Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Martin Nord Flote

Automatic Frequency Regulation Through Hydrogen Production

Master's thesis in Energy and Environment
Supervisor: Federico Zenith
June 2020

NTNU
Norwegian University of
Science and Technology

Martin Nord Flote

Automatic Frequency Regulation Through Hydrogen Production

Master's thesis in Energy and Environment
Supervisor: Federico Zenith
June 2020

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

With an increasing amount of installed capacity from intermittent power sources like solar and wind power, the equilibrium between power production and consumption in the grid will be challenged in the future. To increase grid flexibility, hydrogen energy storage systems can be used as variable loads in order to regulate the power consumption to keep the grid frequency stable. This report investigates the technical and economical potential for a wind-hydrogen system with a 2.5 MW electrolyser participating as a frequency regulating load in Norway, Germany and Spain. Simulations of an up-scaled electrolyser at 45 MW nominal power are also performed.

The results show that electrolysers qualify for participation in frequency regulation in Norway and Germany, while loads cannot offer this service in the Spanish grid. Delivering frequency containment reserve capacity is economically advantageous if the selling price of hydrogen is below 38.8 NOK/kg in Norway and 3.3 EUR/kg in Germany. Selling up-regulating frequency restoration reserve capacity in the German grid is economically advantageous if the selling price of hydrogen is below 8.7 EUR/kg, while for down-regulating reserves the price must be lower than 15.3 EUR/kg.

The revenue from the sale of frequency regulating services justify a larger investment into electrolyser capacity, as any unused capacity can be used for frequency regulation. As the demand for hydrogen grows any unused capacity can be fully utilised for hydrogen production, speeding up the growth of the hydrogen economy. It is also possible that any reductions in selling prices for hydrogen can be covered by the sale of frequency regulating capacity.

Sammendrag

Med økende mengde installert variabel effekt fra sol- og vindkraft blir frekvensstabiliteten i det elektriske nettet utfordret i fremtiden. For å øke fleksibiliteten i nettet kan energilagringsenheter bestående av elektrolysører brukes som variable laster. Økt mengde fleksibel last vil hjelpe til med å holde produksjon og forbuk av energi i likevekt og dermed stabilisere frekvensen. Denne oppgaven ser på det tekniske og økonomiske potensialet i et vind-hydrogen system med en elektrolysør på 2.5 MW som leverandør av frekvensreguleringstjenester i Norge, Tyskland og Spania. Simuleringer for en oppskalert elektrolysør på 45 MW er også inkludert.

Resultatene i denne oppgaven viser at elektrolysører kvalifiserer seg til å kunne levere frekvensreguleringstjenester i Norge og Tyskland, mens det kun er generatorer som kan levere slike tjenester i det spanske nettet. Salg av primærreserver er økonomisk gunstig dersom salgsprisen for hydrogen er lavere enn 38.8 NOK/kg i Norge, og 3.3 EUR/kg i Tyskland. Oppregulerende sekundærtjenester er gunstig ved hydrogenpriser under 8.7 EUR/kg, mens nedregulerende sekundærtjenester er gunstig ved hydrogenpriser lavere enn 15.3 EUR/kg.

Inntektene fra salg av frekvensreguleringskapasitet kan rettferdiggjøre en investering i større elektrolysørkapasitet, siden all ubrukt kapasitet kan brukes som frekvensregulering. Når etterspørselen etter hydrogen øker kan den ledige kapasiteten raskt utnyttes til hydrogenproduksjon. En slik strategi kan hjelpe til med raskere vekst av infrastruktur for hydrogen. Det er også mulig at salg av frekvensreguleringstjenester kan dekke noe av tapene når salgsprisen for hydrogen synker i fremtiden.

Preface

This is a master thesis written at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology for the Energy and the Environment MSc study programme, 2 years. The project was defined by Sintef as a part of the EU-funded HAEOLUS project. My internal supervisor was Federico Zenith at Sintef.

I would like to give my thanks to Federico for answering any and all questions and introducing me to the HAEOLUS project and many of the contacts that are involved with the project. I could likely not have finished this piece of work if not for his knowledge and contacts in this field of research. I would also like to thank said contacts in Varanger Kraft, Statnett SF and Hydrogenics for all the help they have given me.

Table of Contents

List of Tables

List of Figures

Abbreviations

FCR	=	Frequency Containment Reserve
FCR-N	=	FCR activated between grid frequencies 49.9 - 50.1 Hz
FCR-D	=	FCR activated between grid frequencies 49.5 - 49.9 and 50.1 - 50.5 Hz
aFRR	=	automatic Frequency Restoration Reserve
mFRR	=	manual Frequency Restoration Reserve
LFC Area	=	Load-Frequency Control Area
TSO	=	Transmission System Operator
BESS	=	Battery Energy Storage Systems
BRP	=	Balancing Responsible Party
BSP	=	Balancing Service Provider
AGC	=	Automatic Generation Control
LCOH	=	Levelized cost of hydrogen
BCOH	=	Break-even cost of hydrogen
FRS	=	Frequency Regulation Service
FCH-JU	=	Fuel Cell and Hydrogen Joint Undertaking
CAPEX	=	Capital expenditure / investments
OPEX	=	Operating expense, costs of operation
ENTSO-E	=	European Network of Transmission System Operators for Electricity
SA	=	Sensitivity analysis
Cap price	=	Capacity price, used in the sensitivity analysis
a	=	Annualized capital costs
A	=	Capital investment costs
C_i	=	Annual costs for category i
I_i	=	Annual income from category i
N	=	Annual net revenue, difference between annual incomes and costs
m_{H_2}	=	Annual hydrogen production from electrolyser
E_{wind}	=	Energy provided by wind turbines
R_{FCR}	=	Total amount of FCR capacity contracted by TSO [MW/h]
L_{FCR}	=	FCR capacity sold to TSO, [MW/h]
$R_{aut,act}$	=	Total amount of automatic frequency regulation reserve activated [MWh]
$R_{aFRR,act}$	=	Total amount of aFRR activated [MWh]
L_{act}	=	Activated frequency regulation reserve, [MWh]
L_{aFRR-i}	=	aFRR-i sold to TSO [MW/h]
R_{aFRR-i}	=	Total amount of aFRR-i contracted by TSO [MW/h]
E_{ele}	=	Energy flow to electrolyser [MWh]
E_{sold}	=	Energy sold at the electrical spot market [MWh]
P_i	=	Power capacity for category i [MWh]
t_{non-op}	=	Number of hours during the analysis period where the electrolyser is switched off

Chapter 1

Introduction

Due to an increasing amount of installed capacity originating from intermittent power sources like wind and solar power, instabilities in the equilibrium between energy production and consumption in the electrical grid are likely to increase as conventional thermal power plants are replaced by wind turbines and solar panels [1]. These instabilities are handled using frequency regulation capacity, a service provided by the different loads and generators connected to the grid, where they keep power and energy in reserve to balance energy production and/or consumption into equilibrium.

One possible solution to increased grid stability is an investment into energy storage systems. Despite of there being a shortage of power during hours of peak demand, there is an annual surplus of energy in the Finnmark region [2]. Thus, such a storage system can shift energy from times of excess to the hours where more power is required. As an energy storage system, hydrogen production by electrolysis of water is a technology with a highly adjustable power capacity and short power ramping times, in addition to playing right into the European Union's strategy for increasing the amount of clean, renewable energy [3, 4].

HAEOLUS (Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation) is a EU-funded project which aims to increase the reliability of intermittent wind power through storing energy in the form of hydrogen. The project is coordinated by SINTEF with several companies from countries in Europe contributing with both research and monetary funding. Among these is Varanger Kraft, who is responsible for the wind-hydrogen system on the test site of the project in Berlevåg, Norway [5].

The test site, Raggovidda Wind Park, consists of 15 turbines, each with a capacity of 3 MW. There is also an electrolyser and a hydrogen fuel cell installed at the site, courtesy of Hydrogenics, another participant in the HAEOLUS project. While the Raggovidda wind park has the highest capacity factor of the parks in Norway [6] the grid in the area is too weak to handle possible expansions in capacity in the future. Varanger Kraft has already been granted concessions for a total of 200 MW of installed wind power capacity, while the grid only allows for a total of 95 MW to be exported out of the Varanger peninsula local grid [7].

This report will map the technical and economic potential of a 2.5 MW water electrolysis plant in Finnmark, powered by wind power, delivering frequency regulating services. Due to the electrolyser power ramping characteristics, the services delivered here are restricted to faster, automatic services. As the amount of wind power in Norway is relatively small compared to other countries in Europe [8], simulations of wind-hydrogen systems with properties identical to that of the test site are performed to see how market principles, volumes and pricing affect the economic feasibility of the system. These simulations are run for wind-hydrogen systems participating in the German and the Spanish grid.

As a part of a wind-hydrogen system, the electrolyser has been restricted to running purely on energy provided by the wind turbines. As the electrolyser is connected to the grid to deliver frequency regulating services, any activated balancing energy will also either add to or subtract from the total energy flow to the electrolyser. The produced wind energy, in turn, will be used in such a way that the electrolyser can provide as much frequency regulating capacity as possible while maximizing hydrogen production. Any remaining wind energy will be sold as electrical energy. The wind-hydrogen system will prioritize, in descending order, frequency regulating services, hydrogen production and lastly the sale of electrical energy.

Chapter 2

Literature Review

As Europe works towards a future with more renewable energy, securing grid stability becomes more challenging with an increasing share of intermittent power sources like solar and wind power. Grid stability encompasses both frequency and voltage, but the scope of this report is frequency regulating services provided by a wind-hydrogen system identical to the test-site at Raggovidda wind park. As the wind-hydrogen system concept is far from new, research focusing on both technical and economical aspects has already been conducted.

Research on other energy storage systems, mainly battery systems, has also been reviewed to gain insight into certain market mechanisms for new entries into frequency regulation reserve markets.

Santos and Marino [9] analyses the wind-hydrogen system located at Raggovidda with respect to the operation of the electrolyser. Strategies including operation at certain electricity market spot prices as well as a local grid congestion issues have been addressed. The former involves only producing hydrogen when the price of grid electricity is below a certain threshold. Grid congestion involves considering the capacity for export in the local grid, only producing hydrogen when the amount of generated electrical energy exceeds the grid's export capacity. It is concluded that it would be economically feasible to expand the wind power generation capacity beyond the local grid export capacity to ensure higher electrolyser utilisation and consequentially reduce the per-unit production cost of hydrogen.

Santos, Rodriguez and Santiago [10] expands upon the research in [9] and analyse wind farms in Smøla and Raggovidda, Norway and Moncayuelo, Spain. The conclusion for the Smøla case is similar to the Raggovidda case, where low electrolyser utilisation means that small units are most economically desirable. However, congestion management leads to very high production prices for hydrogen for this case. For the Moncayuelo case, the wind farm is used to provide secondary frequency regulation to the Spanish grid.

In the report it is concluded that the inclusion of frequency regulation only marginally reduces the production price of hydrogen, although the operation strategies are not optimised in this case.

Nistor et al. [11] investigates the economical perspective of hydrogen refueling stations located in the United Kingdom with on-site hydrogen production, and compares grid-connected production units to a wind-hydrogen system. It is concluded that while a wind-hydrogen system provides the lowest per-unit-cost of hydrogen, a combined grid- and wind energy-system would reach higher electrolyser utilisation and more reliable delivery of hydrogen.

Alshehri et al. [12] reviews the European ancillary services market, encompassing the shared market of most of Central Europe, and investigates the possibilities of introducing PEM electrolysers and fuel cells as participants in said market. It is concluded that state-of-the-art PEM hydrogen technology fulfills the requirements for participation in future European Frequency Containment Reserve (FCR) and automatic Frequency Restoration Reserve (aFRR) markets and would contribute to increased stability of the grid. A simplified simulation of a part of the Dutch grid shows that replacing conventional synchronous generators with PEM electrolyzers and fuel cells will allow for faster containment of frequency deviations and less oscillation in the grid frequency.

Eichman, Townsend and Melaina [13] investigates configurations and operation strategies for hydrogen systems to deliver grid services to the Californian grid as a link in maximizing profits for said systems. It is concluded that while providing ancillary services results in higher revenues compared to systems only participating in energy markets, investing in fuel cells to re-electrify hydrogen significantly increases system costs while only slightly increasing revenues. Therefore, hydrogen systems should focus on selling the hydrogen as well as focus on delivering ancillary services in order to optimize economical viability.

Fleer et al. [14] studied both technical and economical aspects of a battery energy storage system (BESS) as a participant in the German frequency regulation market. The German FCR market operation is described, as are the changes in the European FCR market. An interesting development is noted, where the price of FCR services decreases sharply in 2016 following a more competitive market with the integration of neighbouring markets and an increased amount of balancing service providers.

Keck, Lenzen, Vassallo and Li [15] investigates the effects of BESS in the Australian grid, and finds that the use of these systems increases grid flexibility. BESS help maintain the production-consumption equilibrium for electrical energy and reduces the amount of necessary installed renewable energy production capacity. It is found that deployment of large-scale BESS is economically feasible only when there is a high degree of penetration of renewable sources in the energy mix. Tesla's 100 MW battery [16] is an example of such a system.

Lastly, Badeda, Meyer and Sauer [17] investigates the effect of a decreasing number of conventional thermal power sources and a growing number of battery energy storage systems on the price of FCR services in the German market. It is concluded that battery systems will become essential to the FCR market and that the price of these reserves will decrease in the future.

Chapter 3

Theory

3.1 The wind-hydrogen system

An electrolyser is an electrochemical device that expends electrical energy to split water (H_2O) into hydrogen gas (H_2) and oxygen (O). The electrolyser studied in this report is a PEM electrolyser consisting of several smaller electrolyser stacks making up the unit. Physical data for the electrolyser in the wind-hydrogen system studied in this report are presented in table 3.1 [9, 18, 19, 20].

The electrolyser has three different operating modi: on, off and standby [9]. While the power consumption is zero in off-mode and between 0.3 and 3.25 MW in on-mode, the electrolyser requires 1 kW to remain in standby-mode. This energy is required to keep the electrolyser pressurised. The response time listed in table 3.1 describes the time it takes for the electrolyser to transition from stand-by mode to full production. The power load increases linearly from 1 kW to 2.5 MW during this time. The start-up time for cold starts describes the time it takes for the electrolyser to transition from off-mode to full production. The electrolyser capacity is limited to 50% during this transition. Power loads during start-up times are not included in the analysis, and it is also assumed that the electrolyser can remain in stand-by mode even with zero output from the wind farm through the connection to the grid. Given the stand-by consumption rate relative to nominal power rate, it is neglected in the economical analysis.

Electrolyser life time expectancy is measured both in calendar time and operating time, and measures the time it takes before overhaul or replacement is required. As the electrolyser utilisation in this analysis is quite high, operating life time expectancy becomes the limiting variable used when estimating overhaul costs. When up-scaling the electrolyser the number of stacks is increased. When the electrolyser is running at low capacities it is assumed that some of the stacks can either be switched off or enter stand-by mode. Thus, while the nominal power is increased to 45 MW, it is assumed that the minimum power remains unchanged at 0.3 MW. It is also assumed that other parameters like response times

Parameter	Value
Nominal power	2.5 MW
Minimum power	0.3 MW
Maximum power	3.25 MW
Hydrogen delivery pressure	30 bar
Hydrogen production rate	45 kg/hour
Response time (warm start)	30 seconds
Start-up time (cold start)	1200 seconds
Ramp rate up/down	60 MW/min
Standby consumption	1 kW
Shut down time (transition to standby)	1 second
Switch off-time	(2 minutes)
Life time expectancy	20 years
Life time expectancy	40,000 operational hours
Overhaul cost	354 € /kW
CAPEX	1328 € /kW
OPEX	60 € /kW/year
Hydrogen factory facility	10-15 MNOK
Hydrogen storage cost	400 € /kg

Table 3.1: Electrolyser physical data

and capital and operation costs remain unchanged. Since up-scaling involves simply increasing the number of stacks, the ramping rate scales linearly with nominal capacity as each stack increases/decreases the load individually. As for hydrogen factory facility costs, this is a rough estimation made by Varanger Kraft and depends on where the factory is located.

Even though the electrolyser is able to operate in the range from 0.3 MW to 3.25 MW, peak electrolyser load has been limited to the nominal capacity as there is uncertainty in how the operating loads influence the operating and overhaul costs. Since the minimum step sizes for both FCR and aFRR are 1 MW/h, as explained later, this limitation does not influence the sale of and income from frequency regulating reserves. However, capping the maximum power will limit the electrolyser utilisation and the amount of hydrogen that can be produced.

Hydrogen production is calculated using the energy flow to the electrolyser and a fixed electrolyser efficiency. This is calculated using the nominal power and the hydrogen production rate listed in table 3.1, which yields an efficiency of 55.6 kWh/kg H_2. A sensitivity analysis with respect to electrolyser efficiency is also performed based on estimations from the FCH-JU multi-annual work plan [4].

It is assumed that the hydrogen storage tanks are emptied once at the start of every week. The weekly hydrogen production is used to determine the storage tank size which is equal to the largest of the accumulated weekly productions, measured in kg. This is used to calculate the cost of storage tanks, which varies depending on the type of reserve capacity is being offered.

Physical and economical data on the Raggovidda wind park are presented in table 3.2 [20].

Parameter	**Value**
Nominal power	45 MW
CAPEX	900 €/kW
OPEX	40 €/kW/year

Table 3.2: Raggovidda wind park data.

As data on energy generation from the wind turbines are available in an hourly resolution [9], it is assumed that the effect delivered from the turbines is constant through the hour. The energy generated at the Raggovidda wind farm is shown in figure 3.1. As the series for 2018 is incomplete, the data set for 2017 is the primary data source in the analysis.

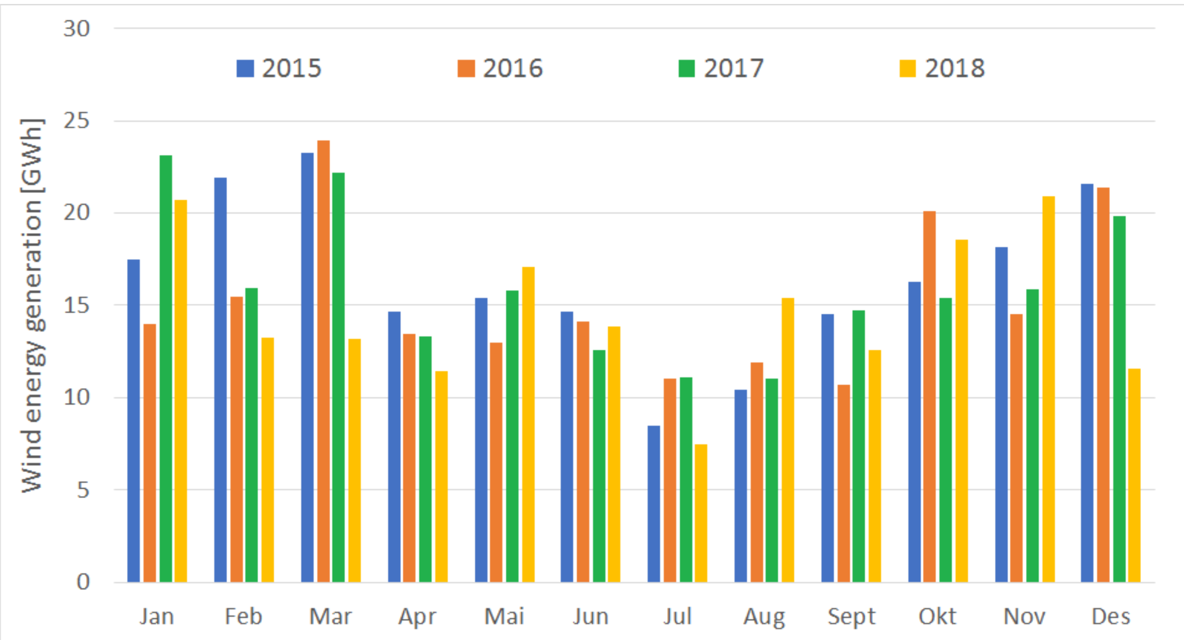

Figure 3.1: Histogram of Raggovidda wind farm energy generation

A fuel cell is an electrochemical device that generates electrical energy by producing water from oxygen and hydrogen gas. Although the fuel cell installed at the Raggovidda test site is so small that it is unable to participate in the market for frequency regulating services, the costs are included in the analysis as the fuel cell has already been installed. Any operation of the fuel cell is not included in the analysis. Physical and economical data for the installed fuel cell are presented in table 3.3 [9].

