The role of electrolysers in energy system

Energy markets, grid stabilisation and transport fuels

Ridjan, Iva; Hansen, Kenneth; Sorknæs, Peter; Xu, Jie; Connolly, David; Mathiesen, Brian Vad

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

THE ROLE OF ELECTROLYSERS IN ENERGY SYSTEMS

Energy markets, grid stabilisation and transport fuels

AALBORG UNIVERSITY
DENMARK

The role of electrolysers in energy system – Energy markets, grid stabilisation and transport fuels

August, 2016

Aalborg University, Department of Development and Planning

Iva Ridjan

Kenneth Hansen

Peter Sorknæs

Jie Xu*

David Connolly

Brian Vad Mathiesen

Aalborg University
Department of Development and Planning

Guest researcher at the Department of Development and Planning*

Publisher:

Department of Development and Planning
Aalborg University
Vestre Havnepromenade 5
9000 Aalborg
Denmark
Photo source: Politiken.dk

ISBN 978-87-91404-86-3

Abstract

Short and long-term role of electrolysis for grid balancing is investigated in this report, followed by an analysis on the feasibility of implementing electrolysis in the energy system and their potential for gas market balancing. Firstly, a literature review is conducted to determine the state-of-the-art knowledge on using electrolysis for grid balancing. Secondly, based on Danish energy system models for 2020 and 2035, which can simulate the operation of electrolysis, the role of both alkaline and SOEC electrolysers is analysed in terms of electricity system balancing. Thirdly, different electrolyser capacities are simulated in 2020 and 2035 to investigate how electrolysis can aid the integration of for renewable energy, followed by a gas-grid balancing analyses. Finally, a comparison is made between SOECs and alkaline electrolysers in the 2035 system, due to the uncertainty of commercializing SOEC and in general terms the necessity for this technology.

The results show that with the implementation of SOECs in 2035, their participation in the balancing reserves is possible, but it will most likely not be required as there are number of other flexible technologies that could be used instead due to their better performance and lower costs. The investments in electrolysis should be driven by the need for meeting the transport fuel demand, as their biggest contribution is for fuel production rather than for renewable energy integration. The grid stability should be seen as an additional benefit from electrolyser integration.

Contents

Nomenclature

Abbreviation	Meaning
AEC	Alkaline Electrolysis Cell
BAU	Business-as-usual
CHP	Combined Heat and Power
DSM	Demand Side Management
ENTSO-E	European Network of Transmission System Operators for Electricity
FCEV	Fuel Cell Electric Vehicles
PCR	Primary Control Reserve
PEM/PEMEC	Proton Exchange Membrane Electrolytic cells
PtG	Power to gas
PtL	Power to liquid
SCR	Secondary Control Reserve
SOEC	Solid Oxide Electrolysis Cell
TCR	Tertiary Control Reserve
TSO	Transmission System Operator

1. Introduction

With an aim of becoming 100% renewable in 2050 and already high share of wind energy in the system, Denmark needs to transform the system to one that creates flexibility within it as the resource flexibility is lost by shift from fossil fuels to renewable energy. There is therefore a need for wide selection of technologies that can accommodate the high share of renewable energy and provide grid stability, energy storage or a hybrid system to accommodate daily and seasonal changes [1]. One promising solution is electrolysis: splitting water with an electric current producing hydrogen that can be further used for the production of electrofuels[1]. Electrofuels are produced by merging hydrogen with a carbon source, either CO_2 emissions from point sources or blending it with gasified biomass. Electrofuel production for the transport sector as provides the missing link between intermittent renewable energy, resource scarcity and dependence on high-density fuels [2–4]. Electrolysis is a unique conversion technology that can be used not only for fuel production and as a base for different chemicals, but potentially also as a mean to provide grid frequency regulation.

Electrolysis technologies are characterized by the type of electrolyte they use. Currently there are two main types of technologies for electrolysers that are commercially available and undergoing rapid development in the recent years – Alkaline Electrolytic cells (AEC) and Proton Exchange Membrane Electrolytic cells (PEM/PEMEC). High temperature water electrolysis is a third method which is currently in the research and development stage, this type of cell is known as a solid oxide electrolytic cell (SOEC) [5]. In the end of 2014, the first plant of its kind was inaugurated in Germany by Sunfire GmbH integrating SOECs for production of electrofuels [6]. This German company is also participating in EU projects and it is aiming at commercializing SOECs. In Denmark testing and demonstration of SOECs is increasing in the last years and there are currently 5 on-going projects with this technology [7–12]. The ongoing projects are focusing on further development of the technology, its pressurized operating mode, reversible operation, degradation and robustness challenges and its demonstration for fuel production purposes. There are also ongoing projects that are demonstrating other types of electrolysis for gas/hydrogen production. The BioCat project will install 2 x 500 kW of alkaline electrolysers and produce methane from biogas upgrade [13], and a PEM based project, HyBalance with planned 1.2 MW of PEM electrolysers that will be used both for grid balancing services and but also provide hydrogen for industry and transport [14].

