Energy system analyses of the marginal energy technology in life cycle assessments

Mathiesen, Brian Vad; Münster, Marie; Fruergaard, Thilde

Published in:
SETAC Europe 14th Case Studies Symposium - Extended abstracts

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

Energy system analyses of the marginal energy technology in life cycle assessments

Brian Vad Mathiesen [1], Marie Münster [2] and Thilde Fruergaard [3]

[1, 2] Department of Development and Planning, Aalborg University, Fibigerstraede 13, DK-9220 Aalborg, Denmark, e–mail: bvm@plan.aau.dk; mynster@plan.aau.dk
[3] Institute of Environment and Resources, Technical University of Denmark, Bygningstorvet 115, DK-2800 Kongens Lyngby, Denmark, e–mail: thf@er.dtu.dk

1. Introduction

In life cycle assessments consequential LCA is used as the "state-of-the-art" methodology, which focuses on the consequences of decisions made in terms of system boundaries, allocation and selection of data, simple and dynamic marginal technology, etc.(Ekvall & Weidema 2004). In many LCA studies, the energy demand applied is decisive for the results. In this extended abstract, consequential LCA methodology is examined with electricity as the case. The aim is to answer three questions: Which are the expected vs. the actual marginal electricity production technologies and what may be the future marginal technology? How is the marginal technology identified and used today? What is the consequence of not using energy system analysis for identifying the marginal energy technologies? The use of the methodology is examined from three angles. First, the marginal electricity technology is identified in historical and potential future energy systems. Subsequently, key LCA studies of products and different waste flows are analysed in relation to the recommendations in consequential LCA. Finally, a case of increased waste used for incineration is examined using an energy system analysis model. The differences in applying energy system analysis compared to assuming a marginal electricity technology are illustrated. Through the analysis, the current recommended approach of consequential LCA is challenged. In the conclusions, recommendations for identifying affected technologies for consequential LCAs are made.

2. The historical and future marginal electricity in the consequential approach

In this section, it is analysed how the expected and actual marginal electricity technologies have developed. Consequential LCA is applied to historical and contemporary circumstances in order to evaluate the ability of the method to identify the technologies. As recommended focus is placed on the long-term marginal technology (Ekvall & Weidema 2004). The long-term marginal technology with increasing electricity demand is the installed capacity with the lowest long-term production costs implemented. On the other hand, the long-term marginal technology with decreasing electricity demand is the capacity removed with the highest short-term production costs when the demand decreases faster than the replacement rate of the production capacity. These capacities are described as the simple marginal electricity technologies. In (Ekvall & Weidema 2004) a more detailed approach is recommended in which the long-term marginal technology must also be able to adjust the production or production capacity according to the changes in the life cycle. In this paper the dynamic electricity marginal technology is the capacity able to meet the changes in demand minute-by-minute similar to the practise in (Weidema 2003;Weidema, Frees, & Nielsen 1999). The dynamic marginal technologies are a subset of the possible simple marginal technologies.

Two key types of data sources are used in the analysis. The first dataset consists of publications describing the long-term development of the Danish energy system. In these publications, the general development of demands, capacities, costs, etc., is outlined. Two types of publications are included. Official governmental energy plans and other energy plans from various organisations that includes costs and development trends. The publications enable the identification of a simple and a dynamic expected long-term marginal electricity applying the approach described above. The second dataset includes statistics of historical developments of the energy system, i.e. production, demand, capacities, etc. (Energistyrelsen - Danish Energy Authority 2006). With this dataset the actual marginal technology is determined as the installed capacity due to the increased demand in the period, i.e. according the recommendations in the consequential LCA methodology.

