Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway

Anders Arvesen[1,*], Ingrid Bjerke Hauan[1], Bernhard Mikal Bolsøy[2], Edgar G. Hertwich[1]

[1] Industrial Ecology Programme and Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU)

[2] Nord-Trøndelag Elektrisitetsverk Nett AS (NTE Nett AS)

[*] Corresponding author: anders.arvesen@ntnu.no; +4799324154 (mob); IndEcol, Sem Sælands vei 7, NTNU, NO-7491 Trondheim, Norway

Citation

This document contains an unedited manuscript for the following article:

Arvesen, A., I. B. Hauan, B. M. Bolsøy, and E.G. Hertwich. 2015. Life cycle assessment of transport of electricity via different voltage levels: A case study for Nord-Trøndelag county in Norway. *Applied Energy*. 157(1): 144:151.

The final edited and published article is available at:

http://dx.doi.org/10.1016/j.apenergy.2015.08.013

Keywords

Life cycle assessment (LCA); Carbon footprint; Electrical grid; Electricity transmission; Electricity distribution.

Abstract

Electricity transmission and distribution (T&D) plays a vital role in society by connecting electricity producers and consumers. We present a life cycle assessment case study of electricity delivery to consumers in Nord-Trøndelag county in in Norway. We use a coherent framework for assessing electricity transfer via all the main segments of the Norwegian T&D system (local distribution, regional transmission and main national transmission grids). The assessment covers impacts associated with production, transport, and installation of components, power grid losses, and losses of sulphur hexafluoride. The results indicate that for electricity that is transmitted through the three main T&D grid segments, and assuming a Norwegian electricity mix when modelling the effects of power losses, the total carbon footprint of electricity T&D is 7.8 kg CO_2-eq/MWh. Local distribution holds the largest share of this total (~60%), while regional transmission and national transmission both make smaller but significant contributions (~20% each). When classifying impacts as being attributable to either power grid losses or to other processes (e.g., materials and component manufacturing), both power losses and other processes contribute significantly to total impact potentials. Power losses are responsible for 30-43% of the combined electricity T&D impact potentials for climate change, particulate matter, smog-creation and acidification, 21-28% for toxicity and eutrophication, and 14% for metal depletion. For all categories except metal depletion, the relative importance of power losses increases appreciably if Nordic or particularly European electricity is assumed, however. Finally, we compare the environmental impacts of electricity T&D with that of electricity generation. The results of the comparison show that electricity T&D causes fewer impacts than electricity generation, but T&D impacts are not negligible; this is true regardless of what electricity mix is assumed when modelling power losses.

1 Introduction

Existing life cycle assessment (LCA) literature devotes considerable attention to the environmental impacts of electricity generation (e.g., [1] or literature reviews [2-5]), but gives comparatively little attention to electricity transmission and distribution (T&D) [6]. However, few consumers receive electricity directly from power plants: T&D infrastructure plays a crucial role in transporting electricity to consumers. Hence, a good understanding of the environmental impacts of electricity use in society must necessarily involve a sound understanding of both electricity generation and T&D. While electricity T&D is generally a less important cause of environmental damage than generation, it is not negligible and may influence the total impacts connected with electricity supply [6, 7]. Furthermore, a shift towards wind and solar energy as envisaged in energy scenarios [8, 9] requires significant grid extensions or upgrades [10-13], for two main reasons. One, when fossil fuel energy resources are distant from demand centres, the fuel is transported to a power station closer to demand, whereas for wind and solar energy resources it is the electricity that is transported [14]. Two, wind and solar power generation is variable, partly unpredictable and – while it can be curtailed – it cannot be adjusted upwards on demand; on a system-wide level this leads to increased transmission capacity requirements [15, 16]. Because of the connection between renewable energy utilization and electricity T&D requirements, evaluations of renewable energy should ideally consider impacts due to T&D [10, 17, 18].

Even if LCA research pays less attention to electricity T&D than electricity generation, there has been a growing interest in electricity T&D and several peer-reviewed LCA studies exists. Jones and McManus [19] study cables and lines used for electricity distribution; Harrison and colleagues [20] and Blackett and colleagues [21] study electricity transmission in Britain; Bumby and colleagues [22] study electricity distribution in California; Turconi and colleagues [23] study electricity T&D in Denmark; Arvesen and colleagues [13] a North Sea submarine transmission grid; and Garcia and colleagues [24] electricity generation and T&D in Portugal. Jorge and colleagues present assessments of electricity grid components [25, 26] and scale up inventories to assess Norwegian [27] and European [10] transmission networks. To our knowledge, [23] and [24] are the only LCA studies to date to study transmission and distribution in one coherent assessment.

The aim of this study is to contribute to an improved understanding of the environmental impacts caused by transporting electricity to consumers. This is achieved through an LCA case study of electricity delivered to consumers in Nord-Trøndelag county in Central Norway. We compile and analyse life cycle inventory data sets for regional electricity T&D networks in Nord-Trøndelag, and analyse inventory data from previous work [27] to also cover electricity transfer through the national main transmission grid in Norway. All the grid networks are analysed using the same analytical approach and background data, and under common assumptions about system boundaries, recycling benefits, etc. In this way, we establish a coherent framework for assessing electricity transfer via all the three segments of the Norwegian power grid (local distribution, regional transmission and main national transmission), and provide new insights into the environmental impacts of supplying electricity to consumers. Finally, we also compare the results for electricity T&D with results for electricity generation.

2 Characteristics of power grids in Nord-Trøndelag and Norway

The electricity T&D system in Norway comprises three parts, distinguished by different voltage levels (Table 1). Local distribution grids operate at the lowest voltage levels and typically link the T&D system to individual consumers. The main transmission grid, in Norway referred to as *Sentralnett*, operate at the highest voltage levels and enable the bulk transmission of electricity across Norway. *Sentralnett* is owned and operated by the Norwegian transmission system operator, Statnett. Regional transmission grids transmit electricity over shorter distances and provide intermediate links between the distribution grids and the main transmission grid. Large individual consumers such as aluminium production facilities can be connected directly to regional or main transmission grids. NTE Nett is the regional (local) T&D operator in Nord-Trøndelag. Electricity consumption in Nord-Trøndelag is typically higher than electricity production, hence making Nord-Trøndelag dependent on electricity import.

Table 1
Voltage levels and total line lengths for the local distribution grid, regional transmission grid and main transmission grid in Norway [28].

