$I^{in}\boldsymbol{i}$ represents the environmental impact vector made of $\boldsymbol{n}$ elementary flows coming from nature or going to nature, generated at UP $\boldsymbol{i}$ or MUP $\boldsymbol{i}$, where each elementary flow is referred to one unit of the output product $\boldsymbol{i}$. $I^{out}\boldsymbol{i}$ is of the same kind of $I^{in}\boldsymbol{i}$ but accounting for the life cycle inventory of the products coming from outside the modeled system. In Fig. 1 straight black arrowed lines represent product flows which are related to each other. Serpentine red arrowed lines symbolize the material exchange with the environment. The arrow direction is going out the unit process, because this exchange would result in an environmental impact.

The first step in solving the model in Fig. 1, is to calculate all flows rates in the chain to satisfy the demand, in order to calculate the life cycle inventory for the system and finally any life cycle indicator like the global warming potential (GWP) or the cumulative exergy demand (CExD).

The vector $\boldsymbol{P}$, containing values of flows from $\boldsymbol{P_1}$ to $\boldsymbol{P_{10}}$, is obtained by solving the equation system generated for finding the amount of each flow:

$$P = A^{-1}p^o \tag{1}$$

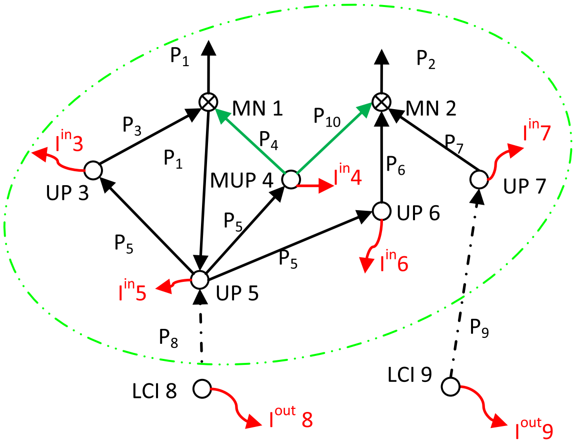

Fig. 1. Life cycle energy system modeling.