The question is what the expected marginal technology would have been, if we wanted to make an LCA at a given point in time from 1976 until now. In Table 1, the results of an analysis of ten different publications from 1976 until 2006 are presented. The publications include a reference energy system projection and most of them also a plan for a changed system. The first step is to identify the trend of the electricity market. This reveals that the expected rate of increased demand has become significantly lower since 1976 and continues to decline. The next step is to examine changes in capacities, i.e. the new or phased out capacities in the publications. In most publications, a simple and dynamic marginal technology can be identified in both a reference and in a proposed energy system. In the ten publications, the expected simple and dynamic marginal technology changes between many different technologies. In the plans for energy systems, the marginal electricity changes between coal-based power plants (PP) to combined heat and power production (CHP) units. The actual simple marginal technology in the 1990s was wind power, as the main long-term investments where made in this sector. In recent years, decentralised natural gas (Ngas) CHP units have been installed and capacity is now able to participate on the electricity markets. Compared to coal PP/CHP, these units seemingly have good abilities to compete on markets dealing with short-term changes and can be defined as the dynamic marginal at the moment. From 2005 until today, the main new capacity installed is coal CHP replacing coal PP and hence, coal CHP is the simple marginal technology at the moment, since it cannot compete with the Ngas CHP on the regulating market as explained above.

There are four main reasons for these and other discrepancies between the reference, the planned and the actual marginal technologies seen in a historical perspective. The first reason is that the objectives in the publications change over time. The second is that not all plans in the publications are implemented. The third is that the focus is placed on today's technologies in the publications and not on modified uses or potential future technologies. An example of this is the exclusion of Ngas CHP and renewable energy in the first publication analysed. Another example is the fact that CHP units in the governmental publications until today have been regarded as non flexible. The fourth reason is that mostly only one or few and low fuel price scenarios are used and that CO_2 quota prices have only been used from 2003. This has significant impacts on the investments made. This is especially visible in the differences in the marginal technologies presented in the governmental publications from 2003 and 2005. All four reasons affect the expected investments heavily. The analyses so far indicate that the methodology of consequential LCA used for identifying the marginal electricity may be too simplified and is disputable. This is further elaborated on in the next section. By applying consequential LCA at least five different types of capacity can be identified as the marginal technology in the next 10-20 years for future LCA studies. This indicates that several scenarios should be taken in to account. Please note that a similar table could be constructed for marginal heat technologies.

Table 1, Marginal electricity technologies from 1976 until 2005 and the actual marginal electricity from 1976 until 2006. (Blegaa et al. 1976;Danish Energy Authority 2003;Hvelplund et al. 1983;Lund & Mathiesen 2006;Ministry of Energy 1981;Ministry of Energy 1990;Ministry of Energy 1993;Ministry of Environment & Energy 1996;Ministry of Trade 1976;Ministry of Transport and Energy 2005)

Period / type of publication	Ref. / planned demand	Ref. marginal tech. simple / dynamic	Main new capacity planned	Planned marginal tech. simple / dynamic	Actual demand / until year	Actual main phased out capacity	Actual marginal tech. simple / dynamic
1975-1995 Gov.	Steep / heavy incr.	Oil PP	Nuclear PP	Nuclear PP / coal PP	Incr. / 1980	Oil PP	Coal PP
1975-1995 NGO	Incr. / small incr.	Oil PP	Ngas CHP	Ngas CHP / Ngas PP			
1981-2000 Gov.	Incr. / small incr.	Coal PP	Nuclear PP	Nuclear PP / coal PP	Incr. / 1990	Oil PP	Coal CHP & Coal PP
1981-2000 NGO	Incr. / steep decr.	Coal PP	Ngas CHP	Coal PP			
1988-2030 Gov.	Incr./ small incr.	Coal PP	Ngas CHP	Ngas CHP / coal PP	Small incr. / 2000	Coal PP	Wind power & (Coal PP)
1988-2005 Gov.	Incr./ small incr.	Coal PP	Ngas CHP	Ngas CHP Ngas PP			
1996-2030 Gov.	Small incr. / decr.	Coal CHP	Biomass CHP	Coal CHP / Norwegian hydro			
2003-2017 Gov.	Small incr. / -	Ngas PP	-	-	Small incr. / 2005	Coal PP	Coal CHP & (Ngas CHP)
2005-2025 / Gov. Price level: 1. Low	Small incr. / -	Wind power / Ngas CHP	-	-	?	?	?
2. Base	Small incr. / -	Wind power / Ngas CHP	-	-			
3. High	Small incr. / -	Wind power / Biomass CHP	-	-			
2004-2030 / Alt.	Small incr. / steep decr.	Wind power / Biomass CHP	Wind power	Coal PP / flex. Technology			