Grid section	Typical voltage levels (kV)	Total line length (km)
Local distribution grid	11, 22 [a]	98842
Regional transmission grid	66, 132	18687
Main transmission grid	132, 300, 420	11062

[a] Transformed to 230 V or 400 V before delivery to consumers.

3 Materials and methods

3.1 Method description

Life cycle assessment (LCA) may be described as the systematic assessment of potential environmental impacts and natural resource use associated with one product, taking into consideration the entire lifespans of the product itself as well as of supporting inputs. In order to achieve in-depth coverage of relevant operations, data collected for this work (such as copper requirements for electrical equipment) are coupled with process data (such as for copper production) defined in the comprehensive Ecoinvent LCA database [29]. We take an attributional and present-oriented approach to LCA, modelling present grid networks as if they were built and operated using an assumed representative mix of present technologies. The Hierarchist ReCiPe impact assessment method is applied. While three versions of ReCiPe reflecting different cultural perspectives are available, the Hierarchist version used in the present study is regarded as the consensus (or default) model [30, 31].

3.2 Study scope and key data and assumptions

We conduct original analyses of the local distribution and regional transmission grids in Nord-Trøndelag county. Impact indicator results are measured per unit of total electricity delivered by the local distribution and regional transmission grids, respectively. Furthermore, to allow for a comparison of results for all three levels of the Norwegian power grid (cf. Table 1), we extend the analysis to also cover the national, main transmission grid. All additional data needed to achieve this are obtained from Jorge et al. [27], who perform a detailed assessment of the main transmission grid specifically. Similarly as with the local distribution and regional transmission grids, indicator results for the main transmission grid are measured per unit of electricity delivered by the system [27]. Finally, to be able to compare results for electricity T&D with electricity generation, we analyse electricity generation using Ecoinvent [29]. For the major part of our analysis, we assume Norwegian electricity generation characteristics when modelling the effects of power losses and power generation, but we also present alternative results under assumptions of Nordic or European electricity[1]. An overview of the model subsystems is provided in Table 2.

Table 2
Overview of subsystems modelled (three electricity grid subsystems plus electricity generation), with information on references and geographical scope.

	Reference, life cycle inventory compilation	Grid data provider	Grid data year	Geographical scope
Local distribution grid	Own	NTE [a]	2011	Nord-Trøndelag
Regional transmission grid	Own	NTE [a]	2011	Nord-Trøndelag
Main transmission grid	[27]	NVE [b]	2009	Norway
Electricity generation	[29]	-	-	Norway [c]

[a] NTE Nett is the regional/local system operator in Nord-Trøndelag.
[b] NVE is the Norwegian Water Resources and Energy Directorate
[c] Results assuming Nordic or European electricity are provided in alternative scenarios.

In general, the amounts of electricity delivered by transmission and distribution networks are different, mainly because electricity is supplied at different voltage levels and large industry consumers are connected directly to transmission grids. The present approach takes such differences into account in a simple manner, by measuring the impacts of various grid sections in relation to the respective amounts of electricity delivered by the individual sections. This approach is a bit different from that used in previous work [23, 24] where

[1] The names of the Ecoinvent processes used are: ‘electricity mix/ NO/’ (Norway); ‘electricity, production mix NORDEL/ NORDEL/’ (Nordic countries); and ‘electricity, production mix RER/ RER/’ (Europe).

impacts of both transmission and distribution are measured in relation to one fixed electricity supply number.

All components in the distribution grid and most of the components in the regional transmission grid are assigned a lifetime of 40 years. The exceptions are overhead lines and masts located in coastal areas and subject to particularly rough weather conditions: 20 years, 25 years and 30 years is assumed for 5%, 25% and 10% of the overhead connections, respectively. We do not consider recycling benefits in the end-of-life phase, but a mix of virgin and secondary materials production is modelled in the production phase in accordance with default Ecoinvent materials production data; i.e., we adopt a cut-off allocation principle in open-loop recycling [32].

3.3 Life cycle inventories for local distribution grid

Data on quantities and technical characteristics of all electrical conductors and equipment that makes up the distribution grid in Nord-Trøndelag are obtained from NTE Nett. The grid comprises overhead lines, underground cables and transformers, as well as various types of switchgear. The main types and quantities of grid constituents are detailed in Tables 2 and 3. Besides the inventories described in the following subsections, lorry transport from assumed production sites to installation sites (770 km for lines and cables; 1800-2700 km for equipment; 500 km for wooden poles) and from installation sites to waste handling (140 km) is included. Diesel consumption of machinery at installation site is included as well, following the assumption of [23] that 1000 l of diesel is consumed per km of overhead line or cable. Power losses in the distribution grid amount to 137 GWh, corresponding to 6.3% of the electricity fed into the system (year 2011). Finally, we include regular inspection of overhead lines using cars (equivalent to 6.5 vehicle-km per km line annually on average).

Table 3
Total line lengths (km) for overhead lines and cables, and number of structures carrying overhead lines, by voltage level in the local distribution and regional transmission grids (year 2011).

	Local distribution			Regional transmission	
	230-690 V	0.4-7 kV	22 kV	66 kV	132 kV
Overhead line (km)	3033	111 [a]	4281	970	91
Structure (units)	50263	974	41748	5550	620
Underground cable (km)	3771	22 [a]	955	21	2
Submarine cable (km)	-	-	-	9	-

The data shown constitute an aggregate representation of the modelling data used.
[a] To simplify our analysis and due to the small quantities of 0.4-7 kV lines and cables, these are modelled as identical to 230-690 V lines and cables.

Table 4
Transformers and switchgear (circuit breakers, load breakers and disconnect switches) modelled for the local distribution and regional transmission grids (year 2011).

Equipment type	Load rating (kVA or MVA) or voltage level (V or kV)	Number, in distribution grid	Number, in regional grid
Transformer	315 kVA [a]	9614	
Transformer	< 50 MVA		44
Transformer	50-100 MVA		12
Transformer	> 100 MVA		3
Circuit breaker	230-690 V	18	
Circuit breaker	3.3-11 kV	40	
Circuit breaker	22 kV	384	
Circuit breaker	66 kV		192
Circuit breaker	132 kV		17
Load breaker	22 kV	6305	
Disconnector	22 kV	5558	

The data shown constitute an aggregate representation of the modelling data used. We make assumptions to match numbers for actual equipment installed to the equipment types for which we are able to establish life cycle inventory data.
[a] The actual rating is about 200 kVA on average; a 315 kVA transformer is modelled here for reasons of data availability.

