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Based on EU Reference Scenario 2016 it is projected that from 2020, electricity demand will experience a 0.7% growth rate every 5 years [1]. Norway''s climate target for 2030, aiming to achieve a more than 40% reduction in greenhouse gas (GHG) emissions compared to the reference year 1990, sets the foundation for its long-term goals. Looking ahead, the country''s commitment will continue to strengthen, with the target progressively increasing towards an ambitious 80-95% reduction in GHG emissions by 2050 [2]. At the same time, high shares of non-dispatchable renewable energy sources, such as solar and wind energy, will create an increasing need for flexibility in European the energy system to mitigate reliability issues [3].

Models that are limited to analyses of power systems have some similar approaches in common. For example, Mara??n-Ledesma and Tomasgard [10] combined long-term investment and short-term uncertainty in a power market model with DR for Europe by using the European power market model called EMPIRE [11]. EMPIRE is formulated as multi-horizon stochastic programming model [12], and its structure is similar to that of the TIMES model used in our study.

One of the purposes of our study is to see how DR complements the flexibility of Norwegian hydropower. In a previous study, Kirkerud et al. [15] used the deterministic energy system model BALMOREL to investigate the role of DR in northern Europe. Their results showed that space heating and water heating were the primary sources of DR in Norway and Sweden. Additionally, they showed that DR variable cost was low enough to compete with regulated hydropower, which is the two countries'' primary source of flexibility. In our model, we have formulated short-term uncertainties that can take into account different weather-dependent stochastic scenarios when considering the interplay between DR and hydropower.

The TIMES model includes long-term capacity expansion decisions and short-term stochastic operations to meet the future energy service demand by minimizing system cost [25]. Energy system models such as TIMES do not typically include a complex transmission network [26]. Also, the TIMES-Norway model does not include details of a power system''s technical constraints (e.g., ramps rates, minimum necessary generation) because the Norwegian system is primarily hydropower-based. These limitations may lead to underestimations of the value of flexibility and DR.

The paper is organized as follows. The next section provides a short overview of Norway''s DR potential and costs. Section 2 presents the TIMES-Norway model. Section 3 describes how to model DR in TIMES. Section 4 analyses the effects of DR on the Norwegian energy system and its export. Section 5 presents our conclusions.

In this section, we elaborate on the costs of DR and the potential in terms of volume. Electricity consumption is discussed in relation to three main consumer groups: industrial, residential, and commercial.

In Norway, the main sources of DR potential are electricity and heat demand from the industrial sector [28]. Figure 1 shows that in Norwegian industries it is possible to achieve 476 MW of load shedding potential for different processes [27]. Such processes are not able to shift their electricity consumption but can switch to other sources of energy. In our model, the only energy source for these processes is electricity, and the load shedding could be done by either substitution with other fuels or stopping production.

The load shedding potential for energy-intensive processes in Norway

We model load shedding in industry with an intervention time of up to 4 h, meaning that load can be shed in four consecutive hours and then be normal for at least 1 h, after which a new DR intervention may start. Load shedding can be activated up to 40 times per year as a model assumption. This is consistent with different process specifications and the DR potential estimations by Gills [27], Paulus and Borggrefe [29], and Stadler [30].

Industrial processes and their load shifting potential in Norway

The total cost of DR consists of fixed costs and variable costs. Variable costs comprise electricity price, and the cost of energy and materials. In Eqs. (1)-(4), the structure of costs is the same as presented by Gruber et al. [31]:

where P is sale price, Pel is electricity price, M is margin, Pma is material cost, VC is variable cost, Pen is energy cost, FC is fixed cost, Pr is profit, OC is opportunity cost.