This report investigates the potential of implementing electrolysis for grid balancing both from a technical and an electricity market perspective in the Danish system in a short-term (2020) as well as a long-term (2035) system. The results are presented in four chapters.

Firstly, a literature review of the electrolysis potential for grid balancing was conducted in order to identify the state-of-the-art knowledge on the topic. As the potential of using electrolysis is rather broad within ancillary services it was important to identify what is the current status and its economical perspective. In order to identify the electrolysis' short-term role in electricity system balancing a regulating assessment was

[1] The term "*electrofuel*" refers to fuel production by combined use of electrolysers with carbon source. If the carbon source is CO_2-emissions the term *CO_2-electrofuel* is used, and in case the carbon source is from the biomass gasification the term *bioelectrofuel* is used. Terminology is defined by Ridjan *et.al* in [64].

carried out that investigates the participation of electrolysis in market based balancing reserves in 2020 and 2035.

Further analyses in a business-as-usual (BAU) Danish energy system for 2020 was conducted to investigate the feasibility of implementing electrolysis in the system, potential for renewable electricity integration and to identify the role of current commercially available alkaline electrolysers. All analyses have tested the integration of seven different electrolyser capacities in the energy system, while varying the amount of intermittent renewable electricity. Some of the capacities tested are related to meeting the 2020 renewable energy goal for transport with electrofuels and regulation for accounting the share of renewable energy. Testing different intermittent renewable electricity shares is important to consider as it reflects the ability of electrolysis to facilitate the integration of renewable electricity in the system and will indicate its potential for replacing fossil fuels in the system. As the electrolysis is simulated in the system for fuel production purposes, it is possible to identify if their role should be for renewable power integration purposes or for meeting the transport demand.

The long-term role was tested in a Danish energy system for 2035, where an adapted IDA Energy Vision 2035 model was used [15]. In this model, both the gas and electricity market context were investigated. The gas market is interesting to investigate as electrofuel production has syngas as the intermediate product and if it is upgraded to methane as a final fuel, it could be used for interacting with gas grid. Previous research [16,17] concludes that as syngas demands new infrastructure to be in place for transport, followed by expensive investments, production of methane would be needed in order to use the natural gas network and minimize costs. The electricity market context was further explored in the Nordic and European context by analysing different electricity market prices expected to occur in 2035. This approach was used to reflect the Danish electricity market trades with other Nordic or European countries. Both analyses in Section 4 and 5 were conducted using the energy system analysis tool EnergyPLAN [11].

2. State-of-the art knowledge on electrolysis for grid balancing – literature review

Many countries around the world have ambitious targets to increase the penetration of renewable electricity such as wind power in their electrical power systems, but the additional supply-side variability and uncertainty can pose new challenges for utilities and system operators who are responsible for balancing generation with demand in real time [18]. The unexpected imbalance between generation and demand will result in unplanned loop flows, grid congestion, and deviation from the nominal frequency and voltage variation [19]. Moreover, the integration of large-scale renewables requires faster response and longer duration ramps for the grid balancing than ever before [20,21]. One potential solution to these problems is to utilise electrolysers to vary loads supplied by the power system in relation to any power imbalance, due to its ramping capability and fast-acting nature [22], especially in the case of a high penetration of renewable power.

Electrolysers have the potential to support the grid system with ancillary services such as demand response, voltage support, frequency regulation, providing spinning or non-spinning reserves, and load following, etc. In addition, the resulting hydrogen can be delivered to multiple markets or uses, including methanation or delivery to fuel cell electric vehicles (FCEVs) [23]. Many studies have been done to explore the potential benefits of participation of hydrogen production by electrolysis to balancing services. Eichman *et al*. [22] found that electrolysers acting as demand response devices can respond sufficiently fast and participate for a long enough duration in energy management on the utility scale, however further work on the impact of dynamic operation on electrolyser lifetime is needed. Due to their characteristics PEM electrolysers are often involved in testing for fast regulation. It was shown that ~40 kW PEM electrolyser systems can change their load point rapidly, in the order of milliseconds, and can shut down in just over a minute. Power2Hydrogen project has simulated the operation of power-to-gas (PtG) plant based on PEM electrolysis and investigated its potential for participation in electricity markets. Two strategies were analysed: trading electricity in the spot market and trading electricity in the spot and regulating power markets [24]. It is concluded that PtG plant can participate both in spot and regulating market. The electrolyser can deliver balancing reserves in form of regulating power, but due to the minimum bid capacity of 10 MW it needs to be combined with other units.