3.3.1 Overhead lines and masts

Lines with voltage levels of 230 V or 22 kV account for practically all line connections in the distribution network. The cross-section conductor area varies. We define four types of overhead lines in the model, two types with voltage level 230 V (conductor cross-section areas 50 mm^2 or 95 mm^2) and two types with voltage level 22 kV (25 mm^2 or 50 mm^2), and match numbers for actual lines in the network to the most appropriate model line. We estimate weights of the conductive metal (aluminium) and insulation (polyethylene or polyvinylchloride) for each of the model lines based on information on total weight and conductor or line thickness from a manufacturer [33], and include wire drawing for the aluminium using Ecoinvent data (a steel wire drawing process is used because data for aluminium is not available). We model wooden masts (poles) with heights 9-11 m.

3.3.2 Cables

Underground cables with voltage levels 230 V and 22 kV comprise, respectively, 80% and 20% of the total distribution grid cable length. Similarly as for overhead lines, we define four cables in the model, estimate their material composition (aluminium conductor and polyethylene or polyvinylchloride insulation) [34-37], and match the actual cable installed to the most appropriate model cable. Energy use (electricity, natural gas), inputs of chemicals and other inputs to cable manufacturing is included based on an industry report [38] and Ecoinvent data for wire drawing.

3.3.3 Transformers and switchgear

While the average rating of local distribution transformers is about 200 kVA, we model a 315 kVA transformer based on [39], as this is the closest match for which we are able to find data. We define five types of switchgear using data in industry reports [40-42]: three circuit breakers (operating at voltage levels 230 V, 3.3-11 kV and 22 kV), one load breaker and one disconnector. The data cover material requirements and in some of the cases direct energy inputs and waste generation to component manufacturing.

The 3.3-11 kV and 22 kV circuit breakers and the load breaker are sulphur hexafluoride (SF_6) gas-insulated, while the distribution transformer and 230 V circuit breaker do not contain SF_6. SF_6 is an extremely potent greenhouse gas. For equipment containing SF_6, we assume the same operational leakage rate (relative to the amount of SF_6 in equipment) as in [27] for high-voltage equipment installed in Norway.

3.4 Life cycle inventories for regional transmission grid

Similarly as for the local distribution grid, data on quantities and technical characteristics of the transmission lines and equipment comprising the regional transmission grid in Nord-Trøndelag are obtained from NTE Nett (see Tables 2 and 3). In addition to the inventories accounted for in the following subsections, we include lorry transport of components and diesel oil needed for installation (using the same assumed transport lengths and diesel consumption rate as for the local distribution grid) and annual and decadal aerial inspections by helicopter (assuming flying times of 4 and 8 minutes per km power line for annual and decadal inspections respectively). Power losses in the regional transmission grid total 54.2 GWh, or 1.6% of the electricity fed into the system (year 2011).

3.4.1 Overhead lines and masts

For the overhead lines in the regional transmission grid, the conductive metal is aluminium or a combination of steel and aluminium. The NTE Nett data give information on the amount of aluminium and steel used in lines with different cross-section areas. Based on this information we model a mix of twelve types of overhead lines. There are about 6000 masts, virtually all (>99%) of which are made of wood. We assume there are three insulator strings each weighing 4 kg per mast on average, and that the strings are composed of glass and zinc-coated steel [21, 43]. Preservative treatment where the wood is impregnated with creosote is included [29].

3.4.2 Cables

Underground and submarine cables make up only 3% of the total wire length in the regional transmission grid (the remainder is overhead lines). We model cables in the regional grid in a similar manner as for distribution grid cables, using manufacturer data [37, 44] and Ecoinvent.

3.4.3 Transformers and switchgear

The rated capacity of the transformers ranges from 10 MVA to 500 MVA; the voltage levels are 66 kV or 132 kV. We utilize inventories of material and energy inputs, emissions and waste generation in transformer manufacturing compiled by Jorge et al. [25] (the original data sources are [45], [46], [47], [48] and [49]). The inventory data for different transformers are then applied to model the most similar transformers found in the real network. We define three circuit breakers, two of which operate at 66 kV (one is SF_6-insulated and the other is not) and one of which operate at 132 kV (SF_6-insulated). We establish approximate total weights for each of the three types based on NTE data, and assume the breakdown into material types given in [40] is roughly representative for all three types.

The procedure for modelling SF_6 losses from transformers and switchgear is the same as for equipment in the distribution grid.

3.5 Life cycle inventories for high-voltage transmission grid

We adopt the life cycle inventories for the main transmission grid of Jorge et al. [27]. In Jorge et al. [27], the grid system is credited with impacts that are assumed to be avoided when components are recycled to produce valuable outputs at the end-of-life – this is the “substitution by system expansion” or “avoided burden” method in LCA terminology [50]. In the present work, we modify the inventories of Jorge et al. for the main transmission grid to remove end-of-life recycling credits and adopt a cut-off allocation principle, consistent with the approach taken for distribution and regional transmission (section 3.2). Additionally, we make minor adjustments to the original main transmission grid inventories to avoid overlap with the regional transmission inventories.

4 Results and discussion

4.1 Detailed electricity T&D assessment

Fig. 1 shows impact indicator results broken down by grid segments (three bars representing local distribution, regional transmission and main transmission) and main components or activities (six categories stacked within each bar), under the assumption that Norwegian electricity is representative for the power losses (i.e., wasted energy) in the systems. As is evident from the figure, the delivery of 1 MWh of electricity by the main transmission grid causes emissions of 1.4 kg CO_2-eq (of which 0.68 kg CO_2-eq, or 48%, is due to power losses), delivery of 1 MWh by the regional transmission grid causes 1.6 kg CO_2-

eq (0.52 kg CO_2-eq, or 33%, due to power losses), and delivery of 1 MWh by the distribution grid causes 4.8 kg CO_2-eq (2.2 kg CO_2-eq, or 45%, due to power losses). Hence, for electricity generation that is fed into the main transmission grid and then transmitted through all three grid segments, the total carbon footprint of electricity T&D is 7.8 kg CO_2-eq/MWh (1.4+1.6+4.8=7.8) (of which 43% is owing to losses) on average. Correspondingly, for electricity generation fed into the regional transmission grid and transmitted through the regional and local grids, the footprint is 6.4 kg CO_2-eq/MWh (1.6+4.8=6.4); for electricity fed into the local grid and delivered to an end-user connected to the same grid, the footprint is 4.8 kg CO_2-eq/MWh; etc. In this sense, for a consumer connected to the local distribution grid (e.g., a household), the footprint value 4.8 kg CO_2-eq/MWh can be regarded as a lower bound and 7.8 kg CO_2-eq/MWh as an upper bound for the carbon footprint of transport of electricity. In general, electricity is supplied by producers and delivered to consumers at different voltage levels. For electricity fed into the main transmission grid and delivered to an end-user connected to the regional transmission grid, the footprint is 3.0 kg CO_2-eq/MWh (1.4+1.6=3.0), according to the results.

