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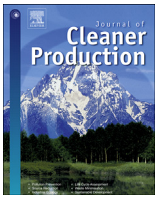

Note from the field

Integration of life-cycle indicators into energy optimisation models: the case study of power generation in Norway

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ABSTRACT

This work presents methodological advances in the integration of life-cycle indicators into energy system optimisation models. Challenges in hybridising energy modelling and Life Cycle Assessment (LCA) methodologies are summarised, which includes imbalances in electricity trade processes and double counting of emissions. A robust framework for the soft-linking of LCA and TIMES is proposed for application to the case study of power generation in Norway. The TIMES-Norway model is used, taking into account the base-case scenario with a time frame from 2010 to 2050. Results show that the life-cycle indicators implemented (climate change, ecosystem quality, and human health) evolve in accordance with the appearance of new power generation technologies. Thus, life-cycle impacts are linked to the entrance of new wind turbines from 2014 to 2035 and, from then on, to the new hydropower run-of-river plants.

1. Motivation and background

Assessments based on energy modelling usually fail in taking into account the environmental profile of energy systems. These modelling exercises are commonly founded on bottom-up optimisation models, where the TIMES model generator is one of the most used (Loulou et al., 2005a, 2005b). These recognised models have been developed from a techno-economic perspective and, even though they may include some environmental aspects by means of emission factors (direct emissions) and/or external costs, further methodological developments are required to cope thoroughly with the environmental dimension of energy systems. In this regard, Life Cycle Assessment (LCA) considers a much broader set of environmental factors, in terms of both processes included and type of impacts.

Herbst et al. (2012) pointed out that techno-economic, bottom-up models are useful but they cannot project net impacts and/or costs for the society from a holistic perspective. Concerning this, Pietrapertosa et al. (2009) included results coming from an LCA study related with the power generation system into the TIMES-Italy model, while Menten et al. (2015) evaluated the performance of a biofuel system in France using a life-cycle approach and a TIMES model. Similarly, Choi et al. (2012) concluded that the link between MARKAL (a previous version of TIMES) and LCA is promising and that it should be investigated thoroughly, while Pieragostini et al. (2012) developed a qualitative study on the benefits of LCA integration into energy optimisation models. Recently, Hertwich et al. (2015) presented the results of a complete LCA study of some electricity production technologies through a comparison between the business as usual and BLUE Map scenarios published by the International Energy Agency.

The first comprehensive experience regarding the methodological hybridisation of LCA and energy optimisation modelling was carried out within the framework of the NEEDS project to estimate the external costs of power generation (NEEDS, 2008, 2009). This hybridisation relies on the use of LCA flows to modify the processes in TIMES and monetise the impacts assuming extra costs (externalities) by using a third tool, ExternE (Bickel and Friedrich, 2005). Brown et al. (2013) used a similar approach by imposing fees to

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selected pollutants (greenhouse gases, NO_x, particulates, SO_2). Since LCA flows (rather than life-cycle impact profiles) are used, the analysis of the evolution of the life-cycle environmental indicators themselves is not addressed.

This paper aims to deeply integrate environmental indicators into the core of TIMES by using the LCA methodology to take into account both direct and indirect environmental burdens. The latter are difficult to allocate in a TIMES model and typically involve a large number of background processes. This methodological LCA-TIMES combination enriches the LCA approach by adding a prospective standpoint through techno-economic optimisation.

2. Methodological framework

Environmental modelling can benefit from the experiences in energy systems modelling (Ekvall, 2002). There are two different approaches to hybridising models: soft-linking and hard-linking. The former means that the results are transferred from one model to another, whereas the latter means that the models are merged becoming a single comprehensive model (Wene, 1996). In this work, soft-linking is considered. The analysis focuses on the electricity mix of the Norwegian energy system resulting from regular modelling, i.e. the base-case scenario. This scenario includes the whole portfolio of power generation technologies required for the Norwegian energy system to satisfy the energy service demand of all sectors (details are given in Table 1). It also includes several policy measures such as support to district heating plants, green certificates supporting new renewable power generation, and technology-specific and commodity-specific taxes.