Parameter	**Value**
Nominal power	120 kW
Minimum power	12 kW
Maximum power	132 kW
Hydrogen consumption rate	9 kg/hour
Response time (warm start)	<5 seconds
Ramp rate up/down	<3 seconds to full power

Table 3.3: Fuel cell data.

3.2 Frequency regulation

The electrical grid is in itself incapable of storing energy. Thus, all the electrical energy that is fed into the grid at any point in time must also be consumed by the units connected to the same grid. In other words, the energy production from connected units (generators) must be equal to the energy consumption of connected units (loads) [21]. In the case of an inequality, the energy surplus or deficiency is absorbed by the producing units connected to the grid. If the energy production is larger than the consumption, the surplus is delivered back to the generators, where it is converted into kinetic energy by increasing the rotational speed of the generators. An increase in rotational speed leads to an increase in the frequency of the electrical signal in the grid. With an energy deficit in the grid, kinetic energy in the generators is converted into electrical energy, resulting in decreased rotational speed and grid frequency.

As grid frequency deviations are potentially harmful to devices connected to the grid, a major task of Transmission System Operators (TSOs) is to make sure that the frequency at all times remains as close as possible to the nominal value. For the Nordic and European synchronous grids, this value is 50 Hz [21, 22]. The TSO must have enough frequency regulating capacity available to handle any unforeseen losses of energy production or consumption that cause deviations from the nominal grid frequency. For instance, the required aFRR capacity in the Nordic synchronous grid in Europe is 300 MW [23]. This total amount of capacity is distributed among the TSOs operating in said grid.

Capacity and/or activation markets for both up- and down-regulating frequency regulating services are tendered by the respective TSOs [24, 25]. For loads, down-regulation involves reducing the consumption and vice versa for up-regulation. A symmetrical reserve capacity combines both of these features simultaneously.

While reserves contracted through the capacity market are secured prior to real-time and is only activated when needed, balancing energy is procured in real-time and remunerated for the volume procured [23]. There is work underway to establish a common market platform for frequency restoration reserves in Europe through ENTSO-E with the aim of harmonizing many of the European markets. Norwegian, German and Spanish TSOs will participate in this common platform.

For roles and responsibilities regarding balancing services the Guideline for Electricity Balancing (GLEB) [26] is consulted. This guideline separates between Balancing Service Provider (BSP) and Balancing Responsible Party (BRP). The BSP must be qualified by the TSO for providing balancing energy or capacity. Any qualified BSPs can submit bids for balancing energy, including reserve type, volume and price. BSPs are also responsible for activating and verifying bids, and is remunerated for the services provided [23]. The BRP is responsible for the real-time balancing, and is financially responsible to the respective TSO for any imbalances. As all bids made in the balancing markets must be connected to a BRP, all participants in the balancing energy markets must either have the role of BRP or be represented by one.

3.2.1 Norway

Energy supply and demand at the Nordic day-ahead and intra-day energy markets results in a production-consumption equilibrium. However, any disturbances caused by unforeseen events must be covered by regulating capacity, contracted through the regulating power market. Frequency containment reserve capacity, as well as both automatic and manual frequency restoration reserve capacity, are procured in markets tendered by the Norwegian TSO, Statnett SF [23].

Two separate products are available on the Norwegian FCR capacity market. FCR-N is a symmetrical reserve that is activated when the grid frequency is in the 50$\pm$0,1 Hz range. FCR-D is a non-symmetrical reserve, activated when the frequency drops below 49,9 Hz. The contracted capacity should be fully activated by the time the frequency reaches 49,50 Hz. For FCR-D, only up-regulating power is available as a remunerable service on the Norwegian market as of December 2019 [22], although there are plans for tendering a market for down-regulation in the future [27].

As of August 2018, loads offering FCR capacity must be able to activate 50% of the contracted capacity within 5 seconds, while the whole capacity must be activated within 30 seconds [23]. Any activated FCR-N volume is remunerated in accordance with prices on the regulating power market, while any activated volume of FCR-D is not remunerated as of December 2019 [22]. If the direction of the activated volume is opposite of the regulating power dominating direction in the area, the activated volume is priced at spot price [27].

As products in capacity markets, there is no guarantee that the procured power reserves are activated. Services are acquired both in day-ahead markets and in weekly markets, although the majority of the volume is procured in the former. As a participant in the Nordic partnership for grid stability, Norway's share of the frequency containment capacity volume is 212 MW FCR-N and 350 MW FCR-D per August 2018 [23].

Per August 2018, aFRR is procured for 30-40 hours per week for specific hours when the power consumption in the grid is ramping up or down. Units providing aFRR must be pre-qualified based on grid-wise location and is only procured in the NO1 and NO5 zones [23]. Therefore the Raggovidda wind-hydrogen system, which is located in the NO4 area, is not eligible for participation in this market. In addition, the minimum bid size of 5 MW/h [28] is larger than the current electrolyser capacity, although a reduction in bid size is expected with the introduction of a common market for aFRR [23].

Manual Frequency Restoration Reserves (mFRR) are procured both through capacity and activation markets [23]. A minimum bid size of 10 MW/h excludes a 2.5 MW electrolyser from participating in manual frequency restoration in the Norwegian grid.

In addition to market solutions, all generators connected to the Norwegian grid capable of delivering 10 MVA or more that are not participating in the frequency regulating market are required to keep 12% of the nominal effect in reserve as a base load to be used in frequency regulation [29]. The apparent power, measured in MVA, and real power, measured in MW, are related through the amount of generator reactance. This amount of base load power is high enough that the need for FCR-D is small compared to FCR-N, but the base load may be abolished in the future [23].

3.2.2 Spain

FCR is used to stabilize the frequency of the system following a disturbance in the equilibrium. In Spain this ancillary service is mandatory for all generating units and is a non-remunerable service. Generating units contributing to the Spanish electrical systems are required to be able to monitor their output by $\pm$1,5% [30].

While FCR is able to stabilize the frequency in the grid, it does not return it to the nominal value [31]. This is handled by the automatic Frequency Restoration Reserve (aFRR), sometimes called secondary regulation reserve or Automatic Generation Control (AGC) in Spain. This service is acquired by the Spanish TSO through an hourly market where generating units offer bids consisting of volume (MW) and an associated price (€/MW) for up-regulating and down-regulating power, respectively [25]. The activation of aFRR can last from 20 seconds to 15 minutes.

Generally, renewable power sources must be authorized by the system operator to be able to participate in the secondary reserve market, and only generating units are allowed to participate [25]. Any manageable renewable production must be authorized by the TSO to be allowed to participate [30]. Remuneration of aFRR consists of contracted capacity

(€ /MW) and energy delivered following capacity activation (€ /MWh). The capacity term is derived from the hourly market, while the energy term stems from energy delivered due to a deviation from the scheduled value and subsequent activation of reserves.

Tertiary regulation, the Spanish equivalent to mFRR, is responsible for correcting deviations between energy production and consumption and to free any activated aFRR capacity. Therefore, mFRR capacities participating in the Spanish grid must be able to fully activate within 15 minutes, and must be able to remain activated for at least two hours. The source of mFRR is specified to be generators only, and renewable power sources can participate in this market as long as the system operator has authorized it. Teriary regulation is procured through an hourly market tendered by the Spanish TSO. Like aFRR, tertiary regulation is remunerated for both available capacity and activated volume through marginal pricing market mechanisms.

3.2.3 Germany

In the German grid, frequency regulating services are provided by loads and generators as one of three products: primary regulating power (FCR), secondary control reserve (aFRR) and tertiary control reserve (mFRR). The German TSOs share a common marketing platform for procuring FCR with system operators in several neighbouring countries. Whereas the total capacity for FCR services in the countries participating in this common market amounts to $\pm$3000 MW, roughly $\pm$1250 MW can be procured through this shared platform [32].

FCR is auctioned as a symmetrical product, and is offered in steps of 1 MW for a duration of one week. FCR capacity is activated by all the TSOs connected to the synchronous grid to handle any imbalances. Full activation of FCR must be happen within 30 seconds, and balancing sources are required to remain activated for 15 minutes at most. Only capacity is remunerated for FCR [14] with a pay-as-bid market principle for capacity price. Unlike marginal pricing, where all contracted reserves receive equal remuneration per MW, pay-as-bid pricing means that all bids are remunerated according to the individual bid prices, which results in more volatile prices [14].

Unlike FCR, minimum bid sizes for both manual and automatic frequency restoration reserves are 5 MW. Smaller bids are allowed only if one bid per reserve type is submitted per load frequency control area (LFC area) [33]. An LFC area is a part of the synchronous grid that is physically defined by interconnections to other parts of the synchronous grid. Both types of reserve capacities are activated in the LFC area where an imbalance occurs. Full activation of any procured aFRR capacity must happen within 5 minutes, while any procured mFRR must be able to fully activate within 15 minutes. German and Austrian TSOs currently share a market platform for aFRR while awaiting the common European market platform for this reserve type [34].

Chapter 4

Analysis

4.1 Background data

The aim of this part of the report is to investigate the economical potential of implementing frequency regulating services as a product from a wind-hydrogen system operator. Thus, a comparison to a reference system that only participates in the electrical energy market is required. The following analysis is based on the economical data from the HAEOLUS test site in Raggovidda, but the concept of selling frequency regulating services is extended to Spain and Germany as well in order to investigate whether this is a business practice that can be applied where the market parameters for these services differ from Norway.

The analysis is conducted over the course of one year, and is based on historical market data sets. This will show whether there have been incentives to participate in the frequency regulation service market in recent years. It is assumed that the wind-hydrogen system is small enough that it does not affect the price of services in any of the markets.

In addition to operation of the electrolyser installed in the proximity to the Raggovidda wind park, the analysis has been extended to include operating an electrolyser with a capacity equal to said wind park. Two different sets of algorithms have been used for electrolysers of 2.5 MW and 45 MW capacity, respectively.

As a first step in the analysis, the annual costs are investigated. These consist of capital and operating costs. Capital costs are annualized through the following equation [35]:

$$a = A\frac{f(1+f)^n}{(1+f)^n - 1} \tag{4.1}$$

Where a is the annual cost to paying off a capital investment A over a course of n years with an interest rate f. The capital investment includes costs for the electrolyser, the fuel cell, storage tanks, hydrogen factory facilities and wind farm. The interest rate in this analysis is set to 0.04 (4%).

When including annual operating costs, the total annual costs, C_{tot}, can be described through the following equation:

$$C_{tot} = a + C_{ele} + C_{ele,oh} + C_{fc} + C_{fc,oh} + C_{wind} \tag{4.2}$$

Where a is the annualised capital costs for , C represents yearly operating costs, ele denotes electrolyser, fc denotes fuel cell, oh denotes overhaul and $wind$ denotes wind farm.

These terms may differ with differing system locations and differing climates. For instance, housing the electrolyser in a remote location may increase capital costs for construction, and a higher ambient temperature may influence the life time expectancy of equipment in the system. These factors will not be addressed in this analysis.

The annual total income for the wind-hydrogen system, I_{tot}, consists of remuneration for frequency regulating reserve capacity, I_{cap} as well as the volume of activated capacity, I_{act}, where applicable, in addition to income from the sale of electricity at day-ahead markets, I_{Elec}:

$$I_{tot} = I_{cap} + I_{act} + I_{Elec} \tag{4.3}$$

Although the purpose of producing hydrogen is to sell it, any sale of hydrogen has not been included in this analysis.

When annual total incomes and costs are calculated, the net annual revenue, N, can be calculated by subtracting the costs from the total income. With this, both break-even and levelized costs of hydrogen can be calculated through the annual hydrogen production, m_{H_2}:

$$LCOH = \frac{N}{m_{H_2}}$$

The levelized cost of hydrogen gives the price of which hydrogen must be sold for the system to be economically feasible. Any selling prices below this will result in annual costs exceeding total annual income. In the cases where the electrolyser has a nominal power of 2.5 MW, the annual costs are never larger than the annual total income due to the relative size of the electrolyser and the sale of electricity. In these cases the break-even cost of hydrogen, $BCOH$, is used instead:

$$BCOH = \frac{N_{FRS} - N_{ref}}{m_{H_2,FRS} - m_{H_2,ref}} \tag{4.4}$$

In equation 4.4 the difference in annual net revenue between the sale of frequency regulating services, denoted FRS, and the reference case, denoted ref, is divided by the difference in annual hydrogen production. The resulting price of hydrogen is the threshold for which selling frequency regulating services is economically advantageous. Specifically for the cases in this report, if the selling price exceeds this threshold, prioritizing hydrogen production over frequency regulation will yield the highest annual net revenue.

The energy flow to the electrolyser, E_{ele}, can be described in the following manner:

$$E_{ele} = E_{wind} - E_{sold} - L_{act} \tag{4.5}$$

Where E_{wind} the electrical energy generated at the wind farm, E_{sold} is the energy sold as electrical energy and E_{act} the energy that is associated with activation of the contracted frequency regulating capacity. The latter does not have a specific sign, but changes depending on the direction of the activated energy. For up-regulation E_{act} is positive, for down-regulation it is negative.

As shown in equation 4.2, the overhaul costs, seen in table 3.1, contribute to the total annual costs for the system. To be able to quantify this term the number of hours per year where the electrolyser is not in operation, t_{non-op} has been calculated. As this number generally depends on the output energy from the wind farm, as described in sections 4.2.1 through 4.2.3, it will vary from year to year, as shown in the table below. The costs associated with overhaul is described in the equation below.

$$C_{ele,oh} = c_{oh} * P_{ele,nom} * \frac{8760 - t_{non-op}}{40,000} \tag{4.6}$$

The cost per installed effect, c_{oh}, and electrolyser nominal power, $P_{ele,nom}$, are retrieved from table 3.1. When modeled this way the overhaul costs are distributed evenly across the 40,000 operating hours between each overhaul. Overhaul costs are not modeled for the fuel cell both because any activation of this unit has not been modeled and because no data is available to describe this aspect of the fuel cell.

Year	Hours without operation	Annual overhaul costs [EUR/year]
2015	843	175,164
2016	984	172,044
2017	872	174,522
2018	978	172,177

Table 4.1: Comparison between number of hours per year where there is insufficient energy to power the electrolyser.

4.2 Power and energy flows for the electrolyser

4.2.1 Frequency Containment Reserve

Capacity: 2.5 MW

The procedure that is used for determining power and energy flows for the electrolyser is shown in figure 4.1.

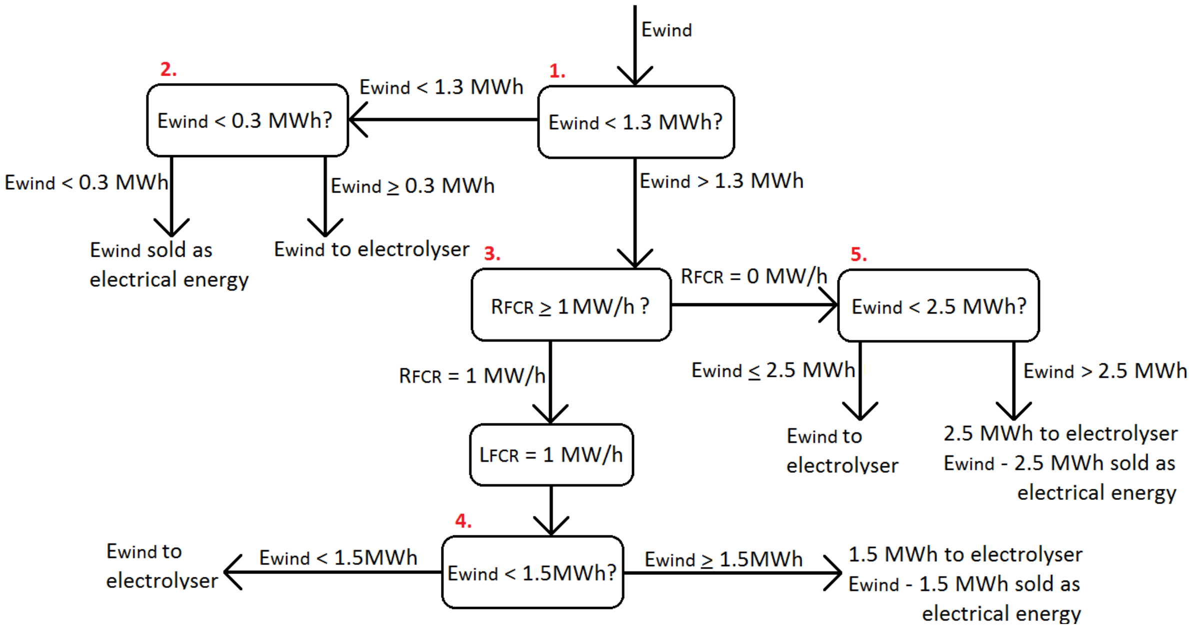

Figure 4.1: Energy and power flow scheme for a 2.5 MW electrolyser providing FCR.

1.: According to the assumption that the electrolyser is powered purely by energy provided by the wind farm, the algorithm first determines if there is enough energy available to power the electrolyser at a load where symmetrical reserve capacity can be sold. With the assumption that the wind farm provides a constant flow of electrical energy through the hour, quantities of energy and effect from the wind farm become equivalent with respect to powering the electrolyser. As FCR is offered in steps of 1 MW/h, and the minimum power at which the electrolyser can operate is 0.3 MW, there must be at least 1.3 MWh available per hour from the wind farm to be able to sell any FCR.

2.: If the amount of energy available is less than 1.3 MWh per hour, FCR capacity can be sold. However, as long as there is enough energy to power the electrolyser at or above minimum power, hydrogen can still be produced. In line with the prioritized operation of the wind-hydrogen system, the procedure checks if there is enough energy available to produce any hydrogen. If there is, all the energy from the wind farm is consumed by the electrolyser. If there is less than 0.3 MWh available, the electrolyser cannot be operated and consequently all the available energy is sold as pure electrical energy.

3.: If the available energy is 1.3 MWh or larger, the electrolyser can participate in the FCR market. As a next step in the procedure, data of contracted FCR, R_{FCR} is checked to see if any capacity is being sold on the market. If FCR is contracted, 1 MW/h of capacity is sold for the price at the respective hour. It is assumed that as long as capacity is being contracted, any capacity from the electrolyser, L_{FCR}, can be sold.

4.: The next step in this chain is to check whether there is excess energy after enough energy has been dispatched to the electrolyser to provide FCR capacity. As the electrolyser load is limited to 2.5 MW and with a step size of 1 MW/hr, a maximum of 1.5 MWh of energy from the wind farm can be consumed by the electrolyser when L_{FCR} = 1 MW/h. If there is more than 1.5 MWh available, this excess energy is sold as electricity. In the case where there is 1.5 MWh or less in the respective hour, all the energy is consumed by the electrolyser.

5.: If the contracted FCR, R_{FCR}, for the respective hour is zero, no capacity from the electrolyser can be sold (L_{FCR} = 0 MW/h). In this case the next step in the procedure is to check whether there is excess energy available after powering the electrolyser at the limiting capacity. If there is, any of this excess energy is sold as pure electrical energy. If not, all available energy is consumed by the electrolyser.

Capacity: 45 MW

At larger electrolyser nominal power capacities, more FCR capacity can be offered. In smaller markets, like the NO4 area in Norway, the amount of capacity that can be offered by a 45 MW electrolyser is sometimes larger than what is contracted by the TSO. Although this aspect may affect the prices in said markets, this effect is not investigated in this report.

1.: The first step taken when determining the energy flow through the electrolyser is to find out if there is enough energy available to sell 22 MW/h of frequency containment reserve capacity. This is the maximum amount of capacity a 45 MW electrolyser can offer. As the minimum capacity remains at 0.3 MW, the energy required to offer this amount of FCR capacity is 22.3 MWh per respective hour.

2.: If this amount of energy is available the next step is to determine the demand for FCR, R_{FCR}. If this is greater than the 22 MW/h that can be offered by the electolyser, it is assumed that this amount is contracted from the electrolyser. Thus, L_{FCR} = 22 MW/h. In the case that the demand for containment reserve capacity, is less than what can be offered by the electrolyser, it is assumed that the demand is fully satisfied by the electrolyser: L_{FCR} = R_{FCR}.

