Regional Effects of Hydrogen Production in Congested Transmission Grids with Wind and Hydro Power

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***Abstract*—Some of the best wind and natural gas resources in Norway are located in rural areas. Hydrogen can be produced from natural gas in combination with carbon capture and storage to utilize the natural gas resources without significant CO_2-emissions. The hydrogen can be liquefied and transported to regions with energy deficits. This creates a demand for hydrogen produced from electrolysis of water, which facilitates wind power development without requiring large investments in new transmission capacity. A regional optimization model is developed and used to investigate sizing of the electrolyser capacity and hydrogen storage, as well as regional effects of producing hydrogen from electrolysis. In the model, the transmission grid is represented by dc power flow equations and opportunities for wind power investments in the region are included.**

The model is used in a case study which shows that hydrogen storage contributes to significantly increase grid utilization, even with small amounts of storage. Increased regional transmission capacity results in more wind power development compared to increased capacity towards the central grid. Hydrogen storage is only profitable to reduce congestion in this deterministic model, thus using hydrogen storage to reduce the costs in the spot market is not profitable.

NOMENCLATURE

Indices

i, j	Bus
t	Time stage

Parameters

Δ	Price addition for import [€/MW]
$\eta^{d/s}$	Conversion factor from power to hydrogen [MWh/Nm^3], directly from electrolyser or from hydrogen storage
γ_i	Conversion factor, effect to energy [MWh/MW]
λ_t^s	Spot price [€/MWh]
$C^{r/i}$	Cost of rationing [€/MWh] or hydrogen import [€/Nm^3]
$C^{v+/v-}$	Cost for violating end reservoir level [€/MWh]
$C^{w/e/s}$	Annualized cost of wind power [€/MW], hydro power [€/MW] or electrolysers [€/Nm^3]
D_{ti}	Electricity demand [MWh]
E_i^{pot}	Potential for electrolyser capacity [MW]
H_t^D	Hydrogen demand from electrolysis [MWh]
H_i^{pot}	Potential for hydrogen storage capacity [Nm^3]
I_{ti}	Inflow to hydro power reservoirs [MWh]
P_t^w	Wind power production profile
$Q_{ti}^{min/max}$	Min or max hydro power production [MW]
S^{ref}	Reference power for the system [MW]
T_{ij}^{max}	Max transmission capacity from bus i to j [MW]
$V_i^{0/max}$	Initial volume or max capacity for reservoir [MWh]
W_i^{init}	Initially installed wind power [MW]
W_i^{pot}	Potential for wind power expansion [MW]
X_{ij}	Reactance on line between bus i and j [$p.u.$]

Sets

$\mathcal{B}$	All buses
$\mathcal{C}_i$	Buses connected to bus i by transmission lines
$\mathcal{H}, \mathcal{W}, \mathcal{H}_2$	Buses with hydro power, wind power or hydrogen plants
$\mathcal{N}$	All normal buses (Market bus excluded)
$\mathcal{T}$	Time stages

Variables

δ_{ti}	Voltage phase angle at bus
c_{ti}	Energy curtailment [MW]
e_i^{max}	Installed electrolyser capacity [MW]
f_{tij}	Power flow from bus i to j [$p.u.$]
h_{ti}^d	Hydrogen supplied to load directly from electrolyser [Nm^3]
$h_{t,i}^{imp}$	Hydrogen imported/ not served [Nm^3]
h_i^{max}	Installed hydrogen storage capacity [Nm^3]
h_{ti}^p	Hydrogen production from electrolysis to storage [Nm^3]
h_{ti}^s	Hydrogen supplied to load from storage tanks [Nm^3]
h_{ti}	Level of hydrogen in storage tank [Nm^3]
$p_{ti}^{imp/exp}$	Power import or export [MW]
q_{ti}	Hydro power production [MW]
r_{ti}	Rationing of power [MW]
s_{ti}	Spillage/ bypass of water [MWh]
$v^{+/-}$	Violation of end reservoir level [MWh]
v_{ti}	Reservoir level [MWh]
$w_i^{exp/max}$	Wind power expansion or installed capacity [MW]
w_{ti}	Wind power production [MW]