3. Reviewing marginal electricity in "state-of-the-art" consequential LCA studies

Here, the current identification and use of marginal energy technologies in consequential LCAs is analysed. For this purpose, ten LCA studies applying the methodology and performed within the last five years are reviewed. Not all studies use the term consequential; nonetheless, in all cases, consequences of a change are modelled and the marginal energy technology is identified. Two criteria are applied for the selection of the studies: 1. the study is change-oriented, 2. energy is an important factor for the results. The studies are found in article databases e.g. the Danish Environmental Protection Agency. For this purpose, the majority of important studies performed are included; however, some may unintentionally have been left out. The overall aim of the review is to assess the type and identification practise of marginal energy technologies in consequential LCAs on the basis of four questions: 1) What is used as marginal technology? 2) How was the marginal technology identified? 3) Was the identified marginal technology in the LCA short or long-term? 4) How important was energy for the results? Both electricity and heat is included in this review, as the affected heat technology is also important in these LCAs. The LCAs all apply to the Nordic countries reflected by the technology choices in Table 2. Some studies use more than one technology. For electricity, the marginal technology is mainly identified as either coal or Ngas, whereas the results for heat are more varied.

Table 2, Identified marginal technologies for electricity and heat production in the ten reviewed studies. (Baky & Eriksson 2003;Dall et al. 2003;Eriksson et al. 2007;Finnveden et al. 2005;Frees 2002;Frees et al. 2005;Jensen & Thyoe 2007;Kromann et al. 2004;Schmidt et al. 2007;Thrane 2006)

	Technology (electricity)	Technology (heat)
Coal CHP	X	X X
Coal PP	X X X X	
Ngas CHP	X X X	X X X X
Mix of coal CHP and Ngas CHP		X
Forest residues (biomass)		X
Complex marginal (mix of different fuel types)	X	X
Central CHP plants		X X
Site-specific (average - not marginal)	X	

The marginal electricity technology has been identified by different approaches more or less following or referring to the guidelines of (Ekvall & Weidema 2004). The arguments for defining Ngas CHP as marginal technology are mainly based on the Kyoto protocol, indirectly constraining the use of coal due to its high CO_2 emissions, and defining Ngas as the cheapest alternative. The arguments for choosing coal PP as the marginal technology are not described in such detail, but one reason is that coal is the most polluting technology resulting in close down of old coal PP. One study refers to (Weidema, Frees, & Nielsen 1999) for identification of the marginal technology for European electricity and one uses (Behnke 2006). In some studies, wind is also mentioned as a potential marginal electricity technology, but is disregarded as it is constrained by wind speed and not market demand, i.e. not a dynamic marginal technology. Only one study differs by using energy system analysis for identifying the marginal technology and thus defining it as a mix of different technologies (Eriksson, Finnveden, Ekvall, & rklund 2007). In the majority of the studies reviewed, a long-term time horizon of 10-20 years is used. This approach is consistent with the recommended methodology (Ekvall & Weidema 2004).

All the assessed studies conclude that energy is important when determining the results. Sensitivity analyses are performed identifying the consequences of another marginal technology in most studies. Especially, in studies comparing recycling to incineration, the marginal technology is important, as it is much more environmentally beneficial to substitute coal than Ngas technologies. It can be concluded that different marginal technologies are identified with varying arguments. Only a few studies take into account whether the demand of electricity and heat is increasing or decreasing compared to the overall demand, in most studies this issue is not mentioned. In nine out of ten of the reviewed studies the arguments are in the line of a simple marginal and some consider that it is a dynamic marginal technology, i.e. as defined and used in section 2. Only one study applies an approach where the marginal is complex. This is analysed further in the next section.

4. Case study: energy systems analyses and technology change

In this section, the consequences of not using energy system analysis for identifying marginal energy technologies are illustrated. A case is analysed where 1 additional TWh waste is incinerated. This situation is important in consequential LCA studies of e.g. waste incineration vs. recycling. Here, identification of a complex set of long-term marginal technologies is analysed. Ten different scenarios are analysed using the EnergyPLAN model, which has also been used for analyses for the Danish Government and for research. It conducts hour-by-hour analyses of different electricity, heat and transport technologies fulfilling the demands, which are given as annual hourly distributions. The model simulates the energy system and marginal Danish technologies, as well as exchanges on the Nordic electricity market. The model and the assumptions behind is described in (Lund 2007). Three parameters are changed to illustrate their importance when identifying the marginal technology: the energy system, the production distribution in time and in geography.