3.: When any capacity is contracted, an energy check is in place to see if there is any excess energy to sell at the electrical spot market. As the maximum power load is 45 MW, the electrolyser can consume 45 MW - L_{FCR} and still be able to activate down-regulating

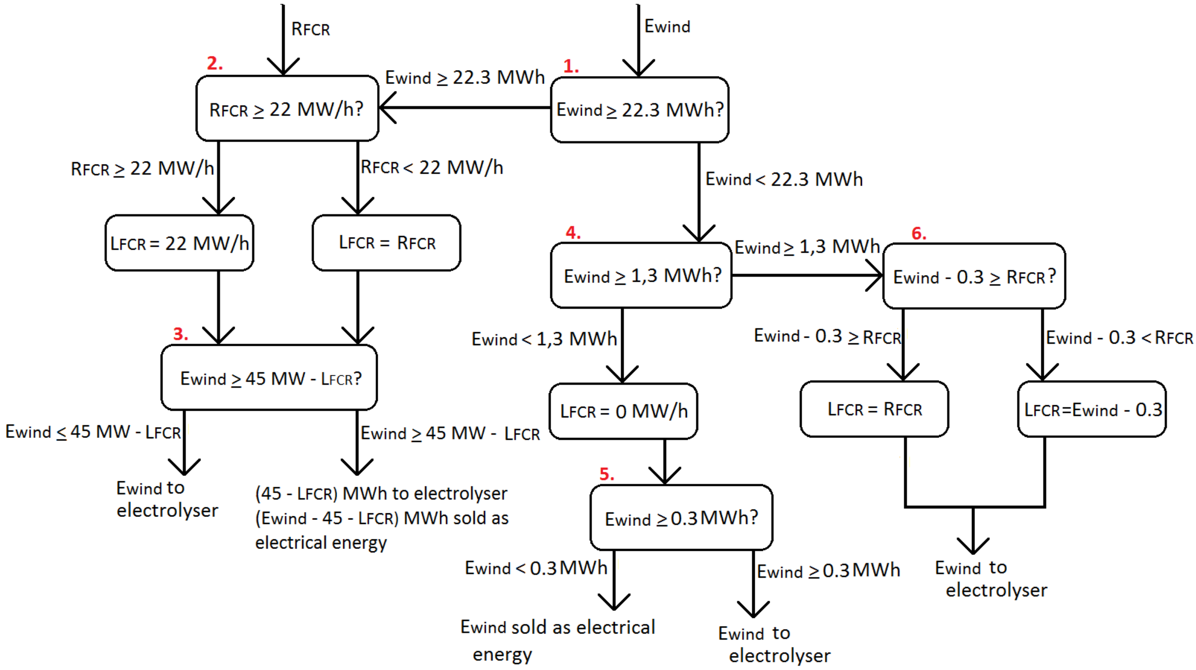

Figure 4.2: Energy and power flow scheme for an electrolyser with a maximum capacity of 45 MW providing FCR.

FCR capacity. Any excess energy is sold as electricity.

4: In the case that there is insufficient energy to offer 22 MW/h of FCR capacity, the next step in the algorithm is to determine if there is enough energy to run the electrolyser at a load rating where it is possible to offer any capacity at all. With the minimum electrolyser capacity and the minimum bid size of 1 MW in mind, the amount of energy required for this is 1.3 MWh per hour. If there is less energy than this, no containment capacity can be offered, L_{FCR} = 0 MW/h.

5.: The next step in this sequence is to determine if there is enough energy to run the electrolyser. If there is less than 0.3 MWh available in the respective hour, all energy generated at the wind farm is sold at the electrical spot market. In the case that there is enough energy available to run the electrolyser, all available energy is diverted to the electrolyser, as per the prioritized operation of the electrolyser.

6.: If there is enough energy available to run the electrolyser at a power rate where FCR capacity can be sold, the next step is to see if the amount of capacity than can be offered is larger than the capacity that is requested. If this is the case then it is again assumed that all demand can be satisfied by the containment capacity offered by the electrolyser, L_{FCR} = R_{FCR}. If there is a greater demand in the market than the electrolyser can satisfy, all available capacity is sold at the market. With the minimum bid size and bid step size both at 1 MW, the resulting available capacity is rounded downward to the closest integer.

Regardless of how much FCR capacity that is contracted, as long as the available energy is between 0.3 and 23 MWh per hour, the electrolyser remains the prioritized target for the generated electrical energy. Consequently, no electricity is sold whenever the wind farm operates in this area.

Activated frequency containment reserve capacity

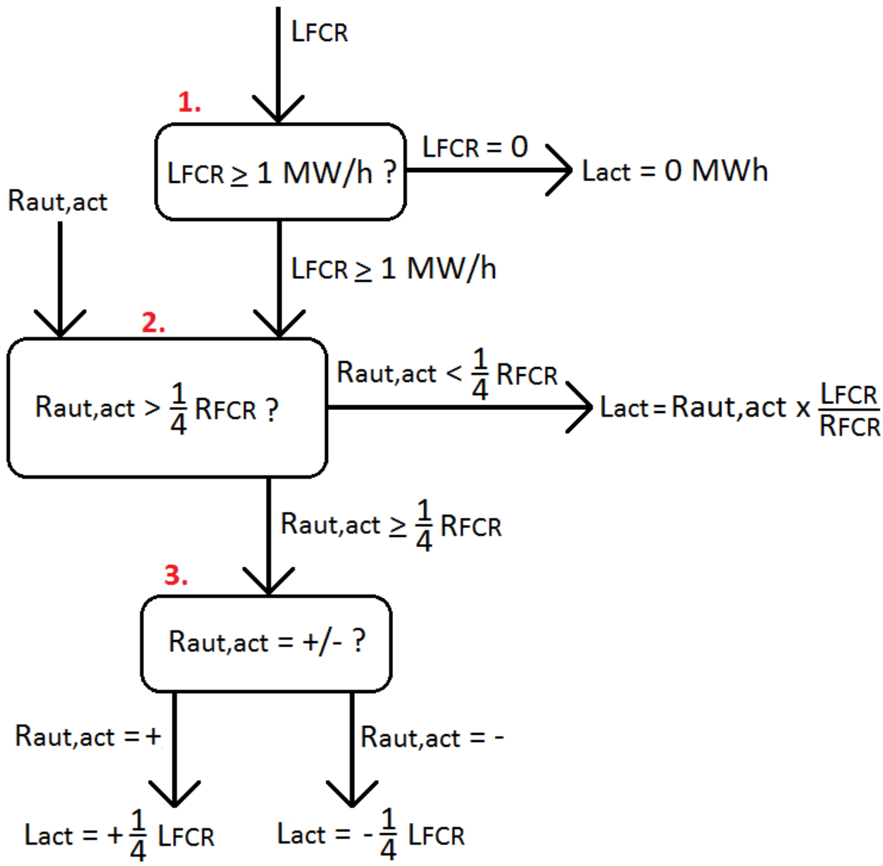

Figure 4.3: Control scheme for determining the amount of FCR capacity that is activated.

1.: To determine the share of the frequency containment reserve capacity sold, L_{FCR}, that is activated the algorithm in figure 4.3 is applied. The first step is to determine if any capacity has been sold. If this is not the case, then there is no nothing to activate, and consequently the activated energy, L_{act}, is equal to zero.

2.: In the case where reserve capacity is being offered, the next step is to check if any of the reserved capacity is activated for the respective hour. As the data available from Nordpool does not distinguish between activated FCR and aFRR, some assumptions must be made for the Norwegian grid. First, it is assumed that FCR is always fully activated before any frequency restoration reserves are activated. In the algorithm this implies that the volume of automatic balancing energy is primarily covered by FCR, while the rest is covered by aFRR. Second, it is assumed that the containment reserves are always activated for 15 minutes per hour before the activation of restoration reserves. With this in mind, a comparison between containment reserves and activated automatic reserves can be made.

As activated reserves are measured in energy and contracted reserves are measured in power, the latter must be multiplied by the amount of time for which they are activated. This results in the next step for the procedure, where it is determined if the amount of activated automatic reserves is larger than what the contracted FCR capacity can deliver if activated for 15 minutes. If this is not the case, it follows the first assumption that FCR is the only automatic reserve that is activated in the respective hour. As the activated volume is shared equally across the contracted capacity, the resulting activated load is calculated as a share equal to:

$$L_{act} = R_{aut,act} * \frac{L_{FCR}}{R_{FCR}} \tag{4.7}$$

Where L_{act} is the activated energy for the electrolyser, $R_{aut,act}$ is the total amount of activated automatic reserves, L_{FCR} is the frequency containment reserve capacity provided by the electrolyser and R_{FCR} is the total amount of contracted FCR.

3.: If the activated energy for the respective hour is larger than what can be provided by fully activating the available FCR, it follows the assumptions made that all containment reserves are fully activated for 15 minutes before the rest of the balancing energy is provided by other reserves. In this case, the next step in the sequence is to check the direction of the activated energy and calculate the resulting energy flow accordingly. As the maximum capacity that can be offered by the electrolyser is 1 MW/h, the resulting maximum activated energy is equal to a quarter of the offered capacity, with direction of activated energy either to or from the electrolyser.

Remuneration

Where FCR is remunerated, both capacity and activation are contributing to the total income for the wind-hydrogen system. When analysing the Raggovidda case, the energy that stems from the activation of reserves is priced differently depending on the direction of the activated energy. If the direction of the activated energy is opposite compared to the dominating direction of activated automatic reserves, the energy is priced at electrical spot price. If the directions are the same, the activated energy is priced at regulating power prices in the respective hour and direction. In addition to remunerated FCR services, sale of pure electrical energy is also included in the total annual income. Both electrical spot prices at the day-ahead markets as well as transmission tariffs and renewable energy remuneration schemes are applied to the energy sold at the electricity market. Neither tariffs nor remuneration schemes are applied to energy fed into or taken out of the grid as a result of activated frequency regulation reserve capacity.

4.2.2 Automatic Frequency Restoration Reserve

Capacity for up-regulation: 2.5 MW

1.: The algorithm for determining power and energy flows for an electrolyser providing strictly up-regulating capacity is shown in figure 4.4. As with FCR, the first step is to determine the amount of energy available from the wind farm. This is done through a three-step check. The first check is to determine if there is enough energy available to deliver 2 MW capacity. With a minimum operating capacity of 0.3 MW, the minimum amount of energy for this is 2.3 MWh for the respective hour.

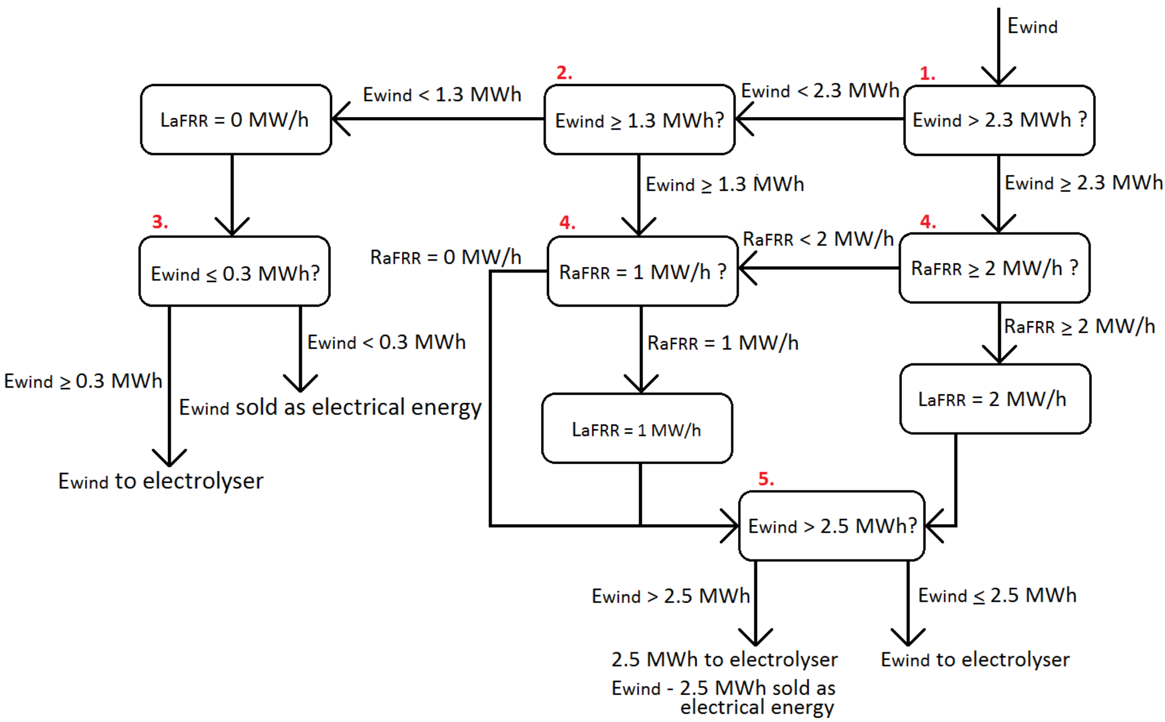

Figure 4.4: Energy and power flow scheme for an electrolyser with a maximum capacity of 2.5 MW providing aFRR-UP.

2.: If there is less than 2.3 MWh available, the second check is to see if there is more than 1.3 MWh available. This amount would enable the electrolyser to deliver 1 MW/h of frequency restoration capacity.

3.: If this is not the case, the last check is to see if there is enough energy to operate the electrolyser at all, i.e. if there is more than 0.3 MWh available for the respective hour. If this is the case, all available energy is consumed by the electrolyser. If there is an insufficient amount of energy, the energy is sold as pure electrical energy.

4.: If there is enough energy available to provide any restoration capacity, be it 1 MW or 2 MW, the next set of checks is to see if there is any capacity being sold in the market. Even if there is enough energy to provide capacity, market demand is the limiting factor. As such, there are checks to determine the amount of restoration capacity contracted on the market, as shown in the two rightmost, second row bubbles in figure 4.4.

5.: After determining the amount of up-regulating frequency restoration reserve capacity, a last check is implemented to determine if there is any energy left for the electricity market. As per the prioritised operation of the wind-hydrogen system, as much energy as possible is to be diverted to the electrolyser. As activation of up-regulating capacity only involves lowering the electrolyser consumption, operating at the limiting capacity of 2.5 MW is possible regardless of the value of L_{aFRR}. Thus, A last check is performed to see if there is more than 2.5 MWh available from the wind farm. If there is not, all energy is consumed by the electrolyser. In the case that there is excess energy, it is sold at the electricity market.

Capacity for up-regulation: 45 MW

1.: As with an electrolyser with a lower maximum power rating, the first check is to see if the electrolyser can be operated at all. If there is less than 0.3 MWh of energy from the wind farm available per hour, no frequency restoration reserve capacity is sold, and the available energy is sold as electrical energy. In the case that there is enough energy to power the electrolyser, the next step is to determine the demand for aFRR-UP in the market.

2.: In the second bubble in figure 4.5 the available up-regulating capacity in the electrolyser is compared to the market demand for said capacity. If there is less demand than what can be offered, it is assumed that the whole demand can be satisfied by the electrolyser, $L_{aFRR-UP} = R_{aFRR-UP}$. In the case that the demand is larger than what can be offered by the electrolyser, the up-regulating capacity offered is determined by subtracting the electrolyser minimum power load from the available wind energy. As the bid step size is 1 MW, this quantity is rounded downward to the closest integer. In the event that any aFRR-UP can be sold, all available energy is diverted to the electrolyser, regardless of the exact quantity of $L_{aFRR-UP}$.

Capacity for down-regulation: 2.5 MW

1.: The first step in the algorithm for providing down-regulating frequency restoration reserve capacity is to determine whether there is enough energy to operate the electrolyser.

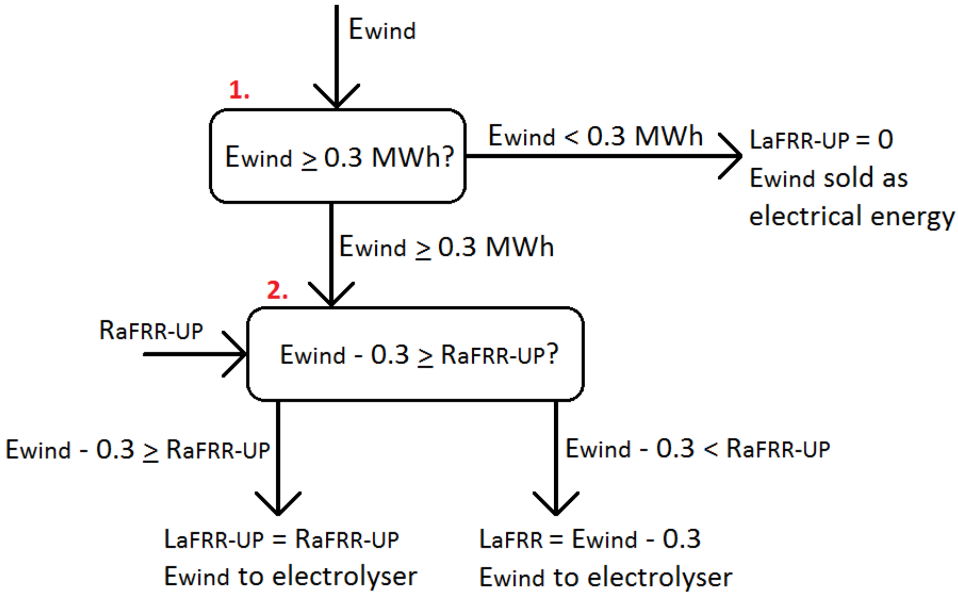

Figure 4.5: Energy and power flow scheme for an electrolyser with a maximum capacity of 45 MW providing aFRR-UP.

If there is not, all available energy from the wind farm is sold at the electricity market. However, as long as there is enough energy to power the electrolyser at minimum load, the market demand for down-regulating capacity is the limiting factor for offering this service. As with the FCR market, it is assumed that as long as capacity is being contracted by the TSO, the electrolyser can sell all available capacity at the market price in the respective hour.

2.: As the electrolyser is the prioritized target for the energy from the wind farm, the nominal operating load for the respective hour largely depends on how much down-regulating capacity is being sold. As seen in the second row of bubbles in figure 4.6, a series of checks are implemented to investigate how much capacity, L_{aFRR}, can be sold with respect to market demand for down-regulating capacity, R_{aFRR}.

3.: Generally, the last check in any of the sequences, dependent on how much capacity is requested in the market, investigates how much energy can be diverted to the electrolyser after a specific quantity of reserve is sold. As the electrolyser is limited to operating at 2.5 MW, a maximum of (2.5 - L_{aFRR}) MWh of wind energy can be consumed by the electrolyser per hour. All energy levels surpassing this quantity is sold at the electricity market.

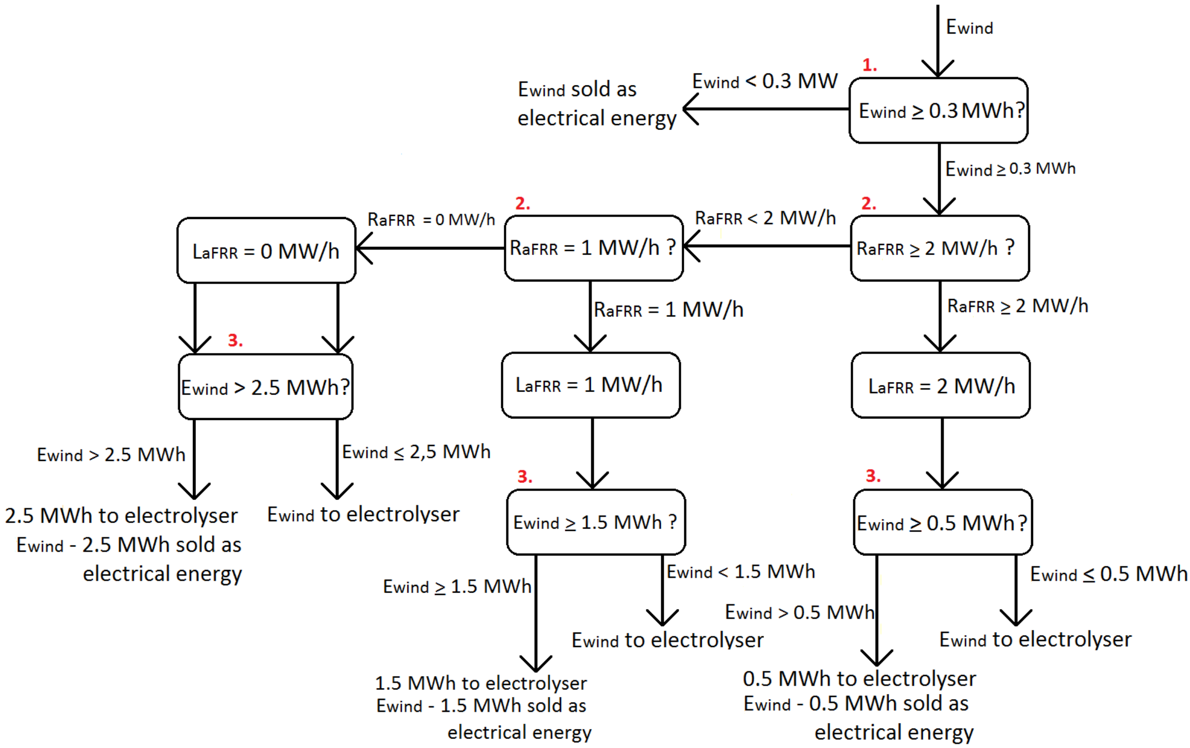

Figure 4.6: Energy and power flow scheme for an electrolyser with a maximum capacity of 2.5 MW providing aFRR-DOWN.