I. INTRODUCTION

In 2015, Norway was the worlds third largest exporter of natural gas exporting 115 billion cubic meter (1219 TWh). In comparison the total hydro power production, which is the backbone of the Norwegian electric power system with 96% of the total production, was 137 TWh as the worlds sixth largest producer [1]. Increased attention to reducing CO_2-emissions as result of their contributions to global warming stresses the importance of finding new ways to utilize the fossil resources without emitting CO_2. One way of utilizing natural gas resources is to produce hydrogen through a process called steam methane reforming (SMR), combining this with carbon capture and storage (CCS) allows the natural gas resources to be utilized without significant CO_2-emissions.

Many of the future natural gas resources are located offshore from rural areas which also has good wind power resources. The development of wind power resources in these areas are constrained by weak transmission grids and the cost of constructing new transmission lines makes these wind resources unprofitable [2], [3]. Producing hydrogen from natural gas in areas with good wind resources results in development of more renewable electricity production, as it also establishes a demand for hydrogen produced from electrolysis of water. Liquefaction of hydrogen is energy demanding and results in an additional increase of electricity demand in the region. Energy can thus be transported out of the region in the form of liquid hydrogen for example by ship, reducing the need for costly grid investments. The combination of hydrogen production from natural gas with CCS, wind and hydro power is part of a project at Sintef Energy Research named Hyper [4], as a part of this project the effects of variable hydrogen production from electrolysis in a transmission constrained power system with good wind power resources needs to be studied further to assess the possible benefits.

Wind-hydrogen systems have been analysed for several years, both as isolated and grid connected systems. Significant efforts have been devoted to this topic by many researchers and test facilities are constructed for studying the properties of these systems. Two examples are the test facilities at Utsira in Norway [5] and at the National Renewable Energy Laboratory in the US [6]. Large scale hydrogen production is considered to facilitate wind power integration in Denmark, Ireland and Germany in [7],[8] and [9] respectively. The main focus in these studies is on balancing generation and demand in power systems with high penetration of intermittent renewable energy sources, as wind and solar power, by storing energy as hydrogen and convert it back to electricity using fuel cells.

In [10] a logical simulation model is used to simulate operation of a wind-hydrogen system with and without storage in a constrained transmission grid, the analysis shows promising result for using hydrogen production with storage as a load management method in constrained grids, contributing to increased utilization of the wind power resources. A model for sizing and operation of wind-hydrogen systems in weak distribution grids based on optimization is developed in [11]. Grid simulations are used to create linearized functions for the limits of export and import to the wind-hydrogen bus based on the load in the local distribution grid. The result shows that it's beneficial to use the power grid as backup power for hydrogen production compared to building a larger hydrogen storage. For electricity markets with large variations in the spot price it would be beneficial to install more wind power, electrolyser capacity and hydrogen storage to produce more hydrogen when prices are low and export more power when prices are high. Both these models are used on small scale wind-hydrogen systems and focus more on operation of a local system, not considering regional effects on other producers, wind power in several buses or the regional transmission grid.

In [12] a stochastic optimization model with dc power flow equations is developed for scheduling of hydro-thermal power systems and solved using a method based on stochastic dual dynamic programming. The model is applied in a case study for future scenarios of the Islandic power system with wind and pumped hydro power. Significant computing resources are needed to solve this model as stochasticity is considered both in power price and generation. It's obvious that considering stochasticity when optimizing the size of electrolyser and hydrogen storage in such a system would not be tractable without significant computing resources.