Table 5 displays total impact indicator values and power losses shares to totals for additional impact categories, and for alternative electricity generation assumptions (Nordic and European electricity, in addition to Norwegian electricity).

Fig. 1 also indicates the total impacts of transport of 1 MWh of electricity via main transmission, regional transmission and local distribution grid systems as percentage shares of estimated total, economy-wide European impact levels (based on [31]; see also the a bit dated but still useful discussion in [51]). The shares are highest for freshwater ecotoxicity, freshwater eutrophication and human toxicity; shares for other categories are 1-3 orders of magnitude lower.

In Fig. 1, transport of electricity via the distribution grid appears as the major cause of environmental impacts. In all cases except metal depletion, the impacts associated with distribution are comparable to or higher than the combined impacts of regional and national (main) transmission (Fig. 1). It can be noted that broadly similar findings on the importance of distribution versus transmission are presented in a study of Danish T&D networks [23], but one should also recognise the difference in approaches between this study and the present study (see section 3.2). Another study reports that > 80% of power losses in Portugal are attributable to distribution and < 20% to transmission [24]. In general for Norway, relatively high power losses in distribution grids are largely explained by low voltage levels and use of underground cables, which tend to waste more energy than overhead lines [28].

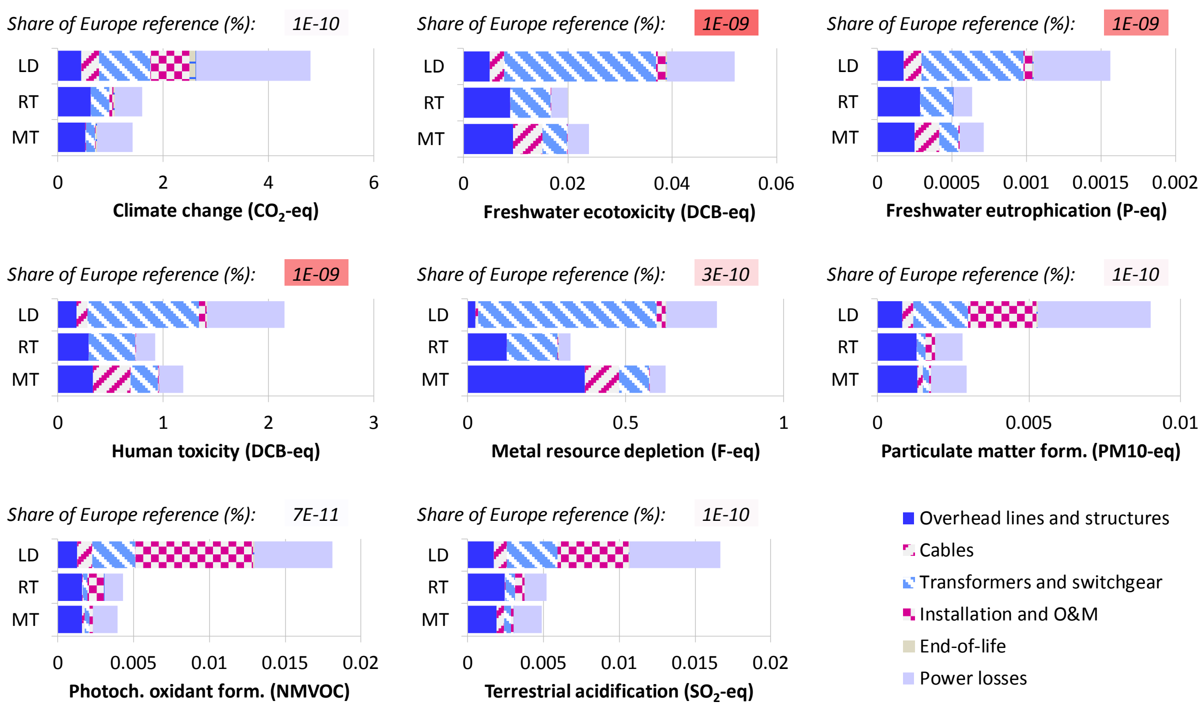


Fig. 1. Impact indicator results for transport of electricity via main transmission (MT), regional transmission (RT) and local distribution (LD) grids by six main components or activities, assuming Norwegian electricity when modelling impacts of power losses. Impact indicator results are in units of kg/MWh (e.g., for climate change, kg CO_2-eq/MWh). Also shown (in italics) are total indicator values per MWh (sum of MT, RT and LD contributions per MWh) as percentage shares of total annual reference values for Europe [31]. For example, 1.4 kg CO_2-eq/MWh from MT, 1.6 kg CO_2-eq/MWh from RT and 4.8 kg CO_2-eq/MWh from LD yield a total of 7.8 kg CO_2-eq/MWh; at the same time, total greenhouse emissions in Europe in year 2000 is 8.15 Gt CO_2-eq according to [31]. Hence, we obtain a percentage share value for climate change of 7.8/8.15·1E-12·100% = 1E-10%. Percentage share values are shaded according to their relative magnitude, with light (heavy) shading denoting small (big) magnitude. O&M = Operations and maintenance.

Table 5

Total impact indicator values (kg/MWh) and relative contributions of power losses (%) for electricity that is transmitted through all three grid segments (local distribution, regional transmission, main transmission), assuming, respectively, Norwegian, Nordic and European electricity generation when modelling impacts due to power losses.

