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Environmental evaluation of power transmission in Norway

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HIGHLIGHTS

- ▶ A life cycle assessment for the transmission of power in Norway is undertaken.
- ▶ Study includes: power lines, cables, transformers and substations installed by 2009.
- ▶ The transmission of 1 kW h of electricity in Norway generates 1.3–1.5 g CO_2 eq.
- ▶ Overhead lines, transformers and SF_6 losses cause most infrastructure impacts.
- ▶ A sensitivity analysis for different power mixes when modelling losses is performed.

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ABSTRACT

Electrical grid systems are required as a consequence of energy not being produced in the same place as it is consumed, and they are a key element of our energy systems. Transmission and distribution assets comprised of power lines, cables, transformers, substations and other electrical equipment generate a wide range of environmental impacts. Throughout the lifetime of the equipment, the impacts originate mainly from power losses during the use phase, but other life cycle stages such as installation, maintenance and dismantling also contribute significantly to some impact categories. In this paper, the environmental impacts of the Norwegian transmission grid are assessed. The methodology used here is Life Cycle Assessment (LCA) with ReCiPe as impact assessment method. In total, 11,097 km of lines and cables, 345 transformers and 121 substations were installed in the Norwegian transmission grid by the end of 2009; the network also included some hundreds of kilometers of sea cables between Norway and abroad. The results show that for each kW h of electricity transmitted in Norway, climate change impacts are of 1.3–1.5 g CO_2 eq., assuming a Norwegian electricity mix. Half of these emissions are associated with power losses, and the other half with infrastructure processes such as materials production, installation, maintenance, and end-of-life. The results also show that after the losses, the infrastructure processes for overhead lines and transformers, and the emissions of SF_6 from Gas Insulated equipment are the most relevant contributors for total climate impacts. A sensitivity analysis is done with respect to the electricity mix used to model power losses in the system. The results show that the contribution of power losses to the total climate change scores increases to 84% and 94%, by replacing the Norwegian mix by the Nordic mix and the European mix, respectively.

1. Introduction

The electricity grid is a key component of our energy systems, allowing power to be transferred from the power plant to the consumer. There is a growing body of scientific literature on environmental impacts for power generation processes, including several Life Cycle Assessment (LCA) studies [1–11] and hybrid life cycle approaches [12,13], to cite a few. However, not many studies on power systems include or provide detailed life cycle data for transmission and distribution (T&D) impacts. T&D is important for every LCA of electricity and understanding its environmental impacts is increasingly relevant in the context of planning future energy systems. The power grid is expected to play a key role in the phasing in of renewable power supply [14], as well as in the electrification of transportation [15]. Many studies throughout the world have demonstrated that increasing network investments towards additional kilometers and capacity to the transmission network are required in order to achieve successful rates of renewable energy integration [16]. Some projects suggest that linking different regions through expansion of the connecting power grid will help meet emissions targets [17] and achieve other environmental benefits [18]. Additionally, other interventions, such as adding communication and control capabilities to optimize network

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operation, are expected to enable the grid system to reduce the overall environmental impacts of the electricity supply system [19]. Although there will be changes in the way they operate, the power grids of the future will still transport power over "copper and iron", i.e. future grids will still be made of power lines, cables, transformers and substations amongst other components. Therefore, knowing the impacts for future grid systems and understanding their potential role for a greener electricity sector requires a good comprehension of today's grids impacts.

The research questions for this article are the following: what are the life cycle impacts of a grid system used for the transmission of power? Which processes and components cause the most emissions? If power losses in the network are modeled with different electricity mixes, how does that change the overall life cycle impacts?