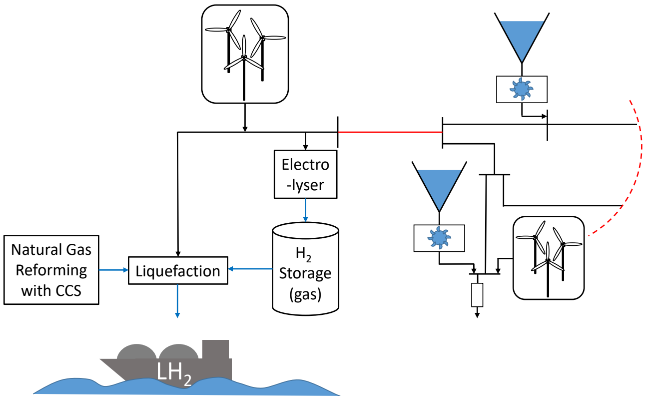

Fig. 1. Illustration of a regional power system with production of hydrogen from wind and hydro power in a constrained transmission grid (red lines).

The scope of this paper is to establish a method for optimizing the size of both the electrolyser and hydrogen storage and to examine the regional effects on the power system due to variable hydrogen production from electric power. A deterministic model for the regional power system is developed and used for this purpose, including dc power flow equations, wind power farms and hydro power plants with reservoirs. Analysis of important economic aspects of the system such as cost of hydrogen production and profits of hydro power producers are also included.

The paper is organized as follows; first the optimization model is described in chapter II, then a case study is presented in chapter III and the results from the case study are presented and discussed in chapter IV. Finally the conclusions are given in chapter V.

II. METHODOLOGY

A illustration of a regional power system with hydrogen production is shown in Figure 1, the system comprise hydro power with reservoirs, wind power, firm loads and hydrogen production plants with electrolysers and storage tanks. The system borders is chosen to exclude the detailed liquefaction process which is instead defined as a constant hydrogen and electricity demand. The regional transmission grid is modelled by dc power flow equations thus neglecting power loss in the transmission grid, while the rest of the power system is modelled by a ”market bus” with a deterministic power price.

The power system is represented by a linear programming model defined by Equation (1) to (9) with hourly time stages. The objective is to minimize investment cost in wind power, electrolysers and hydrogen storage while maximizing the profits from energy exchange between the region and the external power market. Export from the regional system is equivalent with import to the market bus, p_{t0}^{imp}, and import to the regional system is equivalent with export from the market bus, p_{t0}^{exp}. A small price difference on the power price is introduced to avoid importing and exporting at the same time, this reflects the real situation in the transmission grid where the marginal loss part of the tariff is opposite for producers and consumers [13]. The objective also includes penalties for rationing, hydrogen import and end reservoir violations.

$$
\begin{aligned}
\max - \frac{T}{8760}&\Big[\sum_{i\in\mathcal{W}} C_i^w w_i^{exp} + \sum_{i\in\mathcal{H}_2} C_i^e e_i^{max} + \sum_{i\in\mathcal{H}_2} C_i^s h_i^{max}\Big] \\
&+ \sum_{t\in\mathcal{T}}\Big[\lambda^s p_{t0}^{imp} - (\lambda^s + \Delta) p_{t0}^{exp} - \sum_{i\in\mathcal{N}} C^r r_{ti} - \sum_{i\in\mathcal{H}_2} C^i h_{ti}^i\Big] \\
&- \sum_{i\in\mathcal{H}} (C^{v+} v_i^+ + C^{v-} v_i^-) \qquad (1)
\end{aligned}
$$

s.t.