Capacity for down-regulation: 45 MW

1.: The first step in the algorithm is to determine if there is enough energy to power the electrolyser. If there is less than 0.3 MWh available per hour, all energy is sold as electricity.

2.: If the electrolyser can be operated, the next step is to determine whether the market demand for aFRR-DOWN is larger than the maximum possible down-regulating capacity that can be offered by the electrolyser. With the minimum and maximum operating capacity set, this maximum capacity for down-regulating is 44 MW/h.

3.: If the demand for aFRR-DOWN is less than 44 MW/h, it is assumed that the whole demand can be satisfied by the electrolyser, $L_{aFRR-DOWN} = R_{aFRR-DOWN}$. If the demand is higher or equal to what can be offered by the electrolyser, it is assumed that all offered capacity is contracted, $L_{aFRR-DOWN}$ = 44 MW/h. An energy check is in place to calculate the amount of energy to be sold as electricity, as a function of the maximum electrolyser capacity and the contracted down-regulating capacity.

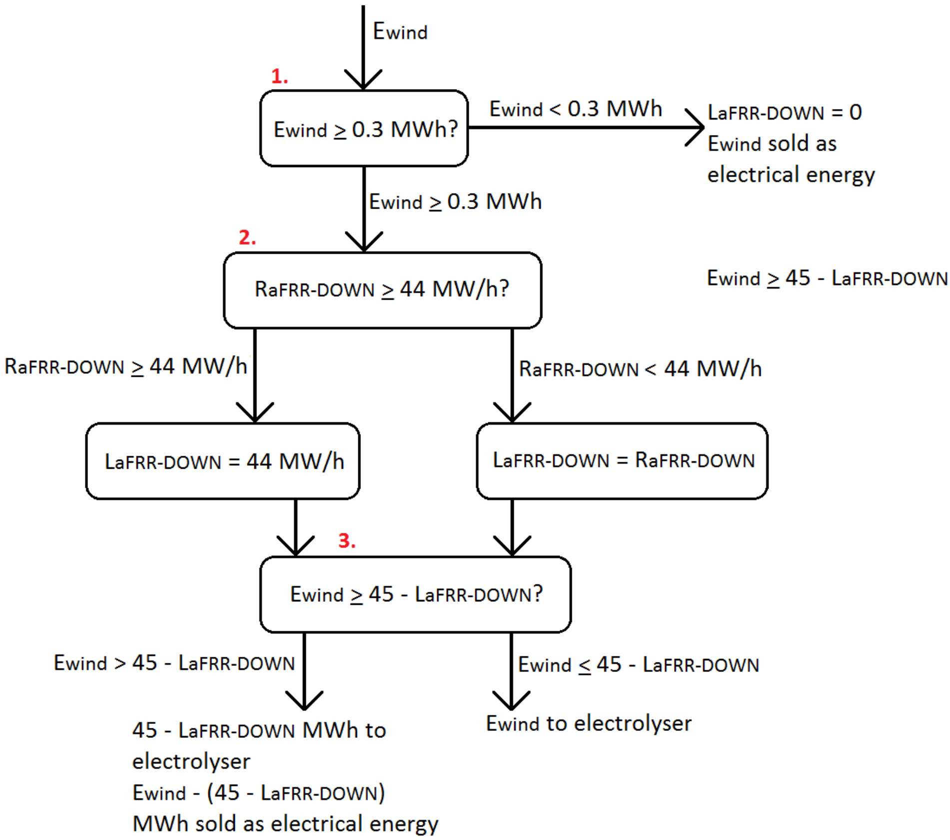

Figure 4.7: Energy and power flow scheme for an electrolyser with a maximum capacity of 45 MW providing aFRR-DOWN.

Assuming there is enough energy to operate the electrolyser, (45 - $L_{aFRR-DOWN}$) MWh can be diverted to the electrolyser where it will still be able to activate $L_{aFRR-DOWN}$ MW/h. If there is more energy available than this, it is sold as electrical energy. In the case where there is less energy available, all of it is consumed by the electrolyser.

Automatic frequency restoration reserve activation

1.: Determining the amount of frequency restoration reserve capacity that is activated is similar to the procedure for activating containment reserve capacities. However, in the grids where offering this type of capacity is possible, data is available to distinguish between activated containment and restoration capacities. As such the procedure somewhat simpler. The first step is to determine whether any capacity has been sold for the respective hour. If not, the activated capacity equals zero.

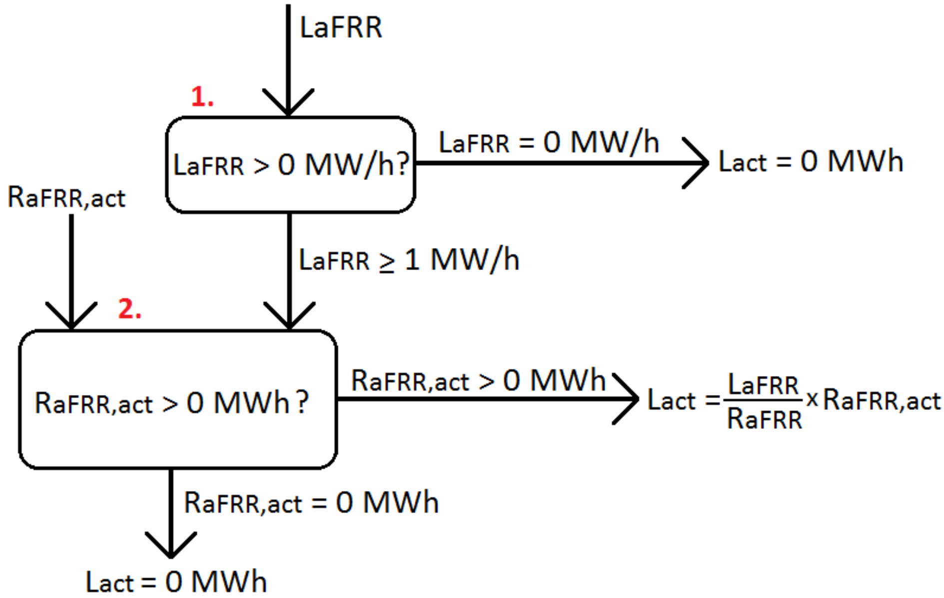

Figure 4.8: Control scheme for determining the amount of aFRR capacity that is activated.

2.: If restoration reserve capacity has been sold, data for activated frequency restoration reserve capacities is used to determine whether any of the contracted capacity has been activated. If this is not the case the activated energy for the electrolyser, L_{aFRR}, equals zero. If any of the contracted capacity is activated, the same principle is used for restoration reserves as for containment reserves. The amount of activated capacity is distributed evenly across the total volume of contracted capacity, leading to an equation for L_{aFRR} that is identical to the one seen in figure 4.3.

Remuneration

While the remuneration of restoration reserve capacity is the same as containment reserve capacity, the former frequency regulation reserve is non-symmetrical. This means that any concerns regarding the direction of the activation with respect to remuneration cease to be. Prices for both capacity and activation are direction-specific and available at the ENTSO-E Transparency Platform.

4.2.3 Reference case: no frequency regulating services

Although the reference case does not include any sale of frequency regulating services, diverting as much energy as possible to the electrolyser, as per the prioritized operation of the wind-hydrogen system, is still the main operating strategy in this analysis.

1.: As can be seen in figure 4.9, the algorithm checks if the available energy is below the minimum power level required to run the electrolyser and the limited maximum capacity. If there is not enough energy to run the electrolyser, it is sold at the electricity market.

2.: If there is any excess energy after running the electrolyser at limited maximum capacity, it is sold at the electrolicity market. If the available energy level is anywhere between these two quantities, all available energy is consumed by the electrolyser.

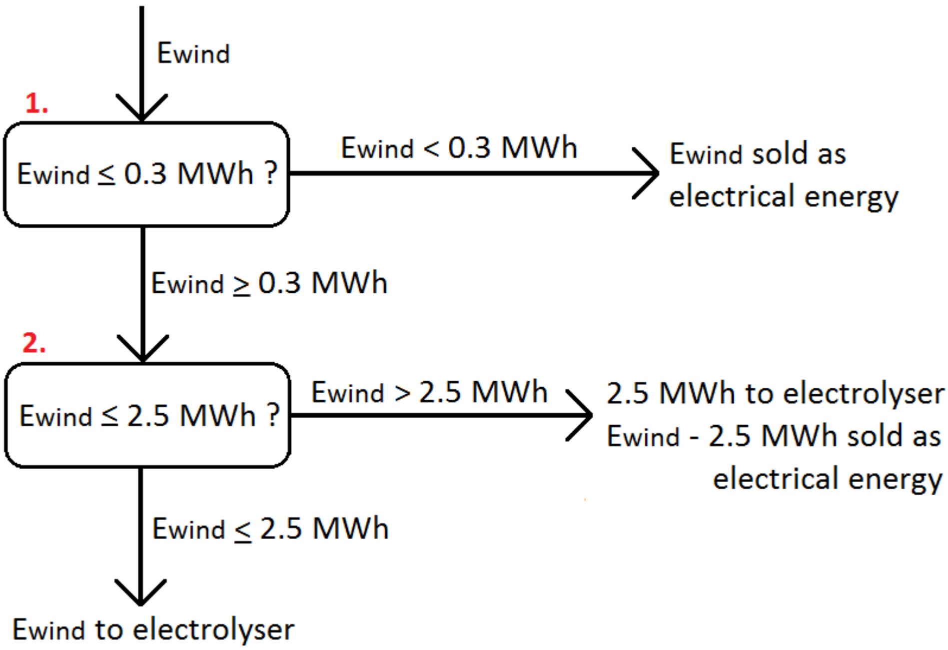

Figure 4.9: Energy flow scheme for an electrolyser with energy supply purely from a wind farm.

4.3 Case studies

4.3.1 Norway

For evaluating the economic incentives in providing frequency regulating services in the Norwegian grid, historical market data for 2018 from Nordpool [36] and Statnett [37] has been used. From Nordpool, this includes regulating power, prices and volume, automatic activated reserve and elspot prices. The analysis has been performed for the NO4 area, with elspot prices for Tromsø. This covers the area in which the Raggovidda wind park and the hydrogen factory are located. Historical market data from Statnett includes volume and price of contracted FCR-N capacity in the NO4 area.

Considering minimum bid sizes and bid size steps of the varying services, the electrolyser is question is only eligible for providing frequency containment reserve capacity when operating in the Norwegian grid. A response time of 30 seconds dictates that the electrolyser can be operating in stand-by mode to offer FCR, but the symmetrical nature of the reserve type requires the electrolyser to run at a certain capacity in order to offer FCR, as described in figures 4.1 and 4.2. With a ramp rate of 60 MW/min the electrolyser is able to activate 50% of the contracted capacity within 5 seconds when in on-mode and can fully activate within 30 seconds. Due to ramping rates linearly scaling with nominal capacity, this is also the case for the 45 MW electrolyser.

In Norway the tariffs included in this analysis is both a fixed term and a term dependent on the spot price for electrical energy. The remuneration schemes for renewable energy includes green certificates and a source of origin-guarantee. All of these values are shown in table 4.2 [38, 39, 40, 41, 42].

Tariff	**Value**
Fixed term	13 NOK/MWh
Energy term	7.2% of spot price
Green certificate	116 NOK/MWh
Source of origin-guarantee	10 NOK/MWh

Table 4.2: Tariffs and remuneration schemes for participants in the Norwegian grid.

4.3.2 Spain

All the data for the Spanish grid and markets are retrieved from ENTSO-E's Transparency Platform. As FCR is a mandatory and non-remunerable service in the Spanish grid, historical market data regarding available is only available for aFRR. The data includes accepted offers and activated balancing reserves, prices of both reserved balancing reserves and activated balancing energy as well as volumes of contracted balancing reserves and day-ahead prices, all for 2019. In addition to the day-ahead prices for electricity, a grid feed-in tariff for energy of 0.5 €/MWh is considered in the Spanish case [43].

It is important to note that only generating units may participate in the Spanish frequency regulating reserve markets, even if the electrolyser satisfies the criteria for reserve capacity activation times. The case study in this report simulates a scenario where loads can participate, in case of changes that may follow a harmonization of the European markets [44]. The analysis is limited to aFRR in Spain.

4.3.3 Germany

All the data used in analysing the sale of frequency regulating services in the German grid is retrieved from ENTSO-E's Transparency Platform [45]. This encompasses historical market data from 2019 of accepted offers and activated balancing reserves, prices of both reserved balancing reserves and activated balancing energy as well as volumes of contracted balancing reserves and day-ahead prices. As both minimum bid size, bid size steps and ramping rates enable the electrolyser to participate in both frequency containment and restoration, data sets are retrieved for both of these services. Offering restoration reserve capacity restricts the electrolyser to one bid per reserve type at the time, but this will not affect the algorithms presented in figures 4.4 through 4.7. The analysis in this report is limited to delivering FCR and aFRR in Germany. Although delivering mFRR is possible, this product has not been included since the fast power ramping characteristics of the electrolyser makes it more suitable for delivering faster, automatic frequency regulating reserves. As no other data is available, prices for reserved balancing reserve capacity for generating units are used.

Since the total amount of activated capacity is used when analysing aFRR, rather than for a specific LFC area, the amount of activated energy is not necessarily correct. Both total amount of contracted aFRR and activated volume for the specific LFC area where the electrolyser is located would be required to calculate the correct amount of activated capacity, L_{aFRR}. Regarding the sale of electricity, as neither tariffs nor renewable energy remuneration schemes are directly quantified, this aspect is not included when evaluating the participation in the German grid [43].

Chapter 5

Results and discussion

5.1 Norway

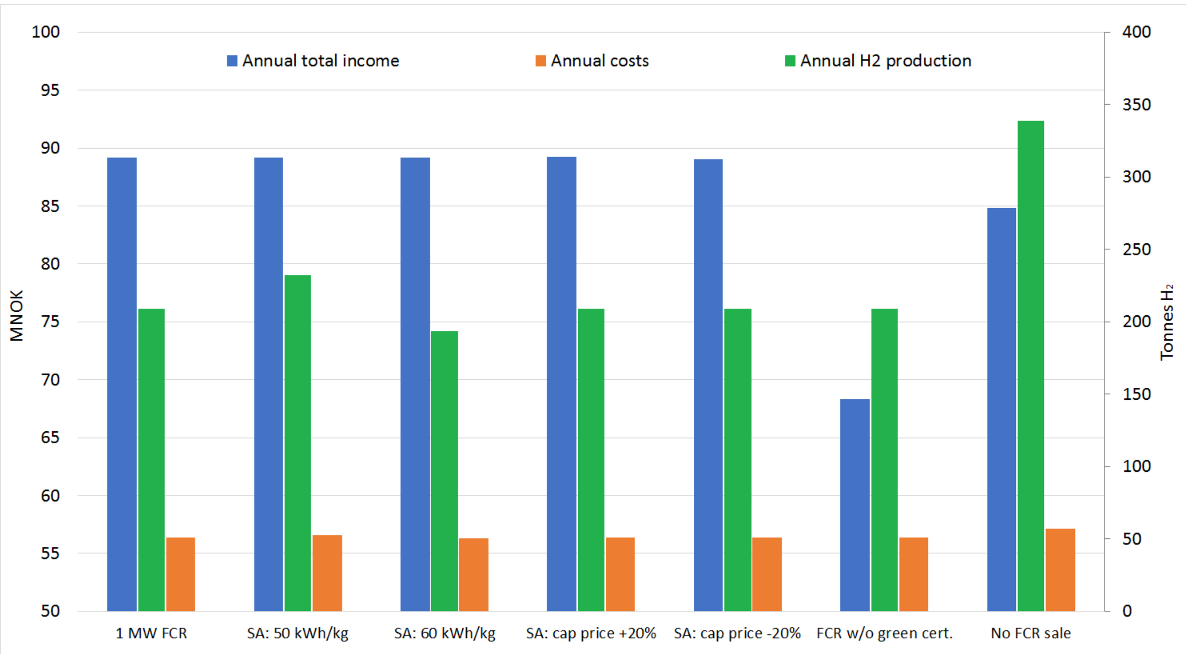

Figure 5.1: Analysis results for a 2.5 MW electrolyser operating in the Norwegian grid. Includes results from sensitivity analysis for electrolyser efficiency and FCR capacity prices.

As seen in figure 5.1, the sale of frequency containment reserve capacity has a positive effect on the total annual income, but incurs a penalty to annual hydrogen production. This is because a share of the electrolyser capacity is held in reserve and is only activated when needed.

When comparing delivery of FCR to a system where no frequency regulating services are being sold, there is an added value of 5.05 MNOK/year to the net revenue n while decreasing hydrogen production m_{H_2} by 130 tonnes per year. This means that for the two cases to be economically equivalent the hydrogen that is produced must be sold for 38.8 NOK/kg. If the price of hydrogen falls below this, the sale of FCR is economically advantageous, while the opposite is true if the price is higher than this break-even cost.

Note that the handling of the hydrogen has not been taken into account in this analysis. It has been assumed that the hydrogen tank connected to the electrolyser are emptied once every week, but there is no data to support an economical evaluation of transporting the hydrogen out of the system. Increased annual hydrogen production will incur economical penalties in the form of increased cost for handling.

A significant share of the income comes from remuneration schemes for renewable energy, here represented by green certificates and source of origin-guarantee. The different products that contribute toward the I_{tot} is shown in table 5.1.

Product	**Value [MNOK/year]**
FCR Capacity	0.3
Activated capacity	0.4
Sale of electrical energy	65.9
Remueration for renewable energy	22.6

Table 5.1: Contributions to the total annual income when selling FCR in the Norwegian grid.

As there is no planned continuation of the green certificate remuneration scheme after 2020, an analysis has also been conducted where the value of this is set to zero. In this case offering FCR will yield an added value of 4.20 MNOK/year in annual net revenue while incurring a penalty of 130 tonnes to the annual hydrogen production. This causes the break-even cost of hydrogen to decrease to 32.3 NOK/kg. This effect is due to a larger sale of electrical energy as a result of the operation of the electrolyser and that the sale of frequency regulating capacity means that less energy can be dispatched to the electrolyser. Lowering the reference case electrolyser load will affect the annual income, costs and hydrogen production as shown in figure 5.2.

In these cases the maximum amount of energy supplied to the electrolyser has been limited to 0.5 MW and 1.5 MW, in addition to the 2.5 MW case shown in figure 5.1. Lowering the peak load to 0.5 MW results in a BCOH of 30.2 NOK/kg, with selling FCR is the economically advantageous option if the selling price of hydrogen is higher than this. While the electrolyser capacity has been significantly lowered, this only makes up a small portion of the total installed capacity of the Raggovidda wind farm. A severe restriction in electrolyser capacity yields a large reduction in annual hydrogen production but only a small reduction for I_{Elec}. These changes can be seen in figure 5.2. The large reduction in

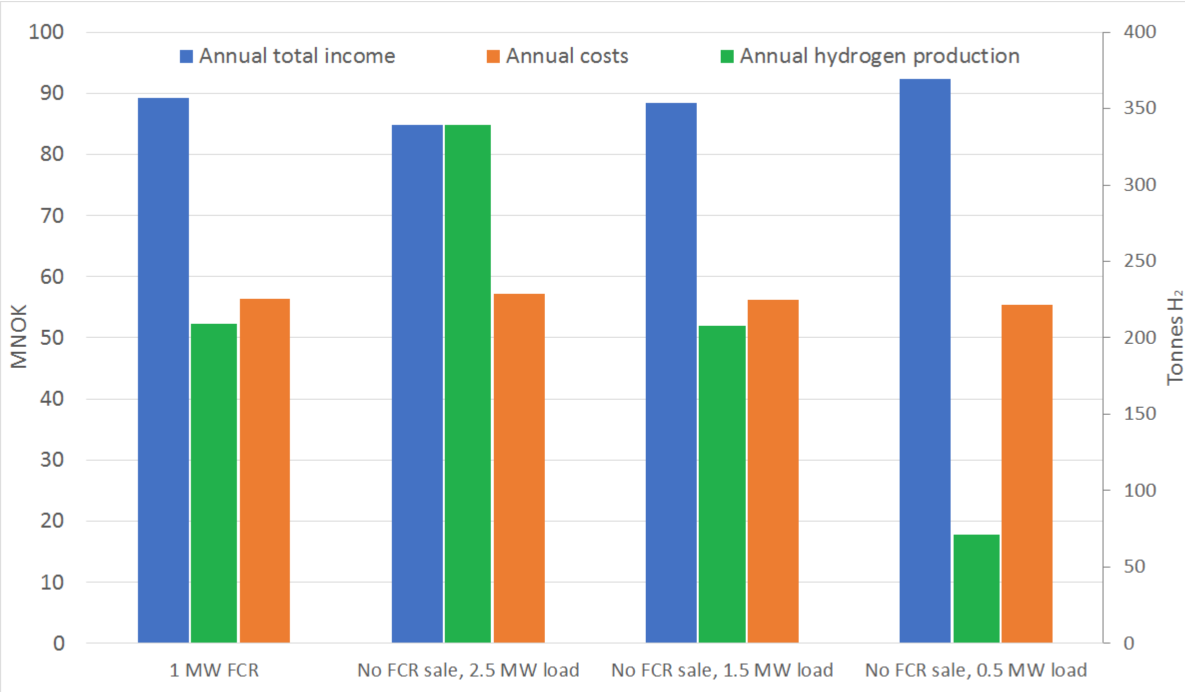

Figure 5.2: Effects of varying electrolyser loads when not selling any frequency regulating services.

hydrogen production results in a reduced storage capacity from 7500 kg to 1500 kg when compared to the case where the electrolyser is providing FCR capacity. Considering the data in table 3.1 this makes up a small portion of the capital costs (6.2% at 7500 kg storage capacity).