The goal of this paper is to estimate and characterize the environmental impacts of the Norwegian transmission system, also called *Sentralnett*. The methodology used here is Life Cycle Assessment (LCA), with the impact assessment method ReCiPe. Detailed data on the infrastructure installed at the *Sentralnett* was provided by the electricity regulator in Norway – NVE [20] and the Norwegian transmission system operator (TSO) – Statnett [21]. Physical and electrical parameters for the installed power lines and cables were obtained from Sintef Energy AS [22]. This study builds on a previous life cycle analysis on the environmental impacts of different components of electrical grid systems – such as power lines, cables, transformers and other equipment [23,24]. This paper takes a step further on the analysis presented in [23,24] by modeling a real grid system and going from a component's perspective to a system perspective. Also, instead of using hypothetical values for power losses, real system data is used in this study. The aim is to understand the relative importance of the different components and life cycle stages for the total grid system impacts. Previous LCAs of T&D systems exist in the literature, but they either have a different scope [25,26], do not include some of the impact categories included here [27] or as previously mentioned, include only components of the system but not the system as a whole [23,24,28–30]. This study can therefore bring a contribution to the field of LCA for T&D. The Norwegian electrical grid is an interesting case study. Norway's electricity production relies almost exclusively on hydro power. In 2009, 96% of the country's total 132.8 TWh of electricity production was generated by hydro power plants [31]. There is an idea of utilizing Norwegian pumped storage power as one of the solutions for balancing North European intermittent renewable power production [32]. This requires an upgrade of the Norwegian and the trading countries electrical grid system along with the construction of several thousand of kilometers of cables from Norway to other countries in the North of Europe, e.g. Germany, Netherlands, UK [33]. The study of the life cycle impacts of the currently installed transmission system in Norway can therefore prove useful for actors working with grid extension planning issues; in fact, the decision makers have already identified the need for LCA studies in helping choosing different transmission solutions [34]. Previous studies indicate that the largest environmental impacts for T&D systems originate from power losses [23,24,27]. According to NVE [31], total losses in the T&D system in Norway are of 7% of the total power production, corresponding to 9296 GW h of losses in 2009. Of these, 2215 GW h, or approximately 24% of the total T&D system losses, occur in the *Sentralnett* [20]. The goal for this article is to estimate and characterize the environmental burdens of transmitting power in the *Sentralnett* system and to understand how the different processes in the life cycle of the network contribute to the overall impacts. Apart from losses, the study aims at identifying which other important processes have a relevant contribution to the total impacts.

2. Material and methods

2.1. Method details

Life Cycle Assessment (LCA) is used to evaluate the environmental performance of the Norwegian transmission system. LCA is a well-established method applied in the calculation of "cradle-to-grave" impacts of products or services. The procedure of the LCA method is defined in the ISO 14,040 and 14,044 standards [35,36]. The results are obtained using the ReCiPe 2008 midpoint-oriented impact assessment method [37]. There is a degree of uncertainty in the knowledge of the mechanisms which lead to climate change and other environmental impacts. As a way of addressing this uncertainty, the ReCiPe method proposes the use of three perspectives – egalitarian, individualistic and hierarchical, which make different scenarios with regard to the environmental consequences of a certain process. By considering different time frames, rates of adaptation, etc., the three perspectives reflect different degrees of optimism for the causality process-effect [37]. In this paper, results are obtained for the three perspectives. From the 18 impact categories addressed by the method, the following are included in this analysis: agricultural land occupation, climate change, freshwater eutrophication, human toxicity, marine eutrophication, metal depletion, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification and water depletion. In order to understand how different electricity mixes affect the final results, a sensitivity analysis is done with respect to the mix used for modeling electricity losses in the network. In addition to the Norwegian supply mix, results are also obtained for the Nordic mix (corresponding to the Nordel mix in Ecoinvent) and for the average European mix. The end-of-life scenarios include processes such as disposal, landfill and recycling, and these have been included. To account for the benefits of recycling, the approach indicated by Ecoinvent is followed here, i.e., recycling of steel is modeled by using pig iron as avoided product and scrap iron as an input. The LCA calculations were performed by linking the foreground system to a background system – the Ecoinvent v2.2 database. The computations were done by using ARDA, an LCA software tool developed by researchers at the Industrial Ecology Programme at NTNU [38].

2.2. Scope and functional unit

Power in the Norwegian grid is transported from generators via the transmission grid (132–420 kV), main distribution grid (47–132 kV), and high-voltage (11–22 kV) and low-voltage (230–400 V) distribution grids to the final consumers [22]. The scope of this LCA study is the Norwegian transmission grid (132–420 kV), also called *Sentralnett*. Overall, by the end of 2009, approximately 300,000 km of lines and cables, 32,500 transformers, and 125,500 substations were installed in Norway [20]. From these, a total of 10,971 km overhead lines, 52 km of underground cables, 1037 km of sea cables, 345 transformers and 121 transformer stations are part of the transmission network, which is evaluated here. The functional unit is 1 kW h of electricity delivered from the *Sentralnett* to the main distribution grid.

2.3. System boundary

This section addresses time and geographical coverage of the study, included components and processes as well as data sources, quality and representativeness. This LCA study refers to the infrastructure installed in the Norwegian transmission grid by the year 2009. The *Sentralnett* infrastructure includes overhead lines, underwater cables, underground cables, transformers and substations,