The results are presented as the marginal change when comparing a reference utilising 13.4 TWh waste with the current geographical distribution and the current constant production. In ten scenarios 1 TWh waste is added to different geographical locations (characterised by the district heating systems they are connected to) and with different time distribution (characterised by the flexibility with which the waste can be used). The analysis is conducted for two possible Danish energy systems in 2030: a business-as-usual system (BAU) with a higher energy demand than today and an energy system with 45% renewable energy (IDA) with a lower energy demand than today, described in (Lund & Mathiesen 2006;The Danish Ministry of Transport and Energy 2005). First the 1 TWh waste is added with the current distribution between areas producing heat only, areas with decentralised CHP and areas with central CHP (scenario 1 & 2). Subsequently, the waste is added first in the areas where heat only is produced (scenario 3 & 4) and then in the decentralised (scenario 5 & 6) and central CHP areas (scenario 7 & 8). In the last scenarios (9 & 10), the waste incineration is assumed to be used flexibly with the current geographical distribution. This requires pre-treatment of the waste. The scenarios are compared with two examples of using the consequential approaches according to the review above of how the energy marginal is used today for incineration i.e. one example with coal PP and heat from N.Gas CHP and one with N.Gas CHP. Both calculated with the energy quality method.

Fig. 1 illustrates the great variations achieved by adding the waste in different energy systems and with different distributions in time and geography. The difference is also big compared to the consequential approach, where e.g. a large amount of coal is substituted in one of the scenarios. In general most natural gas is substituted and lower amounts of coal. In most cases oil is substituted when adding waste in the BAU energy system, whereas biomass may be substituted in the RE energy system. Overall adding the waste in the RE energy system has lower effect as the system is less flexible e.g. due to a large percentage of wind power.

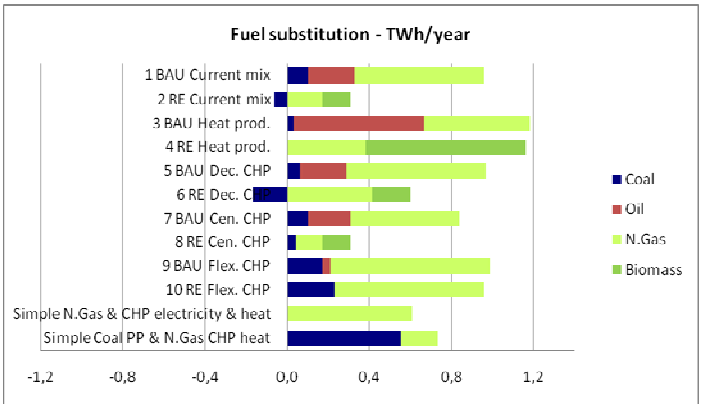

Fig. 1, Fuel substitution compared to the reference scenarios.

It is possible to identify where in the energy system production increases and where it decreases divided on the three areas. Fig. 2 illustrate this for the scenario where the extra 1 TWh waste is incinerated in a decentralised CHP area in the BAU energy system (scenario 5). Although there e.g. is a net substitution of natural gas and coal an increased consumption occurs in the power plants in the central areas whereas fuel is substituted in the decentralised CHP area. There is an increased need for flexibility in the system, as the waste is incinerated as base load. Hence, the substituted technologies are "simple" marginal technologies and the technologies with increased production are "dynamic". The environmental consequences vary depending on which technology the fuel is used in. The energy system analysis can also give data on CO_2 emissions as well as changes in electricity export. Furthermore, it is possible to analyse scenarios with different fuel prices.

The overall conclusion of the case study is that the consequential approach is too simple. The future energy system, the district heating network and the flexibility is very important when determining the marginal energy technology when adding 1 TWh waste into the energy system. In all scenarios analysed a mix of different technologies is affected and for none of the scenarios is coal PP the main affected technology.

