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Emissions from cycling of thermal power plants in electricity systems with high penetration of wind power: Life cycle assessment for Ireland

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HIGHLIGHTS

- Environmental impact of a power system with a high share of wind power assessed.
- Cycling emissions (start-up and part-load) included in LCA for the first time.
- Increased cycling emissions did not negate benefits of higher wind penetration.
- Energy storage combined with base load coal did not reduce system emissions.
- Current life cycle assessment methodology underestimates power plant emissions.

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ABSTRACT

The increase of renewable sources in the power sector is an important step towards more sustainable electricity production. However, introducing high shares of variable renewables, such as wind and solar, cause dispatchable power plants to vary their output to fulfill the remaining electrical demand. The environmental impacts related to potential future energy systems in Ireland for 2025 with high shares of wind power were evaluated using life cycle assessment (LCA), focusing on cycling emissions (due to part-load operation and start-ups) from dispatchable generators. Part-load operations significantly affect the average power plant efficiency, with all units seeing an average yearly efficiency noticeably less than optimal. In particular, load following units, on average, saw an 11% reduction. Given that production technologies are typically modeled assuming steady-state operation at full load, as part of LCA of electricity generation, the efficiency reduction would result in large underestimation of emissions, e.g. up to 65% for an oil power plant. Overall, cycling emissions accounted for less than 7% of lifecycle CO_2, NO_x and SO_2 emissions in the five scenarios considered: while not overbalancing the benefits from increasing wind energy, cycling emissions are not negligible and should be systematically included (i.e. by using emission factors per unit of fuel input rather than per unit of power generated). As the ability to cycle is an additional service provided by a power plant, it is also recommended that only units with similar roles (load following, mid merit, or base load) should be compared. The results showed that cycling emissions increased with the installed wind capacity, but decreased with the addition of storage. The latter benefits can, however, only be obtained if base-load electricity production shifts to a cleaner source than coal. Finally, the present study indicates that, in terms of emission reductions, the priority for Ireland is to phase out coal-based power plants. While investing in new storage capacity reduces system operating costs at high wind penetrations and limits cycling, the emissions reductions are somewhat negated when coupled with base load coal.

1. Introduction

Recent years have seen a steady development of renewables, in particular hydro, wind and solar power, which represented 18% of global electricity generation in 2011 [1]; by 2035 renewables are forecasted to account for almost one third of total electricity output [2]. In 2009 the Irish government set a target of 40%

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renewables in the electricity sector by 2020 [3], most of which will be provided by wind generation. Introducing increasingly high shares of variable and uncertain renewables such as wind and solar poses a challenge to the power system, where dispatchable power plants are requested to continuously increase and decrease their output to accommodate the variability of wind and solar generation, and to ensure that the electrical demand is always fulfilled.

Many studies in recent years have assessed the technical feasibility of power systems with large shares of renewables [4–11], nevertheless the environmental impacts for such systems have only partially been assessed, focusing predominantly on direct greenhouse gas (GHG) emissions at the power plant level. Tonini and Astrup [12] is the only study that the authors are aware of which assesses the environmental impacts over the entire life cycle of a power system with a high penetration of renewables. Life cycle assessment (LCA) is in fact mainly used today to assess the environmental impacts from single generation technology [13–17]. A key limitation to this approach is not contextualizing the power plant within the power system [18]: variable output power sources such as solar and wind generation may induce efficiency penalties in fossil power plants providing balancing reserves [19,20]. These penalties may result in higher GHG emissions due to greater fuel volumes being used and, additionally, air pollution control systems that mitigate other emissions, such as NO_x, may not operate optimally when the generator power level is rapidly changed, further increasing emissions [21]. A common approach within LCA is to identify the emission per unit of energy generated [22]; emissions induced by variable renewables through cycling of fossil power plants are, therefore, usually not included, and have only recently been discussed [9–11,21,23]. This study followed the approach outlined in [9–11], which analyzed entire energy systems and recognized that aggregation reduced both variability of wind power and cycling requirements of the dispatchable power plant fleet. However [9–11] only assessed direct emissions, i.e. at the power plant stack.