$$
\begin{aligned}
& w_{ti} + c_{ti} = \gamma_i w_i^{max} P_{ti}^w && \forall i \in \mathcal{W}, \forall t \in \mathcal{T} && (2)\\
& w_{ti}^{max} = W_i^{init} + w_i^{exp} && \forall i \in \mathcal{W} && (3)\\
& v_{ti} = v_{(t-1)i} - q_{ti} - s_{ti} + I_{ti} && \forall i \in \mathcal{H}, \forall t \in \mathcal{T} && (4)\\
& v_{0i} = V_i^0 && \forall i \in \mathcal{H} && (5)\\
& v_{Ti} - v_i^+ + v_i^- = V_i^0 && \forall i \in \mathcal{H} && (6)\\
& h_{ti} = h_{(t-1)i} + h_{ti}^p - h_{ti}^s && \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T} && (7)\\
& h_{ti}^d + h_{ti}^s + h_{ti}^i = H_{ti}^D && \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T} && (8)\\
& w_{ti} + q_{ti} - \eta^d h_{ti}^d - \eta^s h_{ti}^p && && \\
& \qquad - p_{ti}^{exp} + p_{ti}^{imp} + r_{ti} = D_{ti} && \forall i \in \mathcal{N}, \forall t \in \mathcal{T} && (9)\\
& p_{ti}^{exp} - p_{ti}^{imp} = S^{ref} \sum_{j\in\mathcal{C}_i} f_{tij} && \forall i \in \mathcal{B}, \forall t \in \mathcal{T} && (10)\\
& f_{tij} = \frac{1}{X_{ij}}(\delta_{ti} - \delta_{tj}) && \forall j \in \mathcal{C}_i, \forall i \in \mathcal{B}, && \\
& && \forall t \in \mathcal{T} && (11)\\
& w_{ti} \le w_i^{max} \le W_i^{init} + W_i^{pot} && \forall i \in \mathcal{W}, \forall t \in \mathcal{T} && (12)\\
& v_{ti} \le V_i^{max} && \forall i \in \mathcal{H}, \forall t \in \mathcal{T} && (13)\\
& Q_{ti}^{min} \le q_{ti} \le Q_i^{max} && \forall i \in \mathcal{H}, \forall t \in \mathcal{T} && (14)\\
& \eta^d h_{ti}^d + \eta^s h_{ti}^p \le e_i^{max} \le E_i^{pot} && \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T} && (15)\\
& h_{ti} \le h_i^{max} \le H_i^{pot} && \forall i \in \mathcal{H}_2, \forall t \in \mathcal{T} && (16)\\
& f_{tij} \le T_{ij}^{max} / S^{ref} && \forall j \in \mathcal{C}_i, \forall i \in \mathcal{B}, && \\
& && \forall t \in \mathcal{T} && (17)
\end{aligned}
$$

The wind power plants can produce, w_{ti}, or curtail, c_{ti}, power dependent on the installed wind power capacity, w_i^{max}, the energy coefficient, γ_i, and wind power profile, P_{ti}^w, as stated in Equation (2). As shown in Equation (3) the installed wind power capacity comprise initial wind power capacity, W_i^{init}, and capacity expansion determined by the model, w_i^{exp}.

Hydro power plants are modelled by a reservoir balance shown in Equation (4) where the reservoir volume, v_{ti}, is dependent on the reservoir volume in the previous hour, hydro power production, q_{ti}, spillage, s_{ti} and inflow, I_{ti}. To ensure comparability between different cases the reservoir volume at the end of the model horizon is forced to be equal to the initial reservoir volume by Equation (6), any violations are penalized in the objective.

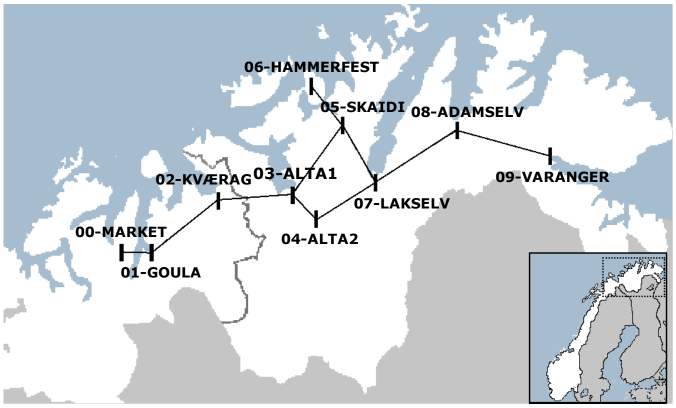

Fig. 2. Illustration of case study system based on Finnmark in Northern Norway.