2.1. *TIMES-Norway modelling assumptions*

TIMES-Norway is a model that represents the energy system of Norway. It includes the projections of energy services demands for the end-use transport, industry and residential sectors. TIMES-Norway is divided into 5 regions (formerly 7) and assumes a 4% global discount rate. The modelling horizon is from 2010 to 2050. The rationale, features, equations, structure and restrictions are the same as described in Loulou et al. (2005a, 2005b) for the TIMES model generator. Further details on the specific TIMES-Norway model/database can be found in Lind and Rosenberg (2013) and Lind et al. (2013).

Hydro and wind power technologies are modelled in detail by means of time slices which define the load curve of the electricity system and the availability factors of the resource. Due to political reasons, neither nuclear nor coal plants are included as potential investments. Regarding natural gas combined cycle (NGCC) plants, there is only one 420 MW plant (Kårstø), but it was dismantled in 2014 (production ceased in 2010). Minor combined heat and power (CHP) plants using natural gas and waste are installed. On the other hand, hydropower technologies currently generate ca. 95% of the electricity produced in Norway, with reservoirs (dams) accounting for approximately 70% and run-of-river (RoR) plants accounting for the rest. Power generation in reservoirs distinguishes between existing plants, new large plants and plants for increased capacity. New RoR plants are modelled considering two options depending on the investment costs: cheap (RoR I) and expensive (RoR II) (Lind et al., 2013).

2.2. *Life-cycle indicators for energy modelling*

The LCA methodology evaluates the potential impacts of a system for a wide set of impact categories regarding the whole life cycle of a product (ISO, 2006). The LCA of the power generation technologies included in the Norwegian portfolio is carried out to provide life-cycle indicators for implementation into the TIMES-Norway model. The inventories of the power generation technologies (processes) are based on the ecoinvent database (Dones et al., 2007; Weidema et al., 2013). Capital goods are included within the scope of the assessment. The functional unit of the study is 1 kWh of electricity produced by each technology.

Table 1 presents the list of technologies as well as the results of their damage assessment using the IMPACT 2002 + method (Jolliet et al., 2003). Three life-cycle indicators are evaluated: climate change (CC), ecosystem quality (EQ), and human health (HH).

2.3. *Other assumptions and challenges addressed*

There are two approaches to the combination of LCA and TIMES: endogenous and exogenous (NEEDS, 2009). On the one hand, in the endogenous approach, the TIMES model is expanded by means of the LCA datasets. On the other hand, in the exogenous approach, material and energy flows linked to the previous phases of the energy-related technologies (mining, construction, transport, etc.) are calculated separately through LCA. Therefore, in this study, an endogenous approach is followed: the selected life-cycle indicators are actually integrated into TIMES by introducing the cumulative burdens from the preceding LCA study.

For the base-case scenario in TIMES-Norway, no user constraints are considered to affect the life-cycle indicators after the reference year (2010). Hence, the electricity mix obtained is not affected by these new indicators. Otherwise, it would be necessary to create bounds for the CC, EQ and HH indicators according to some criteria. This is further explored in Section 3.

In contrast to previous studies that present detailed LCA studies based on predefined electricity mixes (Santoyo-Castelazo et al., 2014; Treyer et al., 2014), this work pursues an actual integration of LCA and TIMES in line with the work by Menten et al. (2015). In this work, a similar analysis to that of Menten et al. (2015) is

Table 1
Damage assessment results of the power generation technologies within the Norwegian portfolio.

	Climate change ($kg\ CO_2\ eq \cdot kWh^{-1}$)	Ecosystem quality ($PDF \cdot m^2 \cdot y \cdot kWh^{-1}$)	Human health ($DALY \cdot kWh^{-1}$)
Natural gas, combined cycle plant	5.78E-02	8.34E-03	3.56E-08
Mini CHP plant, allocation energy	4.66E-02	5.79E-03	2.87E-08
Municipal waste incineration plant	0.00E+00	0.00E+00	0.00E+00
Hydro, reservoir, non-alpine regions	6.65E-03	1.00E-03	4.93E-09
Hydro, run-of-river power plant	3.64E-03	7.55E-04	4.93E-09
Wind, < 1 MW turbine, onshore	1.38E-02	7.55E-03	2.03E-08
Wind, 1–3 MW turbine, onshore	1.46E-02	6.63E-03	2.00E-08
Wind, > 3 MW turbine, onshore	2.51E-02	1.67E-02	3.91E-08
Wind, 1–3 MW turbine, offshore	1.63E-02	6.97E-03	2.17E-08