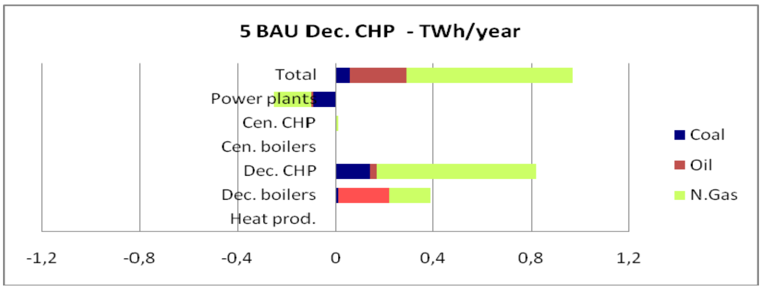

Fig. 2, Fuel substitution with 1 TWh waste added in the decentralised CHP areas in a business-as-usual scenario.

5. Conclusion

The results of the historical analysis illustrate that when applying the recommendations in consequential LCA to identify the future marginal electricity technology, the actual marginal technology is not the same as the one which could have been foreseen. The results also indicate that the future marginal electricity technology can be at least five different technologies. The review of recent LCAs reveals that the studies did not apply the methodology consistently and referred to different arguments for choosing mainly coal PP or Ngas CHP as the marginal technology. In most studies Ngas PP is included in a sensitivity analyses. The energy system analysis of different uses of 1 TWh waste illustrates that complex mixes of technologies are affected depending on the future energy system, where production plants will be placed, and on how flexibly the additional waste is used. Compared to the approach in the reviewed LCAs the energy system analysis revealed that several fuels and technologies are affected. Boundary conditions are however also important in energy system analyses and must be taken adequately into account. The current perfunctory approach of identifying marginal energy technologies illustrated in here is problematic as the identification of the marginal technology by use of the consequential methodology is increasingly important in the practise of LCA studies.

On the basis of the analyses, it can be recommended to improve the current practice by 1) using combined affected technologies, i.e. a complex set of marginal technologies; 2) using long-term perspectives by identifying affected technologies in several possible future scenarios, and 3) identifying the affected technologies based on energy system analysis with realistic geographical distributions and distribution in time.

References

Baky, A. & Eriksson, O. 2003, *Systems analysis of organic waste management in Denmark*, Miljoestyrelsen (Danish EPA), Copenhagen, Report no. 822.

Behnke, K. 2006, *Notat om deklaration af fremtidigt elforbrug - Memorandum on declaration of future electricity demand*, Energinet.dk, Fredericia.

Blegaa, S., Hvelplund, F. K., jensen, J., Josephsen, L., Linderoth, H., Meyer, N., Balling, N., & Sorensen, B. 1976, *Skitse til en Alternativ Energiplan for Danmark (Draft Alternative Energy Policy)*, OOA & OVE.

Dall, O., Christensen, C. L., Hansen, E., & Christensen, E. H. 2003, *Ressourcebesparelser ved affaldsbehandlingen i Danmark (Ressource savings in the waste managament system in Denmark)*, Miljoestyrelsen (Danish EPA), Copenhagen, Report no. 804.

Danish Energy Authority 2003, *En omkostningseffektiv opfyldelse af Danmarks reduktionsforpligtelse (Cost-effective emission reductions)*, Danish Energy Authority (Energistyrelsen), Copenhagen.

Ekvall, T. & Weidema, B. P. 2004, "System boundaries and input data in consequential life cycle inventory analysis", *International Journal of Life Cycle Assessment*, vol. 9, no. 3, pp. 161-171.

Energistyrelsen - Danish Energy Authority 2006, *Energistatistik 2005 (Energy statistics 2005)*, Energistyrelsen - Danish Energy Authority, Copenhagen.

Eriksson, O., Finnveden, G., Ekvall, T., & rklund, A. 2007, "Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion", *Energy Policy*, vol. 35, no. 2, pp. 1346-1362.

Finnveden, G., Johansson, J., Lind, P., & Moberg, A. 2005, "Life cycle assessment of energy from solid waste - Part 1: General methodology and results", *Journal of Cleaner Production*, vol. 13, no. 3, pp. 213-229.