The representation of the hydrogen plants include a storage balance as shown in Equation (7) where the hydrogen storage level, h_{ti}, is dependent on level in the previous hour, hydrogen production, h_{ti}^p, and hydrogen demand supplied from storage, h_{ti}^s. The hydrogen demand can be covered by supplying hydrogen directly from the electrolyser, h_{ti}^d, from the storage tanks or by importing hydrogen, h_{ti}^i, from an external source as stated by the hydrogen balance in Equation (8). Importing hydrogen can also be treated as "hydrogen not supplied", where the cost of imported hydrogen is representing a penalty for not serving the hydrogen load. Supplying the hydrogen demand directly from the electrolyser gives a better conversion factor, $\eta^d \le \eta^s$, as compression to storage pressure is avoided.

The energy balance for a bus is shown in Equation (9), where wind power production, hydro power production, rationing and power import are power injections into the bus while power is extracted by producing hydrogen, covering demand or exporting power. Export and import are subject to the flow balance in Equation (10) and dc load flow equations in Equation (11).

III. CASE STUDY

The case study illustrated in Figure 2 is created based on a region in Northern Norway with good wind conditions and large amounts of future natural gas resources. The region has a constrained connection to the rest of the Nordic power system which is restricting development of wind power. A facility for natural gas processing and liquefaction to LNG currently exist at Melkøya in Hammerfest (bus 6), this bus is thus chosen as the location for the hydrogen production facility in the case study. The power requirements of the LNG plant is currently fully supplied by on-site gas turbines with a capacity of 225 MW. In this case study, the power requirements for the

TABLE I
BUS DATA FOR THE CASE SYSTEM. POTENTIAL WIND POWER IS BASED ON PERMIT APPLICATIONS [15].

Bus Nr.	Wind [MW]	Wind Pot [MW]	Hydro [MW]	Reservoir [GWh]	Load [GWh/yr]
1	0.0	10.0	80	224.8	225.5
2	0.0	0.0	85	231.9	35.1
3	0.0	0.0	17.7	46.5	374.3
4	0.0	0.0	145.2	56.7	22.7
5	40.5	160.0	4.2	5.0	121.5
6	0.0	10.0	1.1	0.0	188.2
7	0.0	0.0	1.7	1.6	136.6
8	40.0	1550.0	55.1	168.5	80.2
9	95.0	453.0	78.3	16.1	680.3
Sum	175.5	2173.0	468.3	751.1	1864.4

liquefaction and hydrogen plant is considered to be supplied by the power system.

The region is the most promising for wind power in Norway according to a study by the Norwegian Water Resources and Energy Directorate (NVE) [14] with almost twice the wind power potential of any other region. A significant number of wind power development projects have applied for permits, most of them are located in the eastern part of the region at bus 8 and 9, far away from the central grid. Table I gives an overview of the most important bus data for the case study including an estimate of potential wind power capacity based on permit applications. The developed wind power is low compared to the wind power potential, mainly as a result of low transmission capacities in combination with a surplus hydro power production and low power prices recent years.

As the transmission capacity from the region is limited the Norwegian TSO, Statnett, is currently building a new transmission line with a voltage level of 420 kV from the market bus to bus 5 in Figure 2. Further expansions from bus 5 to bus 8 is also under consideration but is dependent on the development of load in the region especially from the petroleum industry as it is not regarded viable from a socioeconomic perspective for the purpose of extracting wind power alone [3]. Based on the current plans for the transmission grid, three grid cases are considered by doubling the capacity on the existing lines:

- Local (L): line 5-6 (included in all alternatives).
- Regional (R): line segment 5-7-8.
- National (N): line segment 0-1-2-3-5.