Shivachev [25] investigated the voltage control performance of integrating alkaline electrolyser system into the local grid with high wind penetration based on a DIgSILENT PowerFactory simulation, and found this system showed fully capacity of maintaining the voltage within the allowed limits. Dalmau and Pérez [26] assessed the capability of a power-to-gas system based on alkaline electrolyser to provide voltage regulation and energy management to a Danish distribution grid with a high share of wind power penetration. The results from these simulations showed that such system could eliminate voltage deviation in all buses and decrease losses around 50%, and with a proper market strategy, it can further decrease the active power export by almost 40% during the simulated winter week, while maintaining a similar voltage quality. Kiaee *et al*. [27,28] demonstrated that electrolysers can prevent unacceptable frequency drop and significantly reduce fluctuations in system frequency based on a model developed in MATLAB SIMULINK environment. For the case they examined, five times less spinning reserve is required in order to maintain the power system frequency within operational limits when electrolysers are utilised as a form of demand side management

(DSM), compared to the base case where no electrolyser DSM plant is available. Meantime, the participation of hydrogen production by electrolysis to balancing services is already being experienced. In June 2011, the Hydrogenics Corporation announced that it had successfully completed a trial project with Ontario's Independent Electricity System Operator (IESO) that demonstrated their electrolyser's capability to stabilise the grid frequency [29], but the project utilised only one electrolyser to demonstrate such capability. It is expected that in the future in order to increase the share of renewable power, more electrolysers will participate in such schemes, and their aggregate impact should be investigated from a grid stability point of view.

As for the economic perspective, the integration of electrolysers to the grid is not economically favourable under today's technical conditions and support policies according to existing studies, which are fundamental for the development of hydrogen technologies. With net operating income evaluated by means of energyPRO software, Pozzi [30] estimated the impact of the electrolyzed hydrogen storage system on the overall zonal grid of Italy. The results showed that if staying to the current techno-economic technology status, the 20-year investment is not feasible, but when simulating the future techno-economic development for year 2025, the investment economy improves. Guinot *et al*. [31] analysed the economic viability of a PEM electrolyser plant that provides balancing services to the grid by participating in primary frequency regulation based on the French context. The results indicated that within current economic conditions, the plant operator would not benefit from participating to frequency regulation; to make such participation economically attractive requires compensation that is strongly linked to the value of the capacity component. However, if the electrolysers are coupled with fuel cells, theoretically there might be net revenue accumulated because of the electricity price arbitrage. Dalmau and Pérez [26] found hydrogen production cost would be lowered from 2.19 to 1.43 DKK/Nm^3 if applying PtG Systems to Danish Electric Distribution Networks and exerting proper market strategy. But there is a limit in such cost a reduction. Jørgensen *et al.* [32] confirmed that even when energy prices fluctuate widely, the cost of hydrogen production cannot be reduced by more than 10% when operating with discontinuous electrolysis. Alike, within today's electricity context, the electricity price spreads are too small to enable significant hydrogen production cost reductions through price arbitrage [33].

However, it should also be noted that storing surplus energy electrochemically and returning electricity back into the grid during the peak hours by using fuel cells may not be the best way for the utilization of electrolysers [34]. On one hand it introduces exergy losses into the system and results in lower energy efficiency, on the other hand, it has less economic competiveness. Eichman *et al*.[35] quantified the value for hydrogen energy storage and demand response systems to participate in selected California wholesale electricity markets using 2012 data, and found producing and selling hydrogen much more valuable than producing and storing hydrogen to later produce electricity. Therefore, instead of conversion back to grid electricity, it is likely that competitive electrolysed hydrogen systems will receive multiple revenue streams by providing more than one energy service, or industrial feedstock [23]. Electrolysed hydrogen could be utilised directly as fuel, injected into the natural gas grid, or combined with carbon recycling, and PtG/PtL technologies to generate electrofuels or synthetic natural gas. High-value electrofuel is considered to be necessary to supplement electricity in the transportation sector in a future 100% renewable energy system [3,36]. In a Danish 100% renewable energy context, 75% of the transport energy demand is met by electrofuels [15,34].

All signs show that electrolysers would be a potential way to integrate more intermittent renewable energy in the future, as they provide an option for regulating the energy system by balancing and storing excess

electricity, which is essential when integrating large quantities of renewables into existing energy systems. This is based primarily on computer simulation tools or by testing very small scale and mostly singular units of PEM or alkaline electrolysis. Therefore, there is still a need for more field demonstrations that can confirm the benefits of real-time grid connection especially with more recent types of electrolysers and solid oxide electrolysis cell. Although it is not economically favourable to utilise electrolysers to stabilise according to the literature, electrolysers are expected to have a better development with support policies in the future energy systems, especially for the future transportation sector.