In the case of capping the electrolyser peak load at 1.5 MW both the total annual income and hydrogen production is decreased from selling FCR capacity. As the maximum power delivered from the wind farm in this case is the same as when the electrolyser is actively providing FCR capacity, with the algorithm in section 4.2.1 in mind, the increased hydrogen production (1.3 tonnes per year) is a product of activated reserve capacity. As the effective peak load is the same, the amount of wind energy sold as electricity is also same, meaning that the increase in I_{tot} (0.07 MNOK/year) traces back to the sale of capacity and activated reserve capacity.

As follows from the assumption that the electrolyser is powered purely by energy generated at the Raggovidda wind farm, the annual wind power distribution at the site lays the foundation for revenue generated from the sale of both electrical energy and frequency containment reserve capacity, as well as the annual hydrogen production. Varying annual power distribution results in the changes witnessed in figures 5.3 and 5.4.

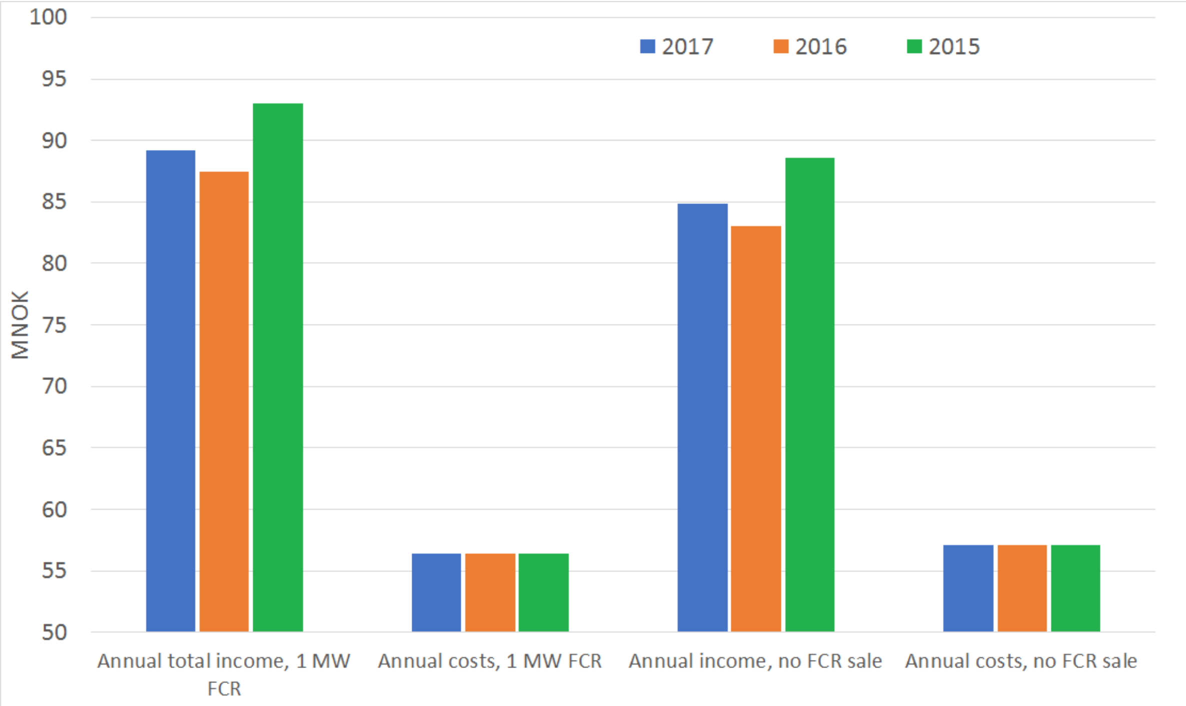

Figure 5.3: Variations in annual costs and incomes as a result of varying wind power distribution.

Given the values for 2015 and 2016, the resulting BCOHs are 39.4 NOK/kg and 39.6 NOK/kg, respectively.

Variations in annual costs C_{tot} are due to a variable annual hydrogen production, given the assumption that the hydrogen storage tanks are emptied once a week. Since the storage capacity in reality is more fixed, the annual net revenue from the wind-hydrogen system is somewhat inaccurate. It is assumed that hydrogen can always be produced and stored, so the storage capacity depends on the largest amount of hydrogen produced per week in the respective year the analysis covers. However, given the small variations in C_{tot} (roughly 0.3%), this effect is neglected. As mentioned earlier, costs related to the handling of the product hydrogen are not included in the analysis.

As shown in the fourth and fifth bar in figure 5.1, representing the system economy's sensitivity to the price of FCR capacity, there are only small changes to I_{tot} (roughly 0.1 %) when compared to the standard case for delivering FCR capacity. This fact is reinforced by the numbers in table 5.1, which show that the FCR capacity remuneration is very small compared to the income from the sale of electrical energy. The results of this sensitivity analysis show that with a 20% increase in capacity price, the BCOH is increased to 39.5 NOK/kg, while a 20% reduction results in a BCOH of 38.2 NOK/kg.

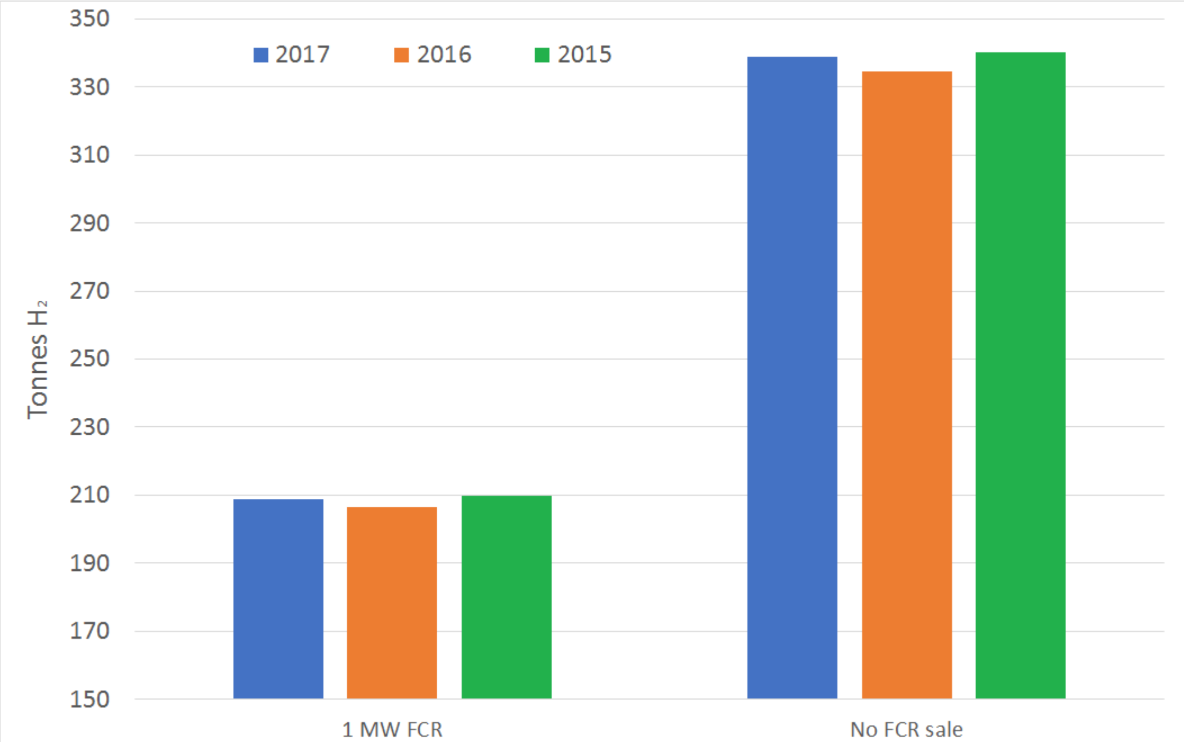

Figure 5.4: Variations in annual annual hydrogen production as a result of varying wind power distribution.

The sensitivity analysis reveals that the system is more sensitive to changes in the electrolyser efficiency. Deviations to 50 kWh/kg or 60 kWh/kg yield BCOHs of 35.5 NOK/kg and 41.5 NOK/kg, respectively. This effect can be explained by the fact that offering FCR capacity reduces the electrolyser utilisation and thus reduces the annual hydrogen production. Assuming a fixed efficiency, the loss of hydrogen production increases linearly with increasing electrolyser efficiency.

Comparing the results presented in figures 5.1 and 5.5 shows that increasing the electrolyser nominal load to 45 MW leads to nearly a tenfold increase in annual hydrogen production, at the cost of reduced income and increased total costs. This means that the hydrogen production does not increase linearly with increased electrolyser capacity, which follows from the assumption that the electrolyser is powered purely by energy generated at the wind farm. Electrolyser utilisation can only reach 100% when the wind park output is 45 MW.

Increasing the electrolyser nominal power results in increased capital costs for both the electrolyser and hydrogen storage tanks as a result of increased annual hydrogen production, as well as increased operating and overhaul costs. The increased investment as-

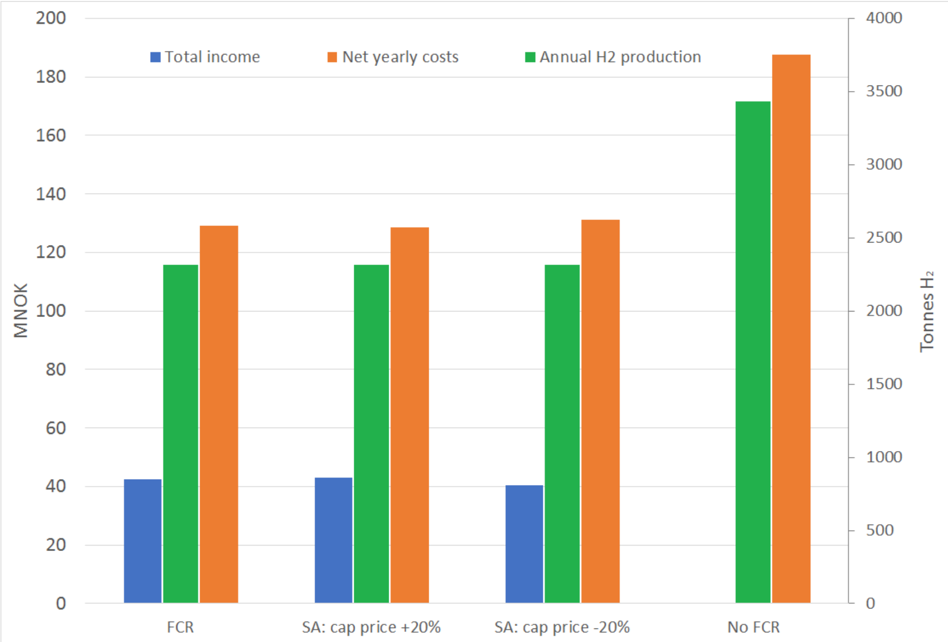

Figure 5.5: Analysis results for a 45 MW electrolyser operating in the Norwegian grid. Includes results from sensitivity analysis for FCR capacity prices.

sociated with larger hydrogen storage tanks is witnessed in comparing between the cases in figure 5.5, as it is the only variable cost between the four cases.

The reduced annual income is a result of a reduction in the amount of the electricity sold at the spot market. This is most evident in the reference case with no frequency regulating services offered, where electricity is only sold when there is insufficient energy to operate the electrolyser. As can be seen in figure 5.5, this sale is negligible when compared to the annual costs.

levelised costs of hydrogen are presented in table 5.2 below. Case comparisons with BCOHs are presented in table 5.3.

Case	**Levelised cost of hydrogen [NOK/kg]**
FCR	55.9
SA: cap price +20%	55.5
SA: cap price -20%	56.7
No FCR	54.6

Table 5.2: Levelised costs of hydrogen for the different cases for a 45 MW electrolyser.

Considering the annual hydrogen production numbers presented in figure 5.5, offering frequency containment services becomes economically advantageous when selling hydrogen below the prices listed in table 5.3. However, for the wind-hydrogen systems to be economically feasible the hydrogen must at least be sold for the numbers listed in table 5.2. As break-even costs are consistently larger than levelised costs, a 45 MW electrolyser will not be economically feasible and advantageous at the same time.

Comparison	**Break-even cost of hydrogen [NOK/kg]**
FCR **VS** No FCR	52.1
SA: cap price +20% **VS** No FCR	52.8
SA: cap price -20% **VS** No FCR	50.4

Table 5.3: Break-even costs hydrogen for cases for a 45 MW electrolyser.

5.2 Spain

Annual income, costs and hydrogen production from an electrolyser operating in the Spanish grid is shown in figure 5.6. As loads offering up-regulating capacity are required to run at higher power ratings, the hydrogen production is comparable to a case where the electrolyser does not offer any frequency regulating capacity. The difference between the cases can primarily be traced to activated up-regulating capacity. Loads offering down-regulating capacity, on the other hand, rely on low base utilization. This results in a significant reduction in annual hydrogen production, as can be seen in the figure below.

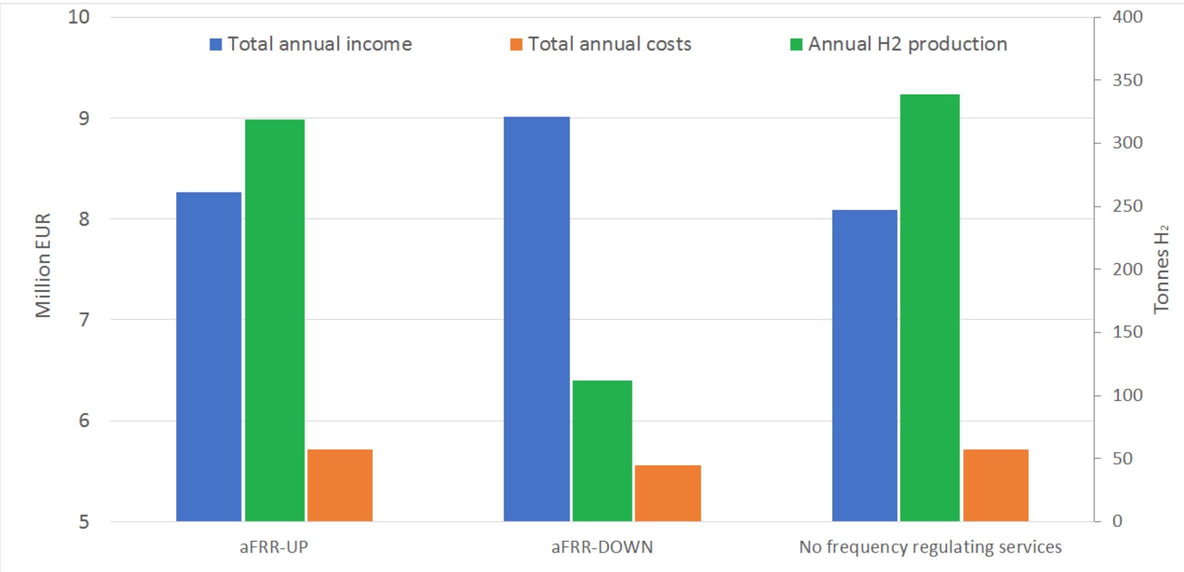

Figure 5.6: Analysis results for a 2.5 MW electrolyser operating in the Spanish grid.

Comparing delivering aFRR-UP to the Spanish grid to the case where no frequency regulating services are offered, the results show a net annual income of 0.17 million EUR while the reduced annual hydrogen production is 20 tonnes. This results in a break-even cost of 8.7 EUR/kg, with offering up-regulating capacity being economically advantageous if the selling price of hydrogen is below this. Comparing the sale of aFRR-DOWN to the same reference case, the analysis shows a net annual income of 1.1 million EUR and a loss of hydrogen production of 227 tonnes per year. The break-even cost of hydrogen in this case is 4.7 EUR/kg.

As shown in figure 5.7, annual total income from frequency restoration reserve services are higher for both down-regulating capacity and reserve capacity activation. Since the price of reserved balancing reserves is symmetrical, this is due to a larger amount of down-regulating capacity being contracted. This is shown in figure 5.8, which shows the amount of capacity contracted differentiated by bid size. The added value for activated capacity remuneration is due to a larger amount of activated energy for down-regulation and a lower amount of down-regulation capacity contracted, since the marginal price of activated balancing energy is larger for up-regulating energy than for down-regulating energy [45].

Although annual income from frequency restoration reserve services contributes to the added value for annual total income seen in figure 5.6, the share that is associated with these services make up a small portion of the added value. While capacity contributes 8300 EUR per year and activated energy contributes 36,000 EUR per year, the added value of increased sale of electricity contributes 750,000 EUR per year. Low base electrolyser utilization results in a larger amount of excess energy that can be sold while simultaneously enabling the electrolyser to contribute with down-regulating capacity.

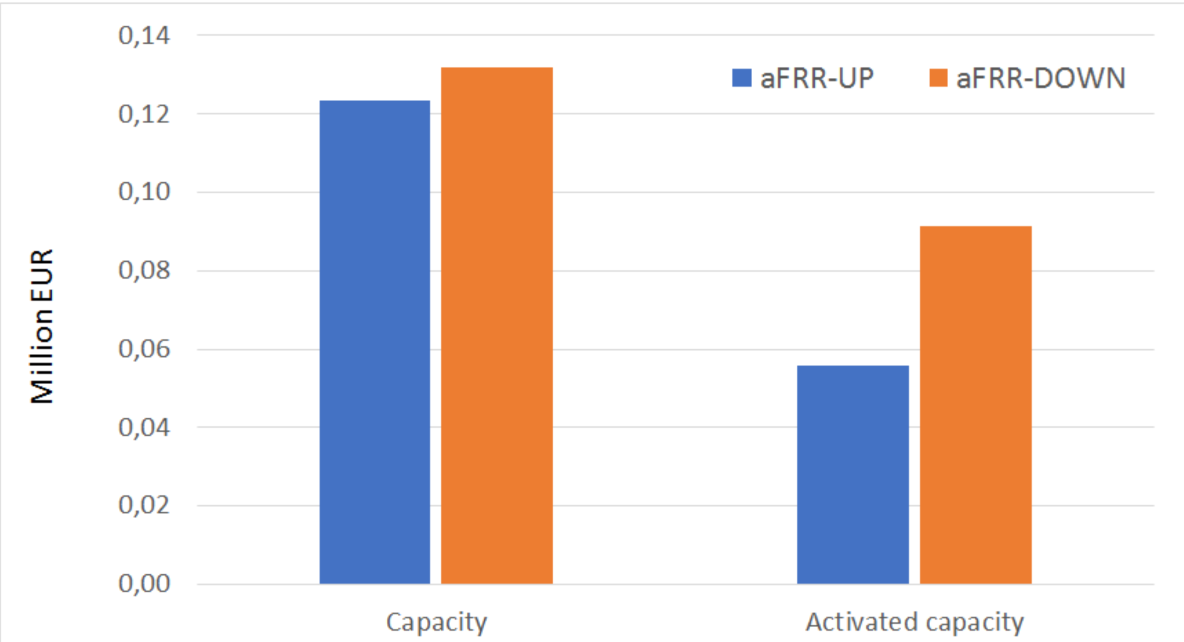

Figure 5.7: Contributions to total annual income from frequency restoration reserve services for up- and down-regulation services in the Spanish grid.