	Norwegian electricity		Nordic electricity		European electricity	
	Total (kg/MWh)	Power loss share (%)	Total (kg/MWh)	Power loss share (%)	Total (kg/MWh)	Power loss share (%)
CC (CO_2-eq)	7.8E+00	43 %	2.2E+01	79 %	5.6E+01	92 %
FET (DCB-eq)	9.6E-02	21 %	1.6E-01	52 %	8.0E-01	90 %
FE (P-eq)	2.9E-03	28 %	5.8E-03	64 %	5.1E-02	96 %
HT (DCB-eq)	4.3E+00	27 %	9.1E+00	66 %	3.3E+01	90 %
MRD (Fe-eq)	1.7E+00	14 %	1.8E+00	19 %	1.9E+00	20 %
PMF (PM10-eq)	1.5E-02	39 %	3.5E-02	74 %	7.8E-02	89 %
POF (NMVOC)	2.6E-02	30 %	5.4E-02	66 %	1.3E-01	86 %
TA (SO_2-eq)	2.7E-02	35 %	6.1E-02	71 %	2.3E-01	92 %

CC = Climate change; FET = Freshwater ecotoxicity; FE = Freshwater eutrophication; HT = Human toxicity; MRD = Metal resource depletion; PMF = Particulate matter formation; POF = Photochemical oxidant formation; TA = Terrestrial acidification.

Previous studies identify power losses as the major culprit behind most types of impacts. For example, power losses are responsible for, respectively, 89-94% and 96-98% of the total impacts of the Danish distribution and transmission grids studied in [23], when looking at six out of eight assessed impact categories (the share attributable to power losses is much lower, 44%, for metal depletion [23]). Similar shares in the order of 85-99% of total climate impacts are attributed to power losses in other assessments too [20, 24-26]. The corresponding power loss shares in the results shown in Fig. 1 are markedly lower, e.g. 44% in total for climate change. This is owing to the use of Norwegian electricity supply when modelling power losses; Norwegian electricity exhibits substantially lower impacts than European electricity for all the impact categories except metal depletion [29]. Power loss becomes a much dominant cause of impacts if Nordic or particularly European electricity is assumed, as table 5 reveals. The metal depletion impact category stands out by showing quite moderate contributions from power losses (14-20%) regardless of electricity mix (Table 5). Similar conclusions with regard to metal depletion are expressed in previous studies [23, 25-27]. For Norway as a whole, 7-8% of annual electricity generation is lost in T&D [28, 52]. This compares to corresponding estimates for European Union-27 and the world of roughly 6% and 9% respectively [53].

Looking at the breakdown of climate change impact potentials by main components (Fig. 1), roughly 20% of the totals are ascribed to ‘overhead lines and structures’ and ‘transformers and switchgear’ each. A roughly similar distribution can be seen for particulate matter formation, smog-creation and acidification impact potentials, although ‘installation and O&M’ is a much more important contributor to smog-creation (owing to NO_x emissions from machinery). With regards to toxic and eutrophying emissions and metal depletion, transformers and switchgear are relatively more important, contributing in the order 35-45% of total impact potentials. Toxic emissions stem largely from disposal of various types of waste in connection with metal mining and production, in particular manufacturing waste, mine tailings and smelter slag (this mirrors similar findings reported in literature for renewable power [1, 54]).

The main transmission grid exhibits 36% of the total metal depletion impacts in Fig. 1, which makes metal depletion the only category where main transmission holds a share of more than one fifth of the total impact. This is largely attributable to relatively large requirements for mining iron, manganese, nickel and chromium, which again derive from use of steel (containing iron, and manganese, nickel and chromium as alloying elements) in overhead lines and masts. It is also attributable to copper use. Looking at the impact results expressed as percentage shares of total European levels (Fig. 1), the estimated share for metal resource depletion falls in the middle range. One explanation for why the share for metal depletion is not higher may be that the grid networks contain a lot of iron and aluminium, but these metals are not associated with particularly high depletion factors in the ReCiPe impact assessment method. Copper, on the other hand, causes relatively more resource depletion by this method. Other studies indicate that future grid expansions to accommodate more renewable power will increase the metal requirements of transmission [10, 55], which may coincide with increased metal requirements for power generation when renewable power replaces fossil fuel-based power [1, 56].

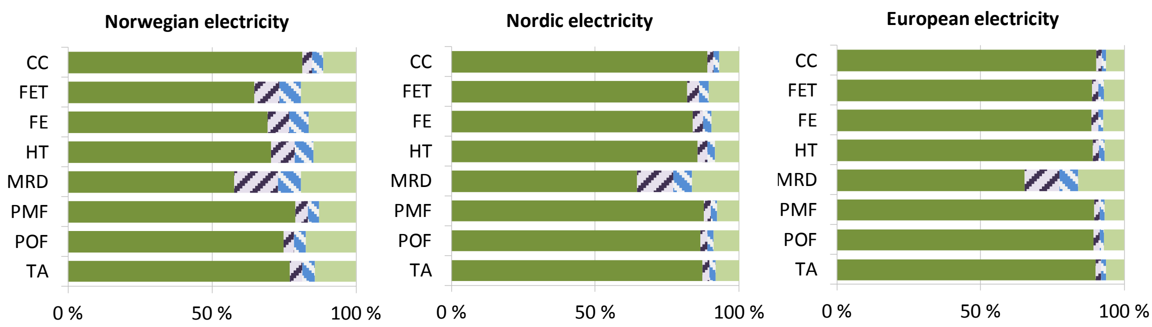
The contribution of SF_6 leakage to the total climate change impact potential is 7% for the main transmission grid, and in relative terms somewhat less important for the local and regional grids in Nord-Trøndelag (4% combined). It should be noted that SF_6 leakages from the local distribution and regional transmission grids are estimated based on the number of SF_6-containing equipment and an assumed (as opposed to measured) SF_6 leakage rate (sections 3.3.3 and 3.4.3). While switchgear is currently the most important source for SF_6 emissions Norway, total SF_6 emissions from this source have declined by 75% since 2002, in conjunction with a voluntary agreement between industry and national authorities to cut SF_6 emissions [57]. According to [23], deployment of 'smart grid' technologies is expected to bring about increased use of SF_6 in coming years.

For the Nord-Trøndelag distribution and transmission grids, we assume power delivery and losses as in year 2011, as this is the year for which we inventory grid constituents. It should be noted however that there is sizeable year-to-year variation in power loss figures for these grids. As an illustration, local distribution power grid losses were 34% higher in 2012 than in 2011, and 12% lower in 2013 than in 2011, while regional transmission grid losses were roughly the same in 2012 and 2011, but 39% lower in 2013 than 2011. Further, in general it is important to be aware that characterization models applied in LCA, and also reference values such as those used to generate the percentage values in Fig. 1 and Fig. 2, may have high uncertainty, as is discussed in life cycle impact assessment literature (e.g., [51, 58-61]). Perhaps in particular, estimates of toxicity, eutrophication and metal depletion have large uncertainty. Toxicity estimates have large uncertainty due to potential gaps in emission inventories, and due to difficulties in characterizing large number of substances with often complex effect chains.