3. Electrolysers role in electricity system balancing

In order to identify the electrolysis' short-term and long-term role in electricity system balancing it is important to understand how the European electricity market is structured and how it operates as a major share of electricity is traded on market basis [37]. Two overall types of markets can be identified, wholesale markets and balancing reserves [38]:

- Wholesale markets represent the context in which trading occurs between market participants. In wholesale markets, both purchase volumes and sale volumes are defined by participations on the market in advance of time of delivery. Wholesale trading can e.g. be done via central electricity exchanges or over-the-counter trading.
- Balancing reserves are different in that the demand in these is set partly by the expectations of potential imbalances between traded supply and demand, and partly by the specific imbalances. Balancing reserves are typically procured by the system responsible party. Balancing reserves are typically traded via central electricity exchanges.

Wholesale markets are organised to handle the main bulk of sales and purchases, while balancing reserves are organised to keep the electricity system in balance in real-time. Generally, the aim of both market types is to keep the electricity system in balance, and as such, a major part of the electricity system balancing occurs in the wholesale markets. However, in this chapter the focus is on the electrolysers' potential to participate in the balancing reserves based on regulating assessment.

3.1. Market-based balancing reserves

Three types of market balancing reserves (see Figure 1) are used by European Network of Transmission System Operators for Electricity (ENTSO-E) [39] which consists of 41 TSOs in 34 countries:

- Primary control reserve (PCR): used to gain a constant containment of frequency deviations. It is expected by ENTSO-E that 50% or less of the total PCR capacity has to be able to activate within 15 seconds, and the remaining has to be active within 30 seconds. This reserve is also known as frequency containment reserve.
- Secondary control reserve (SCR): used to restore frequency after sudden system imbalances. The activation time of units will typically be up to 15 minutes. This reserve is also known as frequency restoration reserve.
- Tertiary control reserve (TCR): used for restoring any further system imbalances. The activation time of units will typically be from 15 minutes to one hour. This reserve is also known as replacement reserve.

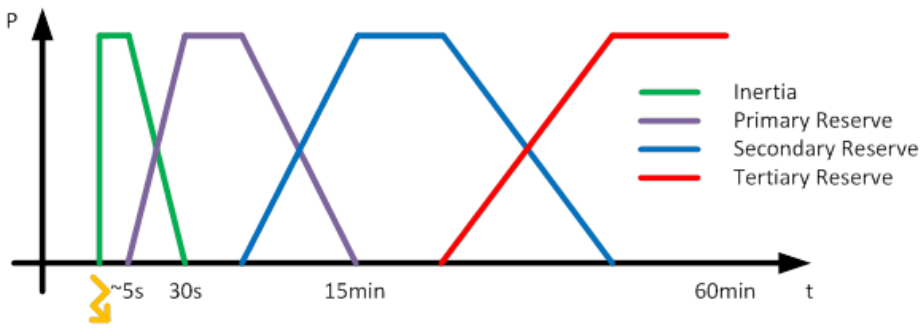

Figure 1. Illustration of market balancing reserves. Adapted from [40]

The PCR responds locally to changes in frequency, while the SCR and the TCR are managed centrally by the TSO, although the SCR is automatically activated while the TCR is manually activated. The different balancing areas operate with different rules for participations within these markets. Generally, the balancing reserves are used for two different situations; downward regulation, activated when there is excess electricity in the system, and upward regulation, activated when there is a lack of electricity in the system.

The specific organisation and utilisation of these three balancing reserves can vary from balancing area to balancing area. Differences in the organisation include, but are not limited to, the period of delivery, asymmetric or symmetric participation, technical requirements for being allowed to participate, settlement principle, etc. An example of the different organisation in different balancing areas is the SCR in Germany which is organised as a weekly tender that is cleared using the pay-as-bid principle[2] and activations have to start within 30 seconds and be fully activated within five minutes [41]. In comparison, in the balancing area of western Denmark[3] the market for SCR is a monthly tender where payment for capacity is cleared using the pay-as-bid principle and activations is cleared based on the prices on the day-ahead wholesale market, and activations have to be fully activated within 15 minutes where a part has to be delivered within 5 minutes by units already in operation [42].

In regards to utilisation, the needed PCR for the synchronously interconnected system of continental Europe is set by ENTSO-E at 3,000 MW, with each country contributing an agreed amount of capacity [39], where e.g. the balancing area of western Denmark has to deliver +/- 23 MW [43]. The SCR and TCR are where the main bulk of balancing energy is delivered, while the PCR is only used to contain deviations for a short period. Of the balancing reserves, the SCR and the TCR handle imbalances within timescales that are most relevant for the integration of variable renewable energy sources [44,45], though the utilisation of these markets for handling