As can be seen in figure 5.9, annual incomes are not sensitive to variations in the price of reserved up-regulating reserves. However, with annual incomes varying by $\pm 0.3\%$ the resulting BCOHs are 10 EUR/kg and 7.5 EUR/kg for increasing and decreasing capacity price, respectively. As with the result shown in figure 5.1, hydrogen production loss increases linearly with increasing electrolyser utilization with fixed efficiencies. The resulting BCOHs when compared to the reference case is 7.8 EUR/kg and 9.4 EUR/kg for increasing and decreasing electrolyser efficiency, respectively.

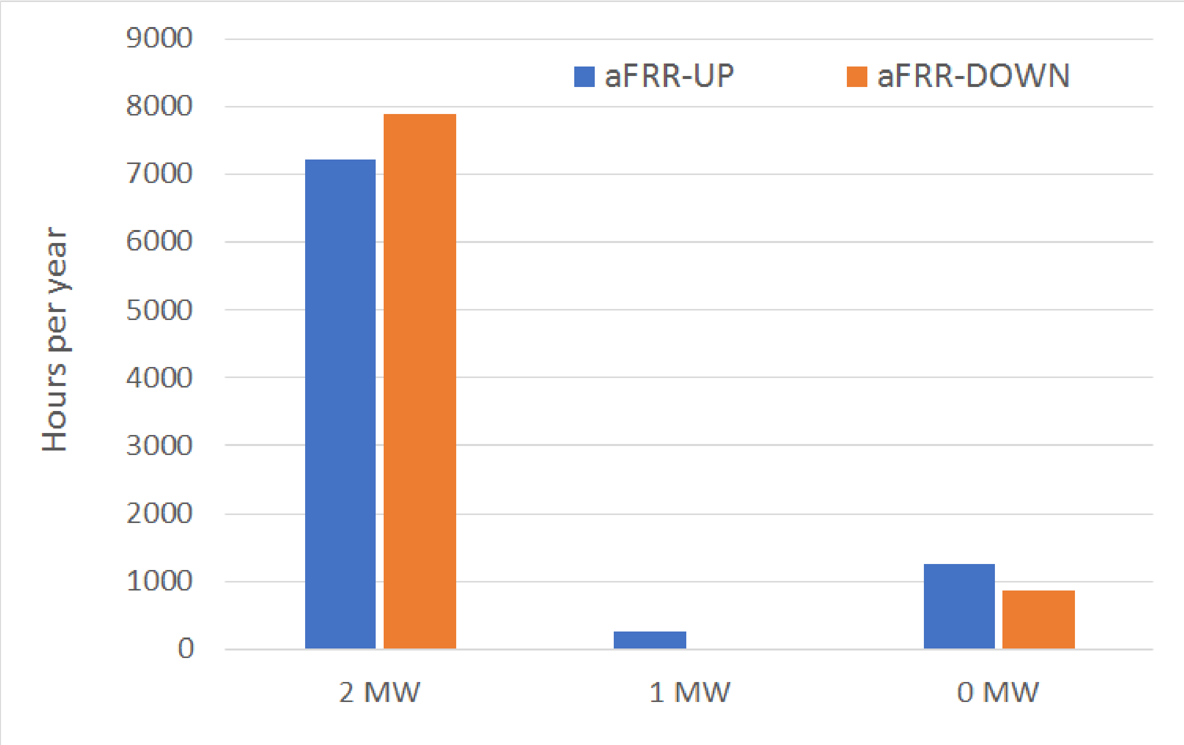

Figure 5.8: Amount of capacity contracted per year, differentiated by bid size.

The results from the sensitivity analysis performed on an electrolyser selling down-regulating capacity are similar to what is seen for up-regulating capacity. With varying prices for reserved down-regulating reserves at roughly ±0.3%, the resulting break-even costs deviate to 4.9 EUR/kg and 4.6 EUR/kg for increasing and decreasing prices, respectively. Low utilization of the electrolyser as a result of offering down-regulating capacity also leads to low variations in annual hydrogen production with varying electrolyser efficiency. The analysis results in 4.3 EUR/kg with increased efficiency and 5.1 EUR/kg with decreased efficiency.

Similarly to offering frequency containment reserve capacity, annual wind power distribution dictates when the electrolyser can be operated. The effect on I_{tot} from variations in wind power distributions is shown in figure 5.11. With variations in annual income ranging from 2.6% to 5.2% relative to 2017, the resulting BCOHs are presented in table 5.4. Variations in annual costs are in the range from 0.01% to 0.3%, while variations in annual hydrogen production are in the range from 0.4% to 0.8%.
f

As offering down-regulating capacity requires much less available energy than up-regulating capacity does, varying wind power distribution has a smaller effect on the break-

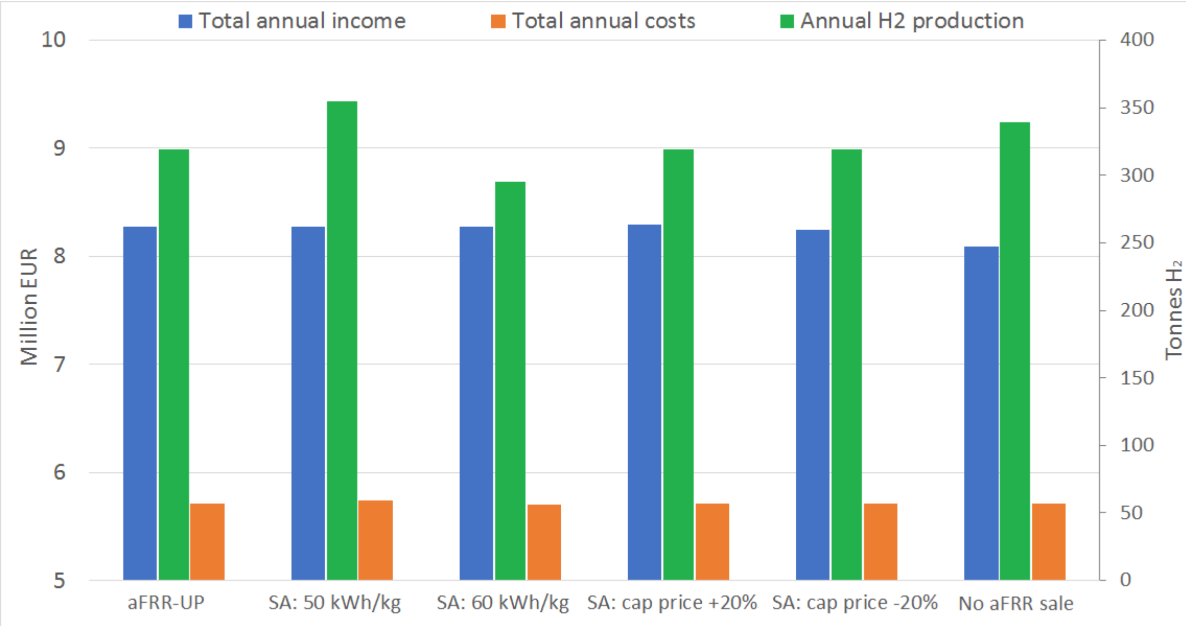

Figure 5.9: Sensitivity analysis results for a 2.5 MW electrolyser delivering up-regulating frequency restoration reserve capacity in the Spanish grid.

Figure 5.10: Sensitivity analysis results for a 2.5 MW electrolyser delivering down-regulating frequency restoration reserve capacity in the Spanish grid.

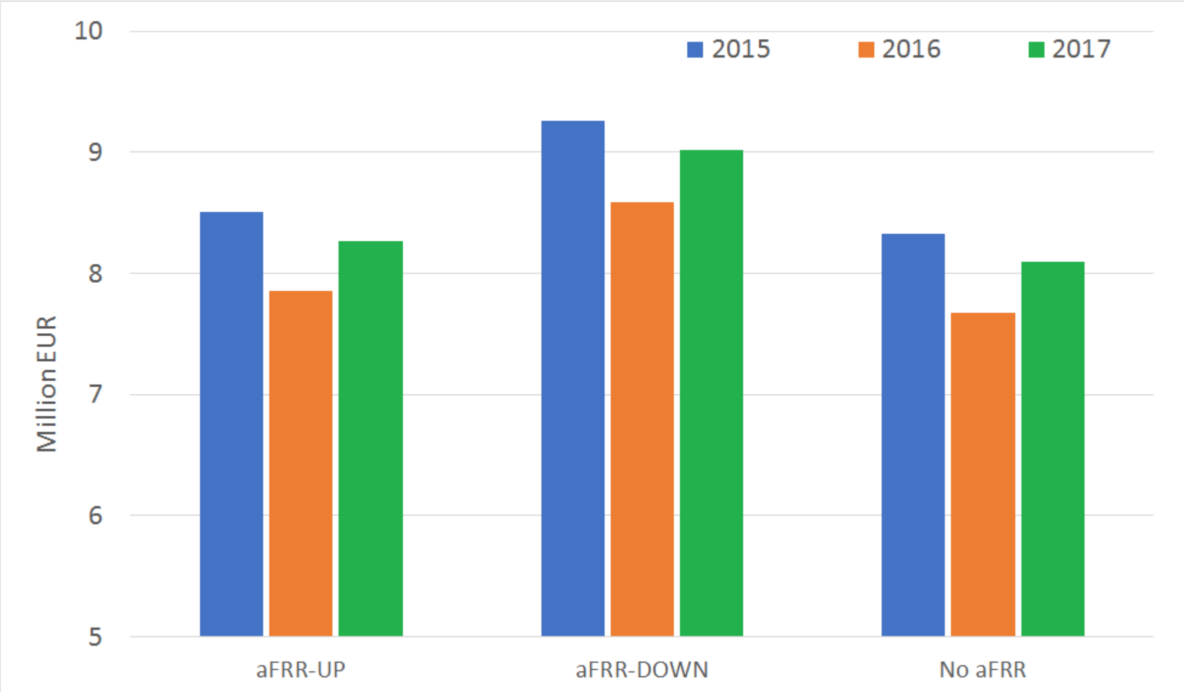

Figure 5.11: Variations in total annual income with varying annual wind power distribution for a wind-hydrogen system operating in the Spanish grid.

Case comparison	**2017**	**2016**	**2015**
aFRR-UP VS **VS** No aFRR	8.7 EUR/kg	8.9 EUR/kg	9.7 EUR/kg
aFRR-DOWN **VS** No aFRR	4.7 EUR/kg	4.7 EUR/kg	4.7 EUR/kg

Table 5.4: Break-even costs of hydrogen for a 2.5 MW electrolyser operating in the Spanish grid.

even cost of hydrogen for the former.

When up-scaling the nominal power of the electrolyser to 45 MW, annual total income, costs and hydrogen production become as shown in figure 5.12. While both total annual costs and hydrogen production increase for all three cases, the I_{tot} behaves differently compared to increasing the nominal power for an electrolyser offering FCR capacity. The reason why offering down-regulating power increases the annual total income is that as increasing the electrolyser nominal power results in an increased peak hydrogen production capacity, there is less energy left to sell at the electricity spot markets. As this income makes up the largest share of the total income, shown in table 5.1, the total annual income decreases significantly. The minimum electrolyser capacity remains at 0.3 MW, and since offering down-regulating capacity means lowering the base electrolyser utilization, the main income category does not suffer the same penalty as other reserve types when up-scaling the electrolyser capacity.

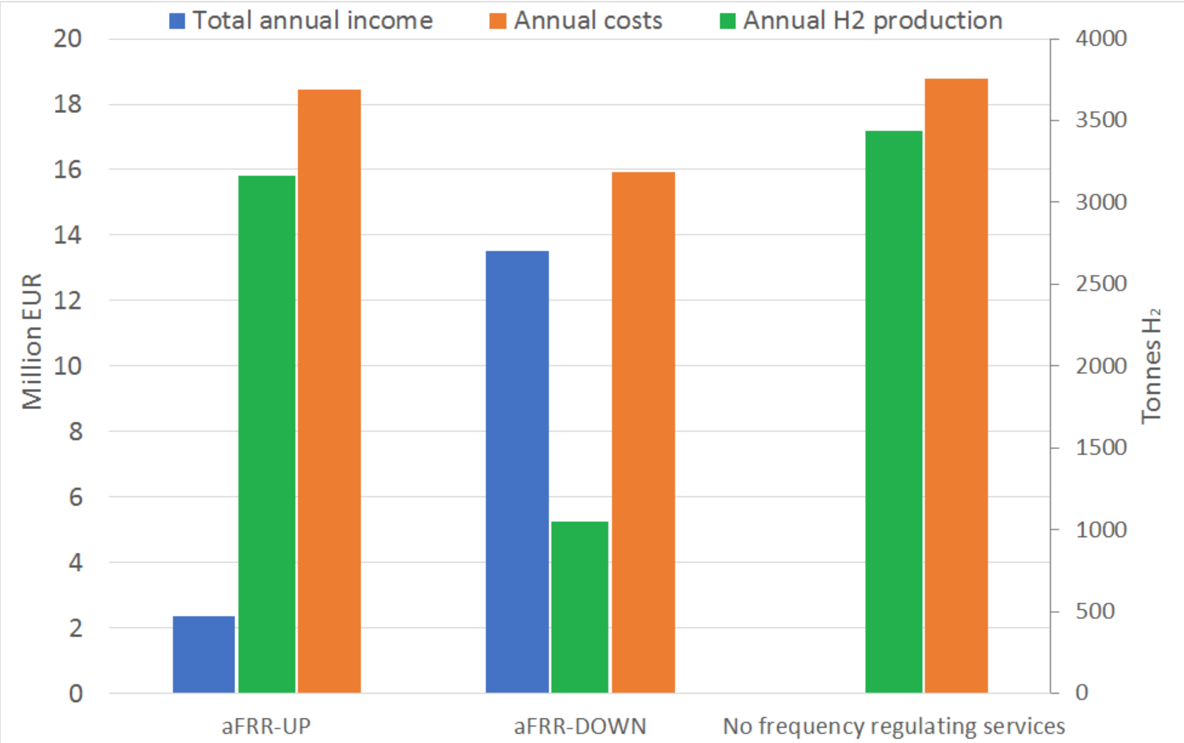

Figure 5.12: Sensitivity analysis results for a 2.5 MW electrolyser delivering up-regulating frequency restoration reserve capacity in the Spanish grid.

The drawback that is suffered is reduced annual hydrogen production. While offering aFRR-DOWN capacity yields an added value of 16.4 million EUR in annual net income compared to the reference case, the penalty to hydrogen production ends up at 2385 tonnes per year. This results in a break-even cost of hydrogen of 6.9 EUR/kg. As the annual costs exceed the income, the levelised cost of hydrogen is 2.3 EUR/kg. This means that, unlike an electrolyser delivering FCR capacity to the Norwegian grid, an electrolyser with a capacity of 45 MW offering aFRR-DOWN capacity can be economically feasible and advantageous simultaneously.

As for offering up-regulating capacity the added value of net annual income is 2.7 million EUR, while incurring a penalty of 270 tonnes per year to the annual hydrogen production. This results in a break-even cost of 9.9 EUR/kg. As a result of annual costs exceeding the annual income, the resulting levelised cost of hydrogen is 5.1 EUR/kg. This means that the wind-hydrogen system is economically feasible if the selling price of hydrogen exceeds 5.1 EUR/kg, and prioritising the sale of aFRR-UP is economically advantageous unless the selling price exceeds 9.9 EUR/kg. For the reference case where no frequency regulation services are sold, the levelised cost of hydrogen is 5.5 EUR/kg.

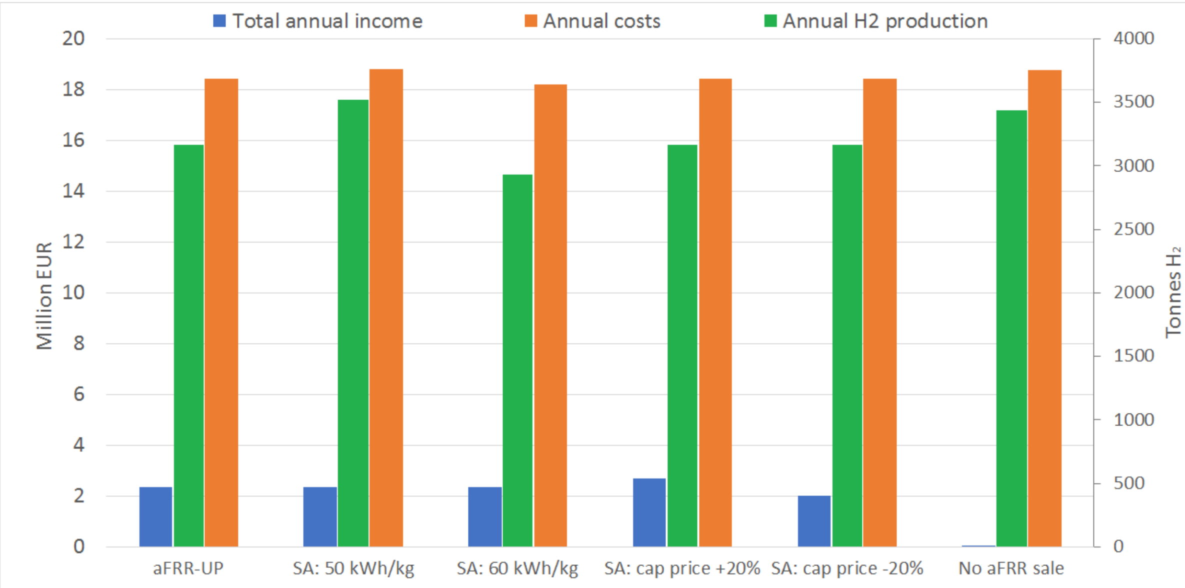

Figure 5.13: Sensitivity analysis results for a 45 MW electrolyser delivering up-regulating frequency restoration reserve capacity in the Spanish grid.

Due to the lack of income from the sale of electricity when offering up-regulating capacity, variations in the price of restoration reserve capacity has a larger influence on the total annual income. Capacity price variations of $\pm 20\%$ results in variations in I_{tot} of $\pm 13.8\%$. The resulting break-even costs of hydrogen are 11.1 EUR/kg and 8.7 EUR/kg for increasing and decreasing prices of restoration reserve capacity, respectively. Similarly, the levelised cost of energy decreases to 5.0 EUR/kg with increasing price of capacity, while a decrease results in a levelised cost of hydrogen of 5.2 EUR/kg.

The effect of varying electrolyser efficiency is greater because of the increased electrolyser hydrogen production capacity. Increasing the efficiency to 50 kWh/kg yields a break-even cost of hydrogen at 8.9 EUR/kg and a levelised cost of hydrogen at 4.7 EUR/kg, while an efficiency of 60 kWh/kg gives a break-even cost at 10.7 EUR/kg and a levelised cost of hydrogen at 5.4 EUR/kg.

With variations in electrolyser efficiency resulting in variations in annual hydrogen productions ranging from 7.4% to 11.1%, the resulting break-even costs are 6.2 EUR/kg and 7.4 EUR/kg with increasing and decreasing electrolyser efficiency respectively, with corresponding levelised costs of hydrogen at 2.1 EUR and 2.4 EUR/kg.

When offering down-regulating frequency restoration reserve capacity, the system economics is more responsive to variations in reserve capacity price when compared to a

Figure 5.14: Sensitivity analysis results for a 45 MW electrolyser delivering down-regulating frequency restoration reserve capacity in the Spanish grid.

smaller electrolyser. Price variations of $\pm 20\%$ yield variations in total annual income of $\pm 4.3\%$. Break-even costs are 7.1 EUR/kg and 6.6 EUR/kg with increasing and decreasing capacity prices, respectively. Similary, levelised costs of hydrogen are 1.7 EUR/kg and 2.8 EUR/kg for increasing and decreasing capacity prices, respectively.

5.3 Germany

As a participant in the German energy markets, minimum bid sizes and bid size steps enable an electrolyser at 2.5 MW maximum capacity to participate in markets for both frequency containment and restoration reserves. The results from the analysis of delivering FCR and aFRR capacities are presented in figure 5.15, along with the results from the reference case analysis.