This study used LCA to assess the environmental impacts of an electricity system with a high penetration of variable renewables, in this case wind power. The island of Ireland (here simply referred to as Ireland) was used as a case study, and five possible portfolio scenarios for 2025 were modeled. Hourly energy modeling was used to quantify the operational consequences of having a high share of renewable sources in the power system, as suggested in [8,23,24]. Particular focus was placed on the "cycling" impacts for fossil fuel power plants which need to operate at partial load and startup/shutdown to ensure that the maximum contribution from renewable electricity is accommodated in the network and that the electricity demand is always fulfilled. These operational aspects are usually accounted for when looking at past scenarios – since actual power plant data is typically used – but are often neglected when modeling future scenarios – because the time resolution is not accurate enough or power plant technical constraints are not included in the energy modeling.

The objectives of this study were (i) to evaluate CO_2, NO_x and SO_2 emissions from possible future plant portfolios for Ireland in an LCA perspective, (ii) to investigate emissions due to cycling (how relevant were cycling impacts compared to the overall emissions, which power plant types were most affected, and how different power plant mixes influenced the overall emission due to cycling), and (iii) to evaluate the results of this study with respect to common approaches in LCA of electricity generation technologies.

2. Methodology

In LCA, potential environmental impacts associated with the life cycle of a product/service are assessed based on a life cycle inventory, which includes relevant input/output data and emissions compiled for the system associated with the product/service in question. The LCA modeling in this study followed the recommended ISO methodology [25,26], and is explained in the following sections.

2.1. Goal, scope and functional unit

The goal of the LCA was to assess the environmental impacts related to five possible future energy scenarios for Ireland. The functional unit of the study was "fulfilling the electricity demand in Ireland in 2025", corresponding to 41 TW h. Attributional LCA was used, since the focus of this study was to identify the environmentally relevant physical flows to and from a product/service's life cycle and its subsystems in a status quo situation [27]. Three emissions were included in the study: CO_2, NO_x and SO_2, representing the main contributors to global warming, acidification and eutrophication from the energy sector [16]. Emission data were obtained as output from the power system modeling (see Section 2.2.1). All additional effects "outside" the system and the functional unit was accounted by system expansion following common approaches for addressing multi-functionality within LCA [27].

Three main sources of impacts during the life cycle of a power plant were included in the modeling, as suggested in [16]: fuel provision (from the extraction of fuel to the gate of the plant), plant operation (direct stack emissions), and infrastructure (commissioning and decommissioning). Within power plant operation, the focus of this study was to identify the role of part-load and start-up related emissions.

2.2. Scenario definition

2.2.1. Power system modeling

Unit commitment and economic dispatch was completed for the Irish power system at an hourly resolution using PLEXOS for Power Systems® [28]. The modeling was performed using mixed integer linear programming, using the Xpress MP solver. Energy and reserves were co-optimized, minimizing the total generation cost for the system. Three categories of operating reserve were included in the optimization, with varying requirements for response time and duration [29]. The primary and secondary operating reserve (POR & SOR) requirements were set to 75% of the largest infeed, while the tertiary operating reserve (TOR) requirement was set to 100%. There was an additional requirement which accounted for load and wind power forecast errors, over the reserve activation period, in addition to forced outages [30]. This resulted in minimal increases in fast acting POR requirements, but larger increases in the slower reserve categories, and varied depending on the level of installed wind generation.

The optimization horizon in PLEXOS is flexible and user-defined, and was set here to 24 h, with a further 24 h look-ahead. This ensured that plant start-ups were scheduled appropriately for plants with high start-up costs. It also ensured that energy remained in the reservoir at the end of the day, depending on the future system needs, for any modeled storage plant.

Costs included in the objective function were fuel costs, carbon costs and start-up costs. Each generator was modeled with a number of constraints which included maximum and minimum generation levels, minimum up and down times, ramp rates and reserve response levels [31]. Fig. 1 shows efficiency as function of the load for dispatchable power plants; each plant was modeled individually. A number of system constraints were also included to ensure system stability, which were based on the system operator's "Operational Constraints Update" [30]. Included within these system constraints was a system non-synchronous penetration (SNSP) limit, which bounded the fraction of demand which can be