Based on the detailed study of hydrogen storage in [16] the annualized cost of hydrogen storage is calculated to be approximately 4.16 and 2.63 €/(Nm^3·yr) for storage at 9.5 and 350 bar respectively, assuming 4% discount rate, 24 years lifetime and 0.5% maintenance cost. The investment cost for a large scale ($\geq$50 MW) state-of-the-art alkaline electrolysis plant is around 500 €/kW [17]. By including a reinvestment of 57% of the initial investment cost after 12 years, maintenance cost of 5% and a total lifetime at 24 years the annualized costs are calculated to be 69.47 €/(kW·yr). The power requirement for hydrogen production delivered directly from the electrolyser to liquefaction at 20 bar is estimated to be 4.66 kWh/Nm^3, when compression to storage pressure at 350 bar is included the power requirement increase to 4.79 kWh/Nm^3.

TABLE II
INSTALLED CAPACITIES FOR ELECTROLYSER AND HYDROGEN STORAGE AND RATIONED ENERGY. HYDROGEN STORAGE IS REPRESENTED BY VOLUME AND HOURS OF HYDROGEN DEMAND.

	Local		Regional		National
Capacities	E	ES	E	ES	
Elec [MW]	107.99	128.87	107.99	110.97	107.99
Storage [Nm^3]	-	231003.8	-	101550.8	0.0
Storage [h]	-	9.97	-	4.38	0.0
Rat [MWh]	199.47	0.0	354.63	0.0	0.0

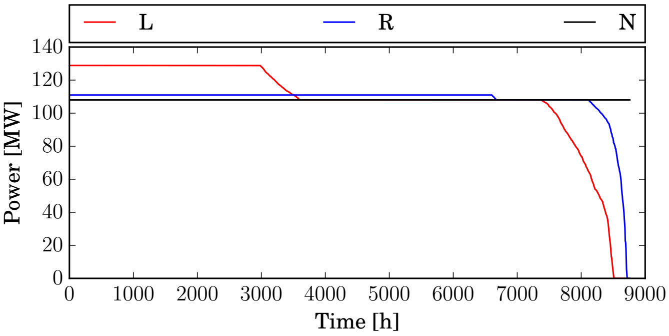

Fig. 3. Duration curve of the electrolyser for hydrogen production with storage.

Four different load cases are considered in the bus with hydrogen production; a base case (B) with no change from the current system, a load case where the electricity demand for liquefaction is included (D), a case with hydrogen production without storage (E) and a case with hydrogen production and storage (ES). Spot price, wind power production and load are based on historic data for the power system from 2015.

IV. RESULTS AND DISCUSSION

As shown from Table II both the local and the regional grid cases requires hydrogen storage to avoid rationing of energy. In the local case the storage capacity is double the size of the regional case. To be able to utilize the storage capacity efficiently the electrolyser capacity is significantly higher in the local case compared to a case without storage, requiring about ten extra electrolysers, while the electrolyser capacity is only slightly higher for the regional case resulting in only one additional electrolyser. As shown in Figure 3 the utilization of the additional electrolysers decrease with increasing storage capacity. In the national case, when the connection to the central grid is strong, it's not profitable to invest in storage only to reduce operational costs from the spot market.

The local and regional case for constant electrolyser production is subject to the highest investments in new wind power capacity due to rationing. Rationing makes it profitable

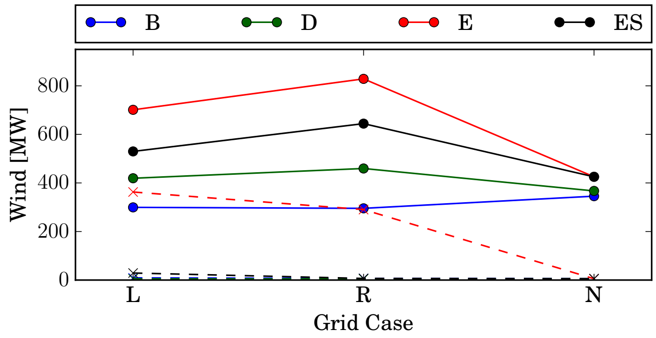

Fig. 4. Total wind power capacity in the region (solid lines) and wind power curtailment (dotted lines) for different cases.