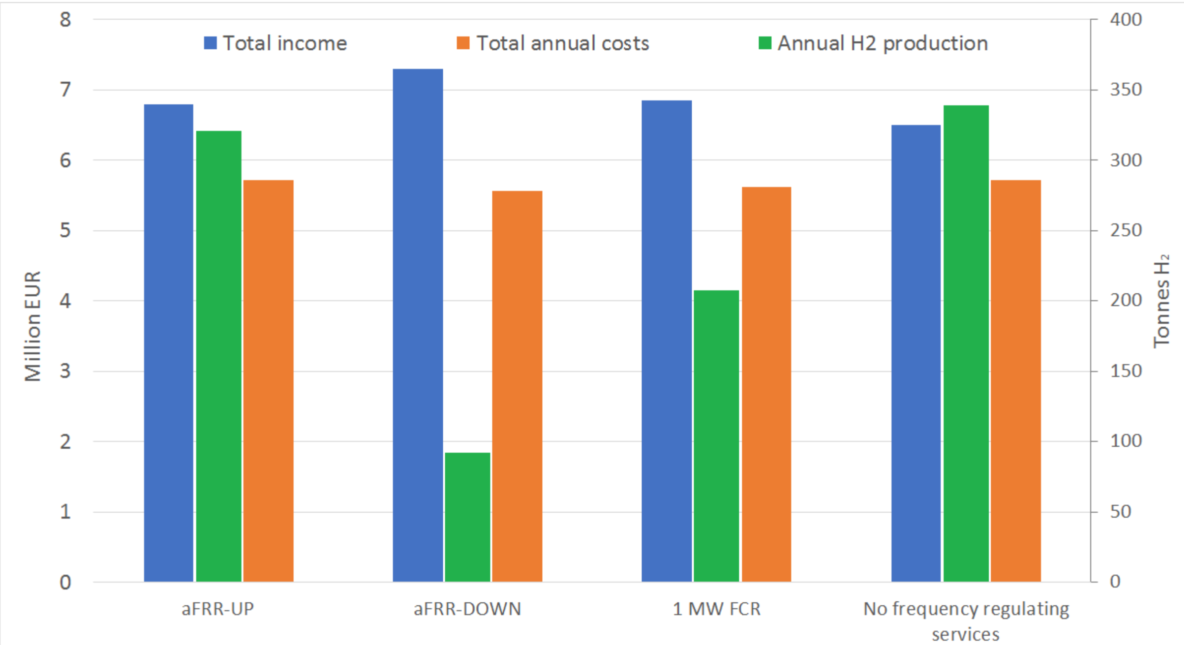

Figure 5.15: Analysis results for a 2.5 MW electrolyser operating in the German grid.

The result characteristics are similar to the sale of FCR in the Norwegian market and the sale of aFRR in the Spanish markets. With the sale of containment reserve capacity the annual income is increased by 430,000 EUR per year compared to the reference case, while the annual hydrogen production decreases by 131 tonnes. This results in a break-even cost of 3.3 EUR/kg, with the sale of FCR capacity being economically advantageous when the price falls below this threshold. Comparing this to the Norwegian case of FCR sales, the break-even cost is somewhat lower in Germany, assuming a currency of 10 NOK/EUR.

As the number of hours per year the electrolyser delivers FCR capacity is nearly identical (7497 hours in the German market, 7493 hours in the Norwegian market), the BCOH in Germany is lower despite the higher capacity price in the German market. Where the average price for 1 MW per hour in Germany was 8.9 EUR in 2019, the same capacity in the Norwegian market in 2018 was 59.9 NOK [46, 36]. Taking the recent trend shown in [17] into account, the difference between the two markets may be even greater. It is also important to keep in mind that while activated capacity is remunerated in Norway, this is not the case in the German markets.

As with the sale of FCR, the results of the sale of frequency restoration reserve capacity in the German market is similar to the results from the Spanish market. For aFRR-UP, I_{tot} increases by 277,000 EUR per year, while simultaneously incurring a penalty to annual hydrogen production of 18 tonnes. This results in a break-even cost of 15.3 EUR/kg. This is even higher than the case in the Spanish markets. Just as with the capacity price comparison to the Norwegian market, the capacity price for restoration reserve capacity is greater in Germany than in Spain. While the average symmetrical price for 1 MW per hour of aFRR is 8.3 EUR in the Spanish market, in the German market the price of the same amount of aFRR-UP is 15.1 EUR [46]. Note that the price of electricity on the day-ahead market is larger in Spain than in Germany [46]. This is also evident when comparing the sizes of the total annual incomes in the two countries in figures 5.6 and 5.15.

For aFRR-DOWN, the added value to net annual income is 946,000 EUR per year compared to the reference case, while annual hydrogen production is decreased by 247 tonnes. The resulting break-even cost of hydrogen is 3.8 EUR/kg, which is a bit lower than the resulting price in the Spanish market. As the average price for 1 MW per hour of down-regulating restoration reserve capacity equals 14.4 EUR, significantly exceeding the symmetrical price for aFRR in the Spanish market [46]. As shown in a comparison between figures 5.6 and 5.15, the annual hydrogen production when selling down-regulating restoration capacity is larger in the Spanish grid. This contributes towards dampening the effects of a higher capacity price. The same figures indicate that the difference in activated aFRR-UP is smaller, contributing to the large difference in BCOH for aFRR-UP.

As the price for aFRR-DOWN is larger compared to the Spanish market, the system sensitivity is more prominent, even if variations in the break-even cost are relatively small due to the large reduction in annual hydrogen production. Increasing prices by 20% leads to a break-even cost of 4.0 EUR/kg, while a reduction of 20% reduces this price to 3.7 EUR/kg. Increasing the electrolyser efficiency to 50 kWh/kg decreases the break-even cost of hydrogen to 3.5 EUR/kg, while increasing the efficiency to 60 kWh/kg increases the price to 4.1 EUR/kg.

Due to a smaller reduction in the annual hydrogen production, the sensitivity to the price of restoration reserve capacity is more visible in the break-even cost of hydrogen. While increasing the price by 20% increases the break-even cost to 17.8 EUR/kg, decreasing it by 20% leads to a price of 12.9 EUR/kg. As the electrolyser efficiency is fixed in all cases, the sensitivity is similar to previous cases. Increasing the efficiency leads to a break-even cost of 13.8 EUR/kg, while decreasing the efficiency increases the price to 16.6 EUR/kg.

Increasing the price of reserved containment reserve capacity by 20% results in a break-even cost of 3.4 EUR/kg, while a decrease by 20% lowers the price to 3.2 EUR/kg. Similarly, an increase in electrolyser efficiency decreases the break-even cost to 3.0 EUR/kg,

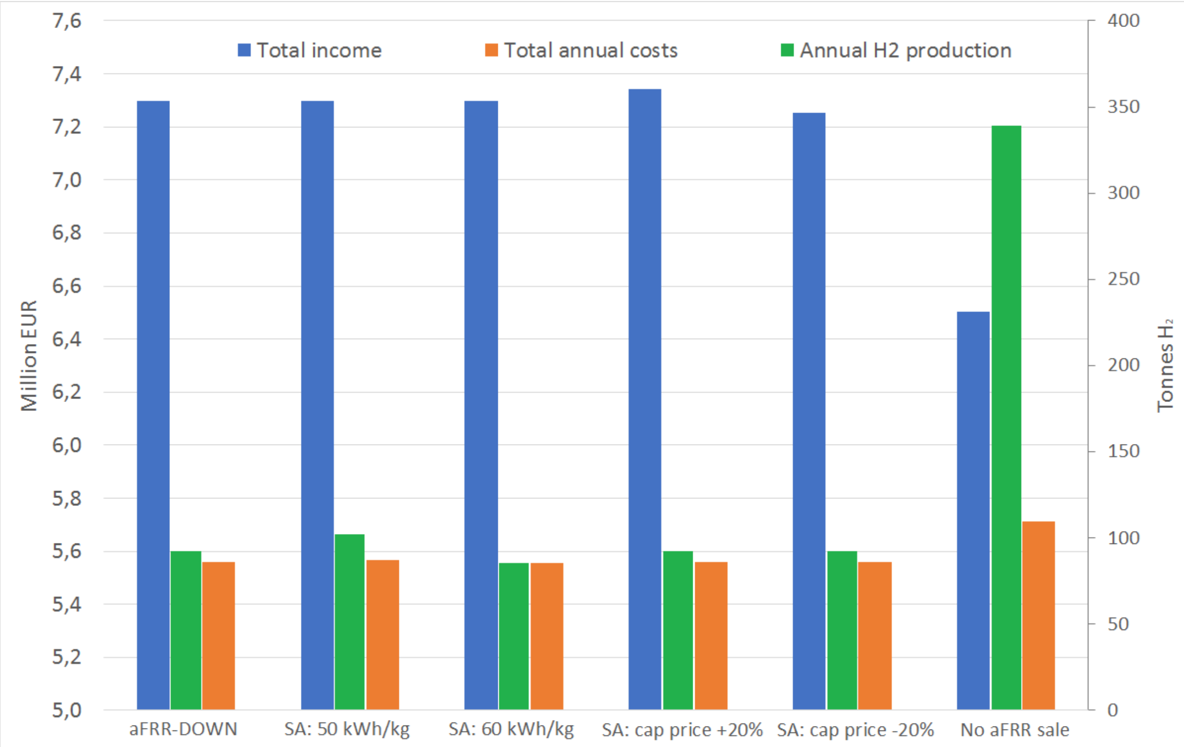

Figure 5.16: Sensitivity analysis results for a 2.5 MW electrolyser delivering down-regulating frequency restoration reserve capacity in the German grid.

while a decrease in efficiency results in a price of 2.5 EUR/kg.

When up-scaling the electrolyser nominal power to 45 MW, the effects of frequency regulating service remuneration are more apparent. Comparing the numbers in figures 5.5, 5.12 and 5.19, total annual income from offering aFRR-UP is increased, while the income is decreased in the case of offering aFRR-DOWN in the German market. Assuming a currency of 10 NOK/EUR, I_{tot} is decreased when compared to selling FCR capacity in the Norwegian market.

The increase in I_{tot} when compared to the case in the Spanish market can be ascribed to increased prices of aFRR-UP. When the electrolyser capacity equals the output capacity of the wind farm, electricity sales decrease significantly. Thus, the higher price for electrical power in the Spanish markets are of less importance. For a 45 MW electrolyser, selling aFRR-UP in the German market yields an added value of 3.7 million EUR to the net annual income, at the cost of 232 tonnes of hydrogen per year. This results in a break-even cost of hydrogen at 15.8 EUR/kg. Further, the levelised cost of hydrogen is 4.7 EUR/kg.

Counter to the operating strategy of an electrolyser selling aFRR-UP, offering down-

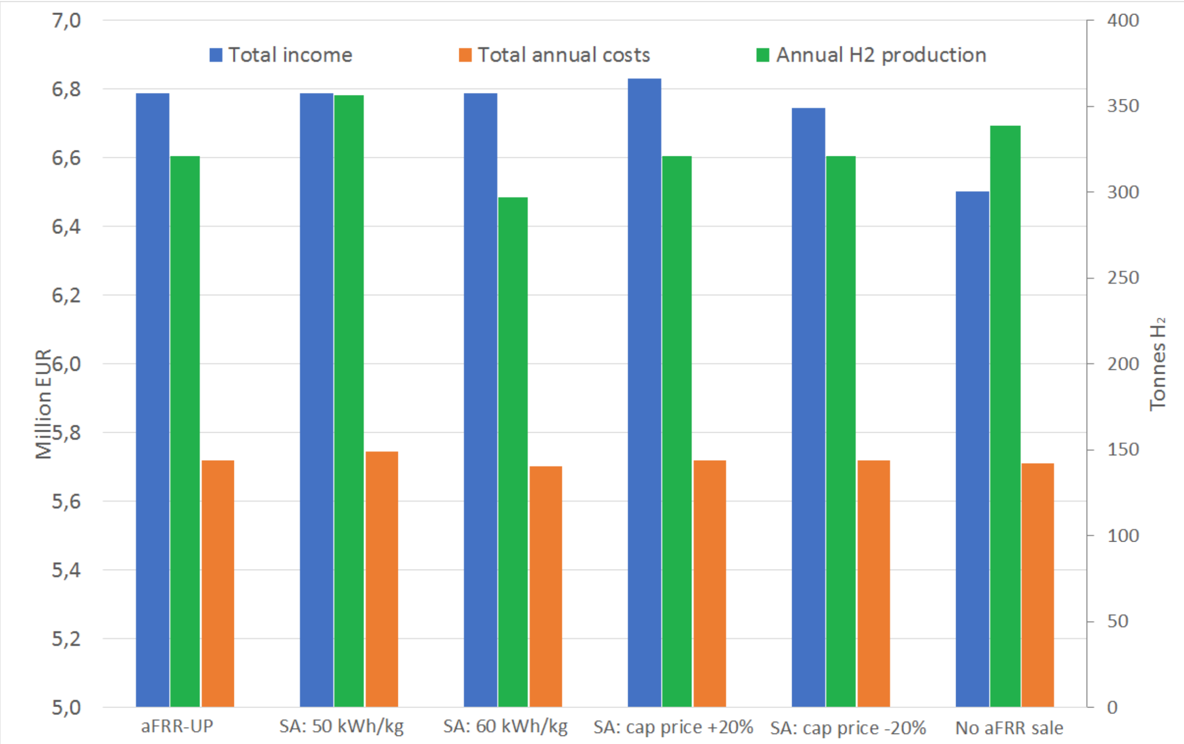

Figure 5.17: Sensitivity analysis results for a 2.5 MW electrolyser delivering up-regulating frequency restoration reserve capacity in the German grid.

regulating capacity requires the electrolyser to run at low initial capacity. This, in turn, leads to a large surplus of energy from the wind farm that can be sold at the electrical day-ahead market. This, in addition to an increased amount of activated reserves, is the main reason for an increased I_{tot} for an electrolyser operating in the Spanish market. Compared to the reference case, a 45 MW electrolyser offering aFRR-DOWN in the German market increases the net annual income by 1.5 million EUR, while reducing the hydrogen production by 2825 tonnes per year. This gives a BCOH of 5.3 EUR/kg. The corresponding LCOH is 6.1 EUR/kg.

When offering FCR capacity, the symmetrical nature of the service leads to an operating strategy intermediate between up- and down-regulating restoration reserve capacity. Compared to the case of an up-scaled electrolyser in the Norwegian grid, and assuming a currency of 10 NOK/EUR, the total annual income is slightly decreased, despite the increased capacity price. As no specific information was available, no remuneration scheme is taken into account for elecitricity sold in the German day-ahead markets. When the annual income from the sale of green certificates is subtracted from the I_{tot} for the case in Norway, the result matches what is found in the case in Germany. If the source of origin-guarantee is removed as well, the total annual income for an electrolyser offering FCR in

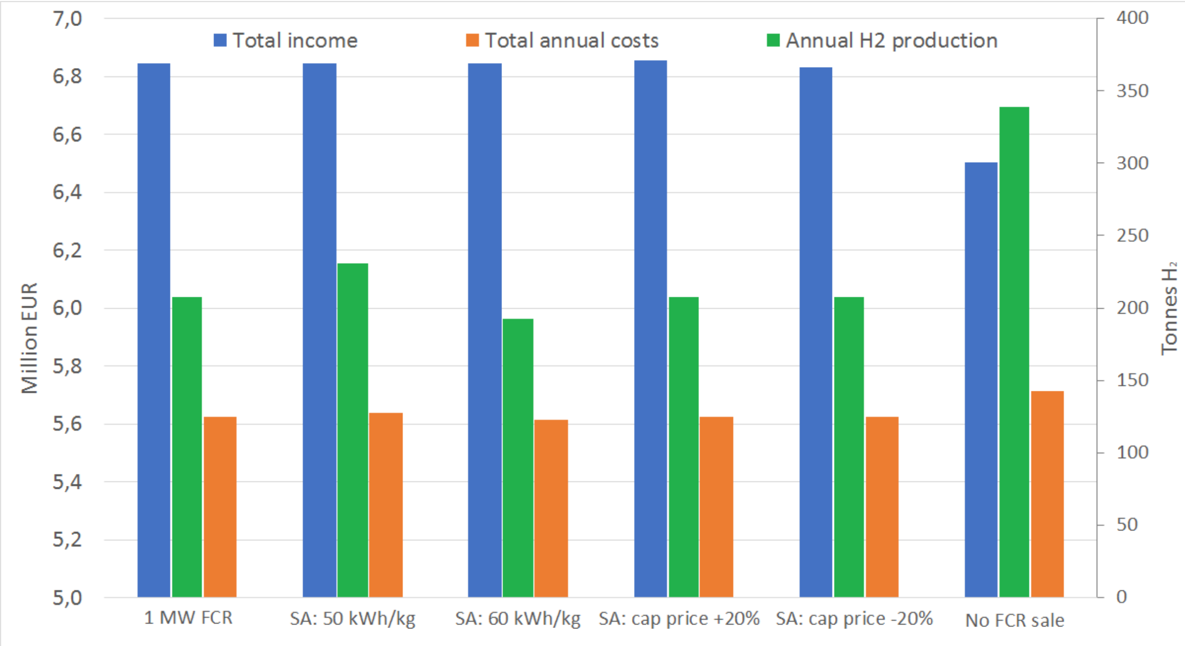

Figure 5.18: Sensitivity analysis results for a 2.5 MW electrolyser delivering FCR capacity in the German grid.

Germany surpasses that of one operating in Norway.

When compared to the reference case, offering FCR in the German grid leads to an increase of 5.1 million EUR to the annual net income while decreasing hydrogen production by 1124 tonnes per year. This results in a break-even cost of 4.5 EUR/kg. The levelised cost of hydrogen in this case is 5.9 EUR/kg.

The results from the sensitivity analysis can be seen in figures 5.20 through 5.22. Break-even costs are summed up in table 5.5 and levelised costs of hydrogen in table 5.6. Sensitivities have the same sources of origin as in the case of a smaller electrolyser.

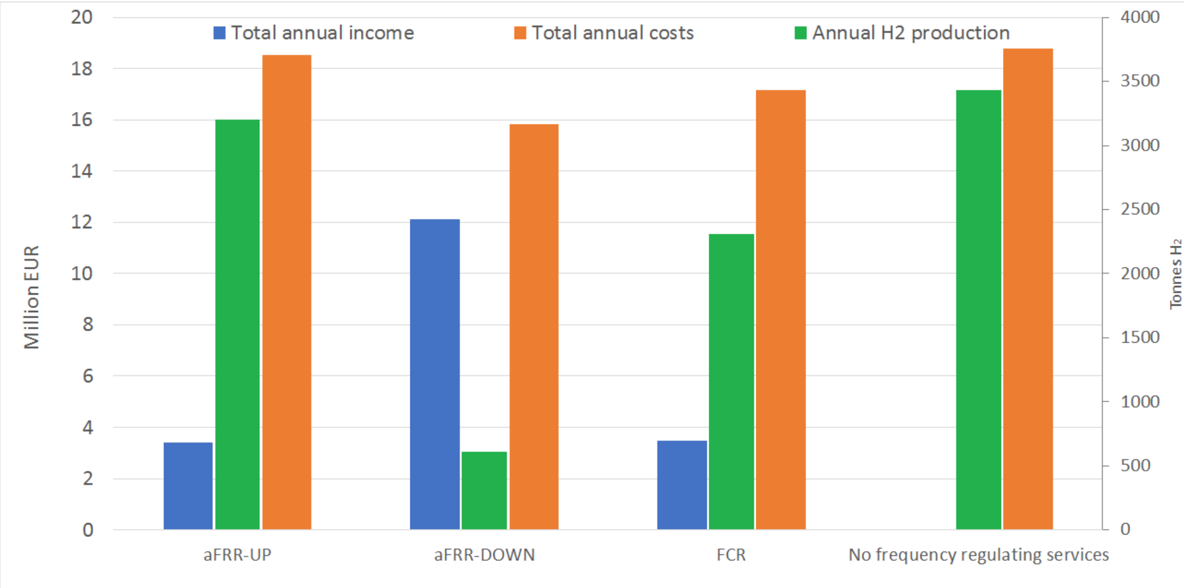

Figure 5.19: Analysis results for a 45 MW electrolyser operating in the German grid.

Case	Break-even cost of hydrogen [EUR/kg]
FCR VS No FCR	4.5
SA: cap price +20%	4.7
SA: cap price -20%	4.3
SA: 50 kWh/kg	4.2
SA: 60 kWh/kg	4.79
aFRR-UP VS No FCR	15.8
SA: cap price +20%	18.0
SA: cap price -20%	13.5
SA: 50 kWh/kg	14.3
SA: 60 kWh/kg	16.9
aFRR-DOWN VS No FCR	5.3
SA: cap price +20%	5.3
SA: cap price -20%	5.4
SA: 50 kWh/kg	4.9
SA: 60 kWh/kg	5.7

Table 5.5: Break-even costs hydrogen for cases with an electrolyser maximum capacity of 45 MW operating in the German grid.