Frees, N. 2002, *Miljoemaessige fordele og ulemper ved genvinding af plast (Environmental advantages and disadvantages by plastic recycling)*, Miljøstyrelsen (Danish EPA), Copenhagen, Report no. 657.

Frees, N., Hansen, M. S., Ottosen, L. M., Tønning, K., & Wenzel, H. 2005, *Miljoemaessige forhold ved genanvendelse af papir og pap. Opdatering af vidensgrundlaget (Environmental impacts related to recycling of paper and cardboard. An update of the knowledge-base)*, Miljoestyrelsen (Danish EPA), Copenhagen, Report no. 1057.

Hvelplund, F. K., Illum, K., Jensen, J., Meyer, N., Norgaard, J. S., & Sorensen, B. 1983, *Energi for fremtiden - Alternativ Energiplan 1983 (Energy for the future)*, Borgen, Denmark.

Jensen, K. H. & Thyoe, K. A. 2007, *2nd generation bioethanol for transport: the IBUS concept - boundary conditions and environmental assessment*, Department of Manufacturing Engineering and Management, Technical University of Denmark, Copenhagen, Master Thesis.

Kromann, L., Madsen, A. S., Schmidt, J. H., & Mathiesen, B. V. 2004, *Madaffald fra storkøkkener (Food waste from large-scale catering establishments)*, Miljoestyrelsen (Danish EPA), Copenhagen, Report no. 1.

Lund, H. 2007, *EnergyPLAN - Advanced Energy Systems Analysis Computer Model - Documentation Version 7.0 -* http://www.energyPLAN.eu, Aalborg University, Aalborg, Denmark.

Lund, H. & Mathiesen, B. V. 2006, *Ingeniørforeningens Energiplan 2030 - Tekniske energisystemanalyser, samfundsøkonomisk konsekvensvurdering og kvantificering af erhvervspotentialer. Baggrundsrapport (Danish Society of Engineers' Energy Plan 2030)*, Danish Society of Engineers (Ingeniørforeningen Danmark), Copenhagen.

Ministry of Energy 1981, *Energiplan 81 (Energy Policy 81)*, Energiministeriet (Ministry of Energy), Denmark.

Ministry of Energy 1990, *Energi 2000 - Handlingsplan for en baeredygtig udvikling (Energy 2000 - Action plan for a Sustainable Development)*, Energiministeriet (Ministry of Energy), Copenhagen.

Ministry of Energy 1993, *Energi 2000 - Opfoelgningen, En ansvarlig og fremsynet energipolitik (Energy 2000 - Follow Up; Responsible and Visionary Energy Policy*, Energiministeriet (Ministry of Energy), Copenhagen.

Ministry of Environment & Energy 1996, *Energy 21 - The Danish Government's Action Plan for Energy 1996*, Ministry of Environment and Energy, Copenhagen.

Ministry of Trade 1976, *Dansk energipolitik 1976 (Danish Energy Policy),* Handelsministeriet (Ministry of Trade), Copenhagen.

Ministry of Transport and Energy 2005, *Energy Strategy 2025 - Perspectives to 2025 and Draft action plan for the future electricity infrastructure*, Ministry of Transport and Energy, Copenhagen.

Schmidt, J. H., Holm, P., Merrild, A., & Christensen, P. 2007, "Life cycle assessment of the waste hierarchy - A Danish case study on waste paper", *Waste Management*, vol. 27, no. 11, pp. 1519-1530.

The Danish Ministry of Transport and Energy 2005, *Energy Strategy 2025 - Perspectives to 2025 and Draft action plan for the future electricity infrastructure*, The Danish Ministry of Transport and Energy, Copenhagen.

Thrane, M. 2006, "LCA of Danish fish products. New methods and insights", *International Journal of Life Cycle Assessment*, vol. 11, no. 1, pp. 66-74.

Weidema, B. P. 2003, *Market information in life cucle assessment*, Danish Environmental Protection Agency, Copenhagen, 863.

Weidema, B. P., Frees, N., & Nielsen, A. M. 1999, "Marginal production technologies for life cycle inventories", *International Journal of Life Cycle Assessment*, vol. 4, no. 1, pp. 48-56.