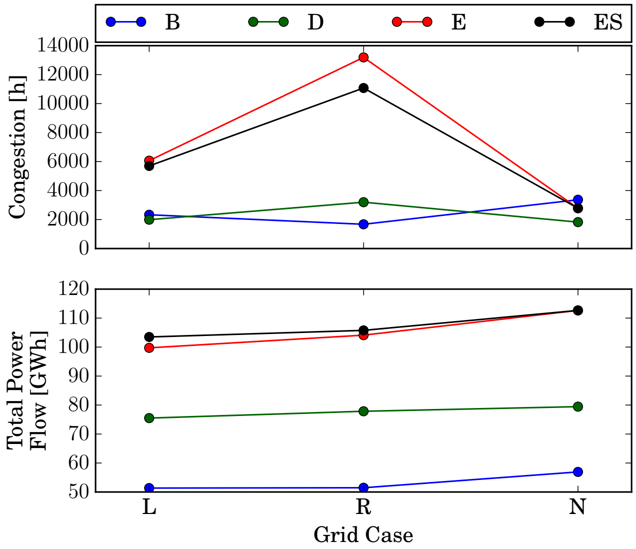

Fig. 5. Total numbers of hours with congestion for all lines (top) and sum of power flow for all lines in the region (bottom).

from a system point-of-view to invest in wind power capacity, considering that grid reinforcements and hydrogen storage are unavailable, even though significant amounts of wind power is curtailed as shown in Figure 4. The largest amount of wind power development, without unacceptable amounts of rationing and curtailment, is for the regional case with hydrogen storage. For the national case the effects of additional loads on wind development is significantly reduced and the differences between the grid cases are small.

Expanding the grid capacity from the local case to the regional case results in increased amounts intermittent energy in the form of wind power in the region for the cases with increased load and thus more congestion as shown in the upper part Figure 5. The congestion is significantly less when a hydrogen storage is included, thus reducing the levels of wind power curtailment and rationing. Even though the hours of congestion is lower when hydrogen storage is included the total power transmitted by the transmission grid is higher as shown in the lower part of Figure 5, resulting in a more efficient use of the transmission grid capacity. The hydrogen storage doesn't effect the total power flow as much in the regional case compared to the local case as the optimal hydrogen storage capacity is lower, but it still has a larger effect with respect to reducing the hours of congestion in the regional case as more wind power is developed.

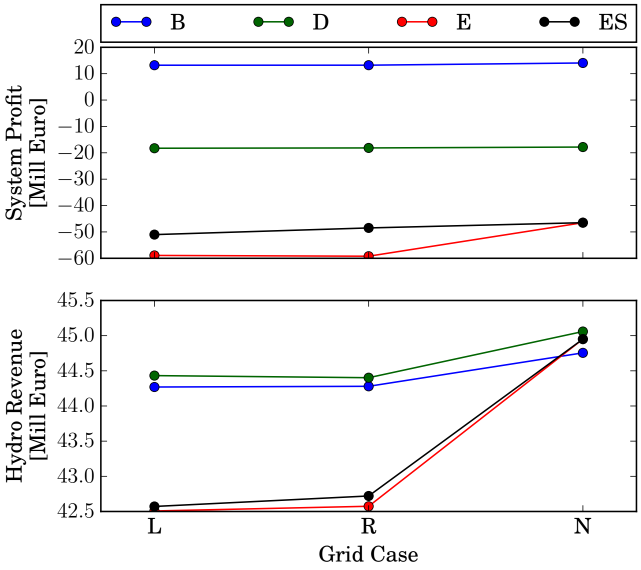

Fig. 6. Total system profit from exchange with the external market, including investment cost for wind power and hydrogen plant and costs from rationing (top). Total revenue for all hydro power plants in the region (bottom).