Finally, in this work we employ a process-LCA method, meaning that the LCA model is constructed using a bottom-up type of thinking and describe operations in physical terms. Process-LCA can support detailed analysis and achieve high levels of specificity, but is prone to underestimation as there is a natural limit to how many activities it is feasible to consider 'bottom-up' [62, 63]. We do not attempt to introduce additional, economic input-output-based inventories, although this could lead to more complete coverage (e.g., [64], [65]).

4.2 Electricity production and electricity T&D combined assessment

Fig. 2 displays breakdowns of impact indicator results into electricity generation, distribution and regional and national transmission. In this figure, results for each of the three alternative electricity assumption scenarios (i.e., Norwegian, Nordic and European electricity) are shown. Among the three modelled electricity mixes, electricity T&D is relatively most important when assuming Norwegian electricity (left panel, upper part in Fig. 2), and relatively least important when assuming European electricity (right panel, upper part). Still, even in the case with European electricity, electricity T&D holds a non-negligible share of about 10% of totals for all investigated impact categories except metal depletion, and 35% for metal depletion. In sum, these results further substantiate findings from previous assessments [6, 13, 23, 24] that i) electricity T&D causes less impacts than electricity generation, but ii) at the same time the T&D impacts are probably too large to be neglected.



Share of Europe reference values (%)

	Norway el.	Nordic el.	European el.
CC	5E-10	2E-09	7E-09
FET	3E-09	1E-08	9E-08
FE	3E-09	1E-08	1E-07
HT	3E-09	1E-08	7E-08
MRD	8E-10	1E-09	1E-09
PMF	7E-10	3E-09	7E-09
POF	3E-10	1E-09	3E-09
TA	5E-10	2E-09	9E-09

Fig. 2. Impact indicator results for electricity generation fed into the main transmission grid, transmitted through the three grid systems and delivered to a consumer connected to the local distribution grid, broken down by contributions from electricity generation, main transmission (MT), regional transmission (RT) and local distribution (LD), for three alternative electricity assumption scenarios (Norwegian, Nordic or European electricity generation). Also shown are total indicator results per MWh (sum of all generation, MT, RT and LD contributions per MWh) as percentage shares of total annual reference values for Europe [31] (see also explanation in caption to Fig. 1). Percentage share values are shaded according to their relative magnitude, with light (heavy) shading denoting small (big) magnitude. The shadings are commensurate across impact categories for a given electricity assumption scenario, but do not commensurate across the electricity assumption scenarios or with Fig. 1. CC = Climate change; FET = Freshwater ecotoxicity; FE = Freshwater eutrophication; HT = Human toxicity; MRD = Metal resource depletion; PMF = Particulate matter formation; POF = Photochemical oxidant formation; TA = Terrestrial acidification.

5 Conclusions and outlook

The current study adds to the body of knowledge on the environmental impacts of electricity T&D, by examining the case of electricity supply in Nord-Trøndelag in Norway. We compile and analyse life cycle inventories for different power grid segments in a consistent manner, ensuring appropriate comparison and no overlap in data. To our knowledge, the present study is one of the first studies to analyse environmental impacts of transport of electricity via both transmission and local distribution in a coherent framework, and the first such study to take into consideration the different quantities of electricity that different grid sections deliver. The current case study hence provides new empirical findings and an original perspective on the environmental burdens associated with electricity T&D.

For electricity production fed into the main transmission grid, transmitted via the three main grid systems and delivered to a consumer connected to the Nord-Trøndelag local distribution grid, we find that the main shares of T&D impacts are attributable to local distribution, and smaller but not insignificant shares to regional and national transmission. Assuming a Norwegian electricity mix, infrastructure and power losses both contribute significantly to total impacts. Regardless of the assumed electricity mix, impacts caused by electricity T&D are significant or nonnegligible in comparison to impacts caused by electricity generation.

This study takes a snapshot of grid infrastructure, power delivery and power loss in a single year, and performs LCA as if systems are built in one go and as if their extent and configurations are fixed. Such an approach can offer useful insights into the impacts associated with current systems. At the same time, the approach is limited in that it does not address changes over time. In Nord-Trøndelag and Norway (and indeed elsewhere too) grid extensions and upgrades are key to achieve secure supply under changing electricity generation profiles and demand levels in the future. Extended or more sophisticated modelling may address this limitation, for example by performing LCA of future projections or scenarios emanating from investment plans or models [10, 13], by combining LCA and vintage capital modelling to capture transition dynamics ([1, 66]; see also [67] for a related discussion), or by coupling LCA and power system modelling [17].

Acknowledgments

The analysis builds on the MSc thesis of Hauan supervised or supported by Hertwich, Bolsøy and Arvesen. Arvesen's contribution was funded by the Research Council of Norway through the Centre for Sustainable Energy Studies (grant 209697). We are grateful to Raquel Santos Jorge for providing us with the raw data for her work on *Sentralnett*.

Appendix A. Supplementary material

Additional information on life cycle inventory data for the local distribution and regional transmission grids can be found in the Supporting Information (SI).

References

[1] Hertwich EG, Gibon T, Bouman EA, Arvesen A, Suh S, Heath GA, et al. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. PNAS. 2015; 112: 6277-6282.
[2] Masanet E, Chang Y, Gopal AR, Larsen P, Morrow WR, Sathre R, et al. Life-Cycle Assessment of Electric Power Systems. Ann Rev Environ Resour 2013;38(1):107-36.
[3] Sathaye J, Lucon O, Rahman A, Christensen J, Denton F, Fujino J, et al. Renewable Energy in the Context of Sustainable Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)]. 2011.
[4] Bashmakov IA, Bruckner T, Mulugetta Y, Chum H, Navarro ADLV, Edmonds J, et al. Energy systems. In Working Group III contribution to the IPCC 5th Assessment Report