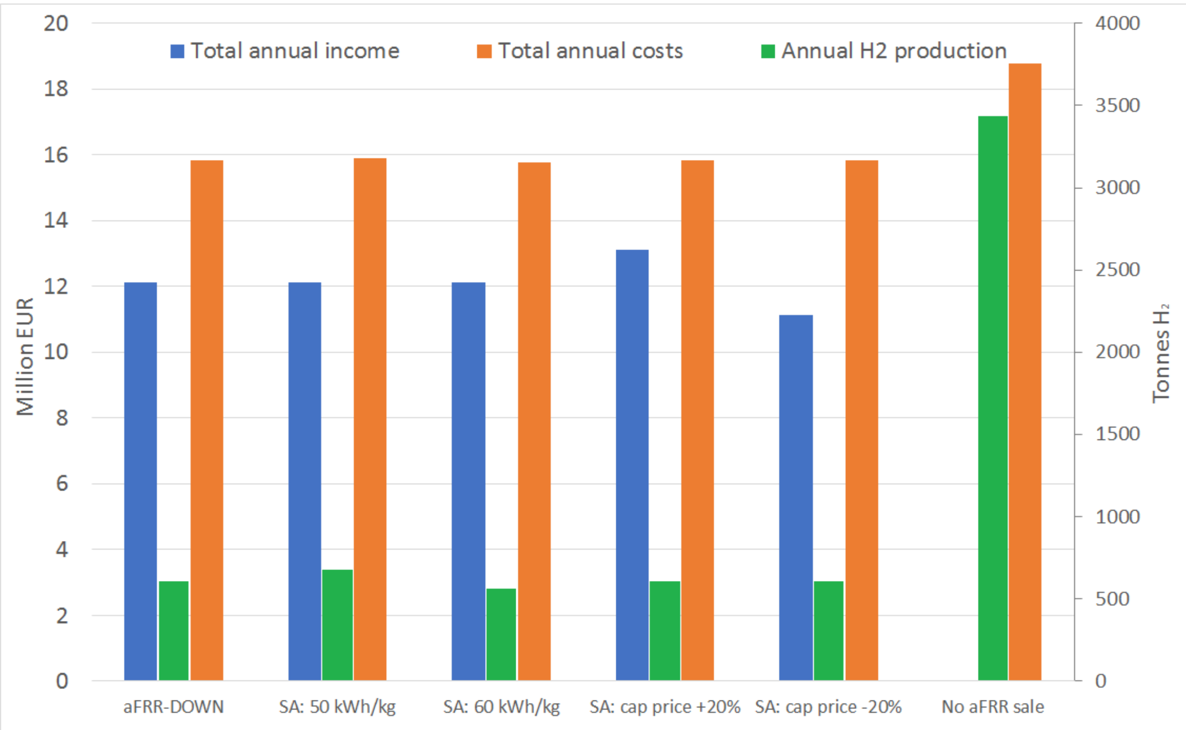

Figure 5.20: Sensitivity analysis results for a 45 MW electrolyser delivering down-regulating aFRR capacity in the German grid.

Figure 5.21: Sensitivity analysis results for a 45 MW electrolyser delivering up-regulating aFRR capacity in the German grid.

Case	Levelised cost of hydrogen [EUR/kg]
FCR	5.9
SA: cap price +20%	5.8
SA: cap price -20%	6.0
SA: 50 kWh/kg	5.4
SA: 60 kWh/kg	6.3
aFRR-UP	4.7
SA: cap price +20%	4.6
SA: cap price -20%	4.9
SA: 50 kWh/kg	4.4
SA: 60 kWh/kg	5.0
aFRR-DOWN	6.1
SA: cap price +20%	4.4
SA: cap price -20%	7.7
SA: 50 kWh/kg	5.6
SA: 60 kWh/kg	6.5
No FCR	5.5

Table 5.6: Levelised cost of hydrogen for the different cases with an electrolyser maximum capacity of 45 MW operating in the German grid.

Figure 5.22: Sensitivity analysis results for a 45 MW electrolyser delivering FCR capacity in the German grid.

5.4 Summary discussion

The results presented in sections 5.1 through 5.3 show that although all cases of selling automatic frequency regulating services reach achievable break-even costs of hydrogen [47], there are significant differences. The sale of aFRR-UP, in particular, results in the highest break-even costs. This is mainly due to a smaller reduction in annual hydrogen production compared to the sale of other frequency regulating services. While the relatively large annual production improves the system's economics, the demand for such a large volume may not be present. This imposes extra cost as the hydrogen must be transported to an area where the hydrogen infrastructure is more well established, and the demand is higher. It also poses a risk as there may be problems in selling such large volumes of hydrogen.

Offering either FCR or aFRR-DOWN capacity enables any unused electrolyser capacity to be used in frequency regulation, contributing to the annual total income from the wind-hydrogen system in the place of income from the sale of hydrogen. Even should the current selling price of hydrogen be higher than the break-even cost found in this analysis, participation in the frequency regulating markets can justify investments into larger electrolyser capacity as a part of a growing hydrogen infrastructure. When the demand for hydrogen increases, any unused capacity can be utilized to increase supply accordingly. As the price of hydrogen drops in the future, the sale of frequency regulating services may also abate the loss of income from the sale of hydrogen and increase the net revenue from the system. This presupposes that the price of frequency regulating reserve capacity does not drop significantly in the future.

While up-scaling the electrolyser to match the installed capacity at the Raggovidda wind farm increases the hydrogen production significantly, the corresponding increase in capital investment as well as operating and overhaul costs cause the annual costs to exceed the total income. As the bulk of the resulting LCOH are in the range of 4-6 EUR/kg, investing in such large electrolyser capacity may not be economically feasible in the future. The exception to this is the sale of aFRR-DOWN in the Spanish market, with a levelised cost of hydrogen of 2.3 EUR/kg. With increased electrolyser efficiency, this cost drops to 1.7 EUR/kg, which is within EU's ambitions of 1-2 EUR/kg [47]. This presupposes that loads are allowed to deliver frequency regulating capacity in the Spanish grid in the future. Future work may include optimizing the electrolyser size with respect to the installed wind power capacity to maximize the system revenue in order to bring down the levelised cost of hydrogen.

While offering FCR capacity provides results intermediate between up- and down-regulating restoration reserve capacity, the symmetrical nature of the capacity restricts the operation of the electrolyser. Offering non-symmetrical capacity increases flexibility, and combining operating strategies for providing the two types of restoration reserve capacities would increase the annual hydrogen production compared to the sale of exclusively aFRR-DOWN, while increasing net annual income compared to the sale of exclusively aFRR-UP. Non-symmetrical FCR capacities, such as FCR-D, will work the same way. This reserve type has not been considered here due to a much smaller volume of up-regulating FCR-D compared to FCR-N, as well as a lack of down-regulating product on the market [23].

Future work should include looking into providing a mix of different frequency regulating capacities to optimize the revenue from the system,. Including mFRR in the mix is also possible, even if the fast ramping rates are unnecessary for this product. To determine the net revenue, data sets regarding both costs of handling and the selling price of the product hydrogen are required. Additionally, changes in prices and volumes in the frequency regulating capacity markets should be tracked over the course of more than one year, to investigate the effects of variations within a longer time span. This would also allow for a more accurate calculation of the system net present value.

As a BSP, it is assumed that the electrolyser can always deliver the contracted frequency regulating capacity, and so will avoid any fines associated with failure to deliver what has been offered. However, when the electrolyser has been limited to running on an intermittent power source, like the wind farm, there are instances where failure to deliver may occur. To circumvent the effects of intermittent power supply, all wind energy can be fed into the grid and sold as electrical power. The electrolyser can then be powered by electricity through the grid without the possibility of suddenly losing any power supply. This involves the consumption of grid electricity and the balance between selling and buying prices for electrical energy, in addition to added costs associated with using the grid. A more detailed approach regarding grid congestions management may also be necessary in this case.

To avoid having to deal with any tariffs and other intermediary costs associated with using the grid [39] this way, it has been assumed that the electrolyser is connected to the wind farm through a single radial owned by Varanger Kraft, in addition to the grid where frequency regulating reserve capacity is delivered. The largest effect of increased tariffs will be felt by the 45 MW electrolyser, since it will draw more power from the grid. The 2.5 MW electrolyser will be most affected by any possible grid congestions, since more energy will be sold due to small local loads and consequently fed into the transmission grid.

In addition to the intermittency of the power source used in this analysis, the grid in the Varanger peninsula is N-0 the whole year around [2], meaning that if any power cables fail, the connection to the transmission grid will be broken. In this case the peninsula grid will enter island mode, where the electrolyser can make up a central part of the frequency regulation capacity in the grid [48]. The technical and economical aspects of this situation would have to be explored in future studies.

Investigating the variations with time will allow for additional features to be studied. In addition to variations in volumes and prices for frequency regulating capacity, the effects of electrolyser efficiency degradation [9] should be studied. As the sensitivity analysis in this report showed, the electrolyser efficiency has a significant effect on both LCOH and BCOH.

Further, the physical properties of an electrolyser providing frequency regulating capacity should be analysed. Modelling each stack as a separate unit with regard to load, start-up time, temperature and moisture transients, and efficiency. Tracking the effect of these parameters on each unit's life time expectancy may yield more data regarding this aspect of total costs associated with the electrolyser. When life time expectancy is known, overhaul costs can be modeled more accurately. Distributing this cost evenly across the operating hours, as is done in this analysis, is an underestimation of said costs due to currency inflation. Modelling the electrolyser stacks separately could also give information about the interaction between the stacks when ramping up or down from intermediate loads to either maximum or minimum electrolyser load.

Chapter 6

Conclusion

The technical and economical potential of a wind-hydrogen system offering automatic frequency-regulating services from a 2.5 MW electrolyser to the electrical grid in Finnmark, Norway as well as the German and Spanish grids has been investigated. A set of algorithms for determining the amount of frequency regulating capacity, activated capacity as well as energy sold is developed with this in mind, and historical data is used for an economical analysis with a scope of 1 year. This is also extended to a possible scenario where the nominal electrolyser capacity is up-scaled to 45 MW to match the installed wind turbine capacity. Additionally, an analysis has been performed to test the sensitivity to both price of reserved frequency regulating capacity and electrolyser efficiency.

The technical investigation shows that the electrolyser's power ramping capabilities qualifies it for offering (FCR) to the Norwegian and German grids, and (aFRR) to the German grid. The maximum electrolyser capacity of 2.5 MW disqualifies it from offering aFRR to the Norwegian grid, and FCR is a mandatory, non-renumerable service in the Spanish grid, and is thus not investigated. Only generating units are allowed to offer frequency regulating services to the Spanish grid, but the economical potential has been investigated nonetheless in case this changes with further harmonization of European frequency regulation markets.

Among the key results from the economical analysis is that a 2.5 MW electrolyser delivering FCR capacity is economically advantageous when the selling price of hydrogen is below 38.8 NOK/kg in the Norwegian grid, or 3.3 EUR/kg in the German grid. Delivering up-regulating aFRR capacity is economically favourable if the selling price of hydrogen is below 8.7 EUR/kg in the Spanish grid and 15.3 EUR/kg in the German grid. Similarly, delivering down-regulating aFRR capacity is profitable if the selling price of hydrogen is below 4.7 EUR/kg in the Spanish grid or 3.8 EUR/kg in the German grid. Up-scaling of the electrolyser to 45 MW increases these price thresholds, at the cost of introducing another price threshold which determines whether the wind-hydrogen system is economically feasible.

These results show that the wind-hydrogen system can operate at moderate electrolyser loads as the hydrogen economy is growing while making profit from offering the unused capacity for frequency regulating purposes. This gives incentives to invest in larger electrolyser capacities and may help speed up the transition into a larger hydrogen infrastructure.

Bibliography

[1] Frida Holand. Fremtidens frekvensstabilitet i kraftsystemet, December 2014, https://docplayer.me/9854480-Fremtidens-frekvensstabilitet-i-kraftsystemet.html.

[2] Varanger Kraft. Regional kraftsystemutredning, 2018, https://varanger-kraftnett.no/getfile.php/132721-1529401580/Dokumenter/Nett/Energiutredninger/Kraftsystemutredning

[3] European Comission. Communication from the commisson: The European Green Deal, December 2019, https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640.

[4] FCH2 JU Governing Board. Multi-annual work plan 2014-2020, https://ec.europa.eu/research/participants/data/ref/h2020/other/legal/jtis/fch-multi-workplan_en.pdf.

[5] European Comission. Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation, September 2019, https://cordis.europa.eu/project/id/779469.

[6] Norges Vassdrags. og Energidirektorat. Rekordproduksjon i norske vindkraftverk, May 2019, https://www.nve.no/nytt-fra-nve/nyheter-energi/rekordproduksjon-i-norske-vindkraftverk/.

[7] Varanger Kraft. Hydrogenfabrikk - Berlevåg, https://www.varanger-kraft.no/hydrogen/.

[8] British Petroleum. Statistical review of world energy, 69th edition. 2020. last downloaded 25.june 2020.

[9] Maider Santos and Iker Marino. HAEOLUS Deliverable D5.1: Energy analysis of the Raggovidda integrated system, January 2019.

[10] Maider Santos, Raul Rodriguez, and Santiago Garcia. HAEOLUS Deliverable D5.3 Draft: Techno-economic analysis of wind-hydrogen integration.

[11] Silviu Nistor, Saraansh Dave, Zhong Fan, and Mahesh Sooriyabandara. Technical and economic analysis of hydrogen refuelling. *Applied Energy*, 167:211–220, April 2016.

[12] Feras Alshehri, Víctor García Suárez, José L. Rueda Torres, Arcadio Perilla, and M.A.M.M. van der Meijden. Modelling and evaluation of PEM hydrogen technologies for frequency ancillary services in future multi-energy sustainable power systems. *Heliyon*, 5(4):e01396, April 2019.

[13] Joshua Eichman, Aaron Townsend, and Marc Melaina. Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets, February 2016.

[14] Johannes Fleer, Sebastian Zurmühlen, Jonas Meyer, Julia Badeda, Peter Stenzel, Jürgen-Friedrich Hake, and Dirk Uwe Sauer. Techno-economic evaluation of battery energy storage systems on the primary control reserve market under consideration of price trends and bidding strategies. *Journal of Energy Storage*, 17:345–356, June 2018.

[15] Felix Keck, Manfred Lenzen, Anthony Vassallo, and Mengyu Li. The impact of battery energy storage for renewable energy power grids in Australia. *Energy*, 173:647–657, April 2019.

[16] Tesla mega-battery in australia activated. *BBC News*, December 2017, https://www.bbc.com/news/world-australia-42190358. Last read 26. June 2020.

[17] Julia Badeda, Jonas Meyer, and Dirk Uwe Sauer. Modeling the influence of installed battery energy storage systems on the German frequency containment reserve market, September 2017.

[18] Gerardo A. Perez-Valdes, Sigrid Damman, Miguel Muñoz-Ortiz, and Vibeke Nørstebø. HAEOLUS Deliverable D2.5: Impact of Hydrogen-Wind Systems, February 2020.

[19] Hydrogenics. Personal communication, March 2020.

[20] Varanger Kraft. Personal communication, April 2020.

[21] Regelleistung. General information on control reserve - technical aspects, April 2020, https://www.regelleistung.net/ext/static/technical?lang=en.

[22] Rita B. Johnsen. Informasjon om endring av vilkår for primærreserve (FCR), October 2019, https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/marked/reservemarkeder/informasjon-om-endring-av-vilkar—fcr—gjeldende-fra-02.12.2019.pdf.

[23] Statnett SF. Roller i balansemarkedene of vilkår for aggregerte bud, August 2018, https://www.statnett.no/contentassets/d27d9d5efd7a4371abe2b17c97ef4a64/27-august-2018-roller-i-balansemarkedene-og-aggregering.pdf.

[24] Statnett SF. Utvikling av systemtjenester 2016-2021, https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/utvikling-av-kraftsystemet/utvikling-av-systemtjenester-2016-2021.pdf, last read 26. june 2020. Technical report.

[25] ENTSO-E WGAS. Survey on Ancillary Services Procurement and Electricity Balancing Market Design. Technical report, ENTSO-E, March 2019, https://www.entsoe.eu/publications/market-reports/#survey-on-ancillary-services-procurement-and-electricity-balancing-market-design.

[26] European Commission. Commission regulation (EU) 2017/2195: establishing a guideline on electricity balancing. Technical report, November 2017, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2017.312.01.0006.01.ENG&toc=OJ:L:2017:312:TOC#d1e1675-6-1.

[27] Statnett SF. Personal communication, March 2020.

[28] Statnett SF. Vilkår for tilbud, aksept,rapportering of avregning i sekundærreservemarkedet, https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/systemansvaret/reservemarkeder/vilkar-for-sekundarreserver-afrr-gjeldende-fra-072019.pdf.

[29] Hans Olav Ween. Informasjon om kommende krav og marketsvilkår for funksjonalitet til turbinregulatorer, November 2018, https://www.statnett.no/contentassets/58b9643b54c1460093c44fec3ceb82b9/informasjon-om-kommende-krav-og-markedsvilkar-for-frekvensregulering.pdf.

[30] Pablo Rodilla and Carlos Batlle. Empirics of Intraday and real-time Markets in Europe: Spain, 2015, https://www.econstor.eu/bitstream/10419/111923/3/Report_1st_FPM_2015_Spain.pdf.

[31] RED Eléctrica de España. Operation of the electricity system, https://www.ree.es/en/activities/operation-of-the-electricity-system, read march 2020.

[32] ENTSO-E. Frequency Containment Reserves (FCR), https://www.entsoe.eu/network_codes/eb/fcr/.

[33] Amprion. Balancing capacity in Germany, https://www.amprion.net/energy-market/market-platform/control-energy/.

[34] ENTSO-E. PICASSO, https://www.entsoe.eu/network_codes/eb/picasso/.

[35] Tale Skjølsvik and Kari Håvåg Voldsund. *Forretningsforståelse*. Cappelen Damm akademisk, Oslo, 2016. OCLC: 1028511860.

[36] NordPool Group. Historical Market Data, https://www.nordpoolgroup.com/historical-market-data/, read may 2020.

[37] Statnett SF. Tall og data fra reservemarkeder, https://www.statnett.no/for-aktorer-i-kraftbransjen/systemansvaret/kraftmarkedet/reservemarkeder/tall-og-data-fra-reservemarkeder, accessed 12. may 2020.

[38] Statnett SF. Årets tariff, https://www.statnett.no/for-aktorer-i-kraftbransjen/tariff/tariffer-i-sentralnettet/, read may 2020.

[39] Statnett SF. Tariffer for transmisjonsnettet 2018, https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/tariff/tariffhefte2018-transmisjonsnett.pdf.

[40] Nordkraft. Regionalt samarbeid - fornybar nord nettverket, May 2019, https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/planer-og-analyser/nup-2019-presentasjoner-og–referater/2019-05-27-regionalt-samarbeid-nordkraft.pdf.

[41] NVE and Energimyndigheten. Et norsk-svensk elsertifikatmarked: årsrapport for 2018, 2019, https://www.nve.no/media/8124/et_2019_04_norsk_tilpublikasjon.pdf.

[42] Olje og energidepartementet. Høring - Ordningen med opprinnelsesgarantier og varedeklarasjonen for strøm, December 2018, https://www.energinorge.no/siteassets/div/horingsuttalelse-fra-energi-norge—ordningen-med-opprinnelsesgarantier-og-varedeklarasjonen-for-strom—19122018.pdf.

[43] ENTSO-E Working Group Economic Framework. ENTSO-E Overview of Transmission Tariffs in Europe: Synthesis 2019, June 2019, https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/mc-documents/190626_MC_TOP_7.2_TTO_Synthesis2019.pdf.

[44] European Comission. Electricity market design, https://ec.europa.eu/energy/topics/markets-and-consumers/market-legislation/electricity-market-design_en, last read 26. june 2020.

[45] ENTSO-E Transparency Platform, https://transparency.entsoe.eu/, read may 2020.

[46] ENTSO-E. Market Committee.

[47] European Commission. Communication from the commission to the european partliament, the council, the european economic and social committee and the committee of the regions - draft, 2020.

[48] Rita B. Johnsen, Erik Alexander Jansson, and Jon Nerbø Ødegård. Funksjonalitet for separatdriftsregulering/deteksjon (FCR-l) og dødbånd, December 2018, https://www.statnett.no/contentassets/58b9643b54c1460093c44fec3ceb82b9/funksjonalitet-for-separatdriftsregulering-og-deteksjon.pdf.

NTNU

Norwegian University of
Science and Technology