As shown in the upper part of Figure 6 the system revenue is positive in the base case, supplying power requirements of the natural gas processing and hydrogen liquefaction from the regional power system increases the total system load which results in a negative profit. Further increasing the load by producing hydrogen from electrolysis and investing in electrolyser and hydrogen storage reduce the system profit even more. The system profit is lower when hydrogen storage is not included and the grid is constrained due to rationing.

The total revenue for all the hydro power producers in the region is shown in the lower part of Figure 6 which shows that more load in the region is positive for hydro power producers as long as it doesn't result in significant levels of congestion. The revenue is higher for load case D but significantly lower for the cases with hydrogen production from electrolysis as these cases result in high levels of grid congestion. The hydro power producers are forced to move production to less profitable hours when congestion increase due to more wind power, as hydro power with reservoirs can store energy while wind power plants cannot. This effect is reduced when more grid capacity is available with the regional expansion. The case with hydrogen storage results in less congestion for the cases with low levels of grid expansion and thus also higher revenues for the hydro power producers. The best case for the hydro power producers is clearly the national case with a stronger connection to the central grid as it results in less wind power development and less congestion allowing them

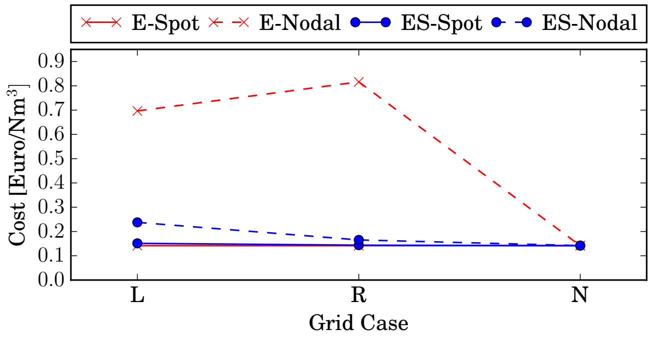

Fig. 7. Hydrogen production cost including investment and operational costs.

to produce at the highest prices.

The cost of hydrogen production is shown in Figure 7 and comprise both investment and operational costs. The operational costs are calculated both from spot and nodal prices, where the nodal prices are obtained from the duals of the energy balance in Equation (9) and is the marginal cost of energy in the given bus. When using the nodal price to calculate the cost of hydrogen production the total cost for the power system is included and the case with hydrogen storage is significantly cheaper than without hydrogen storage. The case without storage results in slightly lower costs when only considering the spot price, thus the main purpose of the storage isn't to reduce the cost of purchasing power from the spot market but to reduce congestion. Grid tariffs would be added to the cost of hydrogen production in addition to the spot price, this tariff is suppose to represent the cost of utilizing the transmission grid [13] and would likely be higher for the case without storage as the nodal price indicates. The differences between the cost of hydrogen production with storage in the regional case and the national case is relatively small, 0.165 and 0.142 €/Nm^3 respectively. The significant uncertainty related to both wind and hydro power would likely increase both optimal hydrogen storage and the cost of hydrogen production.

V. CONCLUSION

The sizing of electrolyser and hydrogen storage in a transmission constrained system is studied and some effects of hydrogen production on the power system are investigated. A case study in Northern Norway is analysed using a deterministic optimization model which also allows for wind power investments. The case study shows that the hydrogen storage has a high degree of utilization and the numbers of electrolysers increases rapidly with the storage capacity. Hydrogen storage is important to avoid rationing when the transmission grid is constrained and helps to reduce the hours of congestion and utilize the transmission grid more efficiently.

A regional expansion of the grid between the hydrogen production and the wind power facilitate wind power development but also increases the congestion level. Hydro power revenue is reduced due to increased congestion, this effect is smaller when hydrogen storage is included as congestion is reduced. Hydrogen storage is important to the cost of hydrogen production in constrained transmission grids due to the reduced congestion, while it's not profitable when a strong connection to the market is available and it would only be used to reduce the operational costs from the spot market.

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