"Climate Change 2014: Mitigation of Climate Change", edited by O. Edenhofer, et al. Genevea: Intergovernmental panel on climate change (IPCC); 2014.
[5] Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew Sust Energ Rev. 2013;28:555-65.
[6] Jorge RS. Environmental consequences of electricity transmission and distribution -- a life cycle perspective. Trondheim, Norway: Norwegian University of Science and Technology, 2013.
[7] Turconi R. Life cycle assessment of electricity systems. http://orbit.dtu.dk/services/downloadRegister/89362197/Roberto_Turconi_PhD_Thesis_WWW_Version.pdf Technical University of Denmark, 2014.
[8] Luderer G, Krey V, Calvin K, Merrick J, Mima S, Pietzcker R, et al. The role of renewable energy in climate stabilization: results from the EMF27 scenarios. Climatic Change. 2014;123(3-4):427-41.
[9] Krey V, Clarke L. Role of renewable energy in climate mitigation: a synthesis of recent scenarios. Climate Policy. 2011;11(4):1131-58.
[10] Jorge RS, Hertwich EG. Grid infrastructure for renewable power in Europe: The environmental cost. Energy. 2014;69:760-8.
[11] Carvalho MG. EU energy and climate change strategy. Energy. 2012;40(1):19-22.
[12] Nelson J, Johnston J, Mileva A, Fripp M, Hoffman I, Petros-Good A, et al. High-resolution modeling of the western North American power system demonstrates low-cost and low-carbon futures. Energy Policy. 2012;43(0):436-47.
[13] Arvesen A, Nes R, Huertas-Hernando D, Hertwich E. Life cycle assessment of an offshore grid interconnecting wind farms and customers across the North Sea. Int J Life Cycle Assess. 2014;19(4):826-37.
[14] Bergerson JA, Lave LB. Should We Transport Coal, Gas, or Electricity: Cost, Efficiency, and Environmental Implications. Environ Sci Technol. 2005;39(16):5905-10.
[15] Williams JH, DeBenedictis A, Ghanadan R, Mahone A, Moore J, Morrow WR, et al. The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. Science. 2012;335(6064):53-9.
[16] IEA. Energy Technology Perspectives 2014: IEA.
[17] Pehnt M, Oeser M, Swider DJ. Consequential environmental system analysis of expected offshore wind electricity production in Germany. Energy. 2008;33(5):747-59.
[18] Arvesen A, Bright RM, Hertwich EG. Considering only first-order effects? How simplifications lead to unrealistic technology optimism in climate change mitigation. Energy Policy. 2011;39(11):7448-54.
[19] Jones CI, McManus MC. Life-cycle assessment of 11 kV electrical overhead lines and underground cables. J Clean Prod. 2010;18(14):1464-77.
[20] Harrison GP, Maclean EJ, Karamanlis S, Ochoa LF. Life cycle assessment of the transmission network in Great Britain. Energy Policy. 2010;38(7):3622-31.
[21] Blackett G, Savory E, Toy N, Parke GAR, Clark M, Rabjohns B. An evaluation of the environmental burdens of present and alternative materials used for electricity transmission. Build Environ. 2008;43(7):1326-38.
[22] Bumby S, Druzhinina E, Feraldi R, Werthmann D, Geyer R, Sahl J. Life Cycle Assessment of Overhead and Underground Primary Power Distribution. Environ Sci Technol. 2010;44(14):5587-93.
[23] Turconi R, Simonsen C, Byriel I, Astrup T. Life cycle assessment of the Danish electricity distribution network. Int J Life Cycle Assess. 2014;19:100-8.
[24] Garcia R, Marques P, Freire F. Life-cycle assessment of electricity in Portugal. Appl Energy. 2014;134:563-72.

[25] Jorge R, Hawkins T, Hertwich E. Life cycle assessment of electricity transmission and distribution—part 2: transformers and substation equipment. Int J Life Cycle Assess. 2012;17:184-91.
[26] Jorge R, Hawkins T, Hertwich E. Life cycle assessment of electricity transmission and distribution—part 1: power lines and cables. Int J Life Cycle Assess. 2012;17(1):9-15.
[27] Jorge RS, Hertwich EG. Environmental evaluation of power transmission in Norway. Appl Energy. 2013;101:513-20.
[28] OED. Meld. St. 14. Vi bygger Norge -- om utbygging av strømnettet [White Paper on power grid development in Norway]. https://www.regjeringen.no/nb/dokumenter/meld-st-14-20112012/id673807/ [Accessed 18.12.14]: Ministry of Petroleum and Energy (OED); 2012.
[29] Ecoinvent. Life cycle inventory database v2.2. Swiss Centre for Life Cycle Inventories; 2010.
[30] Hegger S, Hischier R. ReCiPe - Implementation. Assignment of Characterisation Factors to the Swiss LCI database ecoinvent (version v.2.2). Midpoint method, hierarchist version. (http://www.lcia-recipe.net/). Swiss Centre for Life Cycle Inventories; 2010.
[31] Goedkoop MJ, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Version 1.11 - December 2014. (http://www.lcia-recipe.net/). PRé Consultants, Radboud University Nijmegen, Leiden University, RIVM; 2014.
[32] Ekvall T, Tillman A-M. Open-loop recycling: Criteria for allocation procedures. Int J Life Cycle Assess. 1997;2(3):155-62.
[33] Nexans. Kraftkabel. 1 kV hengeledning [Power cable. 1 kV overhead line]. http://www.nexans.no/eservice/pdf-group/1_kV_hengeledning_EX_.pdf [accessed 10.12.14]: Nexans; 2014.
[34] Nexans. PFSP 1kV med aluminiumsleder [PFSP 1 kV with aluminium conductor]. PFSP 1kV 3x25A/10. http://www.nexans.no/eservice/Norway-no_NO/pdf-product_537255667/PFSP_1kV_3x25A_10.pdf [accessed 12.12.14]: Nexans; 2014.
[35] Nexans. TFPX 1kV. TFXP1kV4G 50 mm^2A. http://www.nexans.no/eservice/Norway-no_NO/pdf-product_540185679/TFXP1kV4G_50_mm_A.pdf [accessed 12.12.14]: Nexans; 2014.
[36] Nexans. TSLF (HD) snodde 1-ledere (3X1) [TSLF (HD) twined 1-conductors]. TLSF (HD) 24kV3x1x95 AQ. http://www.nexans.no/eservice/Norway-no_NO/pdf-product_540175055/TSLF_HD_24kV3x1x_95AQ.pdf [accessed 12.12.14]: Nexans; 2014.
[37] Nexans. TSLF (HD) snodde 1-ledere (3X1) [TSLF (HD) twined 1-conductors]. TLSF (HD) 24kV3x1x150 AQ. http://www.nexans.no/eservice/Norway-no_NO/pdf-product_540175056/TSLF_HD_24kV3x1x150AQ.pdf [accessed 12.12.14]: Nexans; 2014.
[38] ABB. Miljörapport för år: 2007 (Swedish). Environmental report. 2008.
[39] ABB. Environmental product declaration. Distrubution transformer. 315 kVA, 11kV, 3 phase, ONAN.: http://library.abb.com/global/scot/scot292.nsf/veritydisplay/4dab3195c6221de4c1256d630041447f/$File/EPDdtr2.pdf [Accessed 12.12.14]: ABB; n.d.
[40] ABB. Environmental product declaration. Live tank circuit breaker, type LTB 145D. http://www05.abb.com/global/scot/scot292.nsf/veritydisplay/26be1bf0e5605ca1c12571550038d08b/$file/EPD%20Live%20Tank%20Circuirt%20Breaker%20LTB%20145D_en.pdf [12.12.14]: n.d.
[41] ABB. Environmental product declaration. EPD -- ANPA - 6. HD4. http://www05.abb.com/global/scot/scot292.nsf/veritydisplay/dfd45a30770c7268c1256d4100445b8a/$file/EPD_HD_4_PTVH_IT.pdf [accessed 12.12.14]: n.d.

[42] ABB. Environmental product declaration. UniSwitch. Medium voltage equipment. http://www05.abb.com/global/scot/scot235.nsf/veritydisplay/8d51f6839cd95b43c2256caa0047e75e/$file/epd%20uniswitch%20m1.pdf [accessed 12.12.14]: n.d.
[43] MVTS. Insulator catalogue. Contestability approved insulators. MV Technology Solutions; n.d.
[44] Nexans. Kabelboka. Håndbok for e-verkskabler [The cable book. Handbook for power cables]. http://www.nexans.no/eservice/Norway-no_NO/fileLibrary/Download_540200470/Norway/files/Nexans_Kabelboka_e-verk_2014.pdf [accessed 16.12.14]: Nexans; 2014.
[45] ABB. Environmental product declaration. Large distribution transformer 10 MVA (ONAN). http://www05.abb.com/global/scot/scot292.nsf/veritydisplay/57c1d5721712c65fc1256de9003d9401/$file/10%20MVA.pdf [accessed 17.12.14] 2003.
[46] ABB. Environmental product declaration. Large distribution transformer 16/20 MVA (ONAN/ONAF). http://www05.abb.com/global/scot/scot292.nsf/veritydisplay/f9d61dec5a651b81c1256de9003e870d/$file/16-20%20MVA.pdf [accessed 17.12.14]: 2003.
[47] ABB. Environmental product declaration. Power transformer TrafoStar 63 MVA. 2003. http://library.abb.com/global/scot/scot292.nsf/veritydisplay/4af3f4e6a43df7aec1256d630042c2fc/$File/ProductDeclarationStarTrafo63.pdf [accessed 15.04.13].
[48] ABB. Environmental product declaration. Power transformer 250 MVA. Registration nr. S-P-00054. http://www05.abb.com/global/scot/scot292.nsf/veritydisplay/e7c381463152c60bc1256de900407090/$file/pt%20250%20mva.pdf [accessed 17.12.14]: ABB Trasmissione & Distribuzione SpA; 2003.
[49] ABB. Environmental product declaration. Power transformer TrafoStar 500 MVA. 2003. http://www08.abb.com/global/scot/scot292.nsf/veritydisplay/566748ad75116903c1256d630042f1af/$file/ProductdeclarationStarTrafo500.pdf [accessed 15.04.13].
[50] Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, et al. Recent developments in Life Cycle Assessment. J Environ Manage. 2009;91(1):1-21.
[51] Sleeswijk AW, van Oers LFCM, Guinée JB, Struijs J, Huijbregts MAJ. Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. Sci Total Environ. 2008;390(1):227-40.
[52] NVE. Kostnader i energisektoren [Costs in the energy sector]. http://publikasjoner.nve.no/rapport/2015/rapport2015_021.pdf [Accessed 13 February 2015]: Norwegian Water Resources and Energy Directorate (NVE); 2012.
[53] Graus W, Worrell E. Methods for calculating CO2 intensity of power generation and consumption: A global perspective. Energy Policy. 2011;39(2):613-27.
[54] Arvesen A, Hertwich EG. Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. Renew Sust Energ Rev. 2012;16:5994-6006.
[55] Kleijn R, van der Voet E. Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. Renew Sust Energ Rev. 2010;14(9):2784-95.
[56] Kleijn R, van der Voet E, Kramer GJ, van Oers L, van der Giesen C. Metal requirements of low-carbon power generation. Energy. 2011;36(9):5640-8.
[57] SOE Norway. Fluorholdige gasser, utslipp [Fluorinated gases, emissions]. http://www.miljostatus.no/Tema/Klima/Klimanorge/Utslipp-av-klimagasser/Fluorholdige-gasser-utslipp/ [Accessed 05.02.15]: State of the Environment Norway (SOE Norway); 2015.

[58] Hauschild M, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O, et al. Identifying best existing practice for characterization modeling in life cycle impact assessment. Int J Life Cycle Assess. 2013;18(3):683-97.
[59] Kim, J., Yang, Y., Bae, J., Suh, S., 2013. The importance of normalization references in interpreting life cycle assessment results. Journal Ind. Ecol. 17, 385-395.
[60] Steen B. Abiotic resource depletion:Different perceptions of the problem with mineral deposits. Int J Life Cycle Assess. 2006;11(1):49-54.
[61] Pettersen J, Hertwich EG. Critical review: Life-cycle inventory procedures for long-term release of metals. Environ Sci Technol. 2008;42(13):4639-47.
[62] Suh S, Huppes G. Methods for Life Cycle Inventory of a product. J Clean Prod. 2005;13(7):687-97.
[63] Majeau-Bettez G, Strømman AH, Hertwich EG. Evaluation of Process- and Input–Output-based Life Cycle Inventory Data with Regard to Truncation and Aggregation Issues. Environ Sci Technol. 2011;45(23):10170-7.
[64] Arvesen A, Birkeland C, Hertwich EG. The importance of ships and spare parts in LCAs of offshore wind power. Environ Sci Technol. 2013;47(6):2948-56.
[65] Bush R, Jacques DA, Scott K, Barrett J. The carbon payback of micro-generation: An integrated hybrid input–output approach. Appl Energy. 2014;119(0):85-98.
[66] Arvesen A, Hertwich EG. Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment. Environ Res Lett. 2011;6(4):045102.
[67] Pauliuk S, Wood R, Hertwich EG. Dynamic Models of Fixed Capital Stocks and Their Application in Industrial Ecology. J Ind Ecol. 2014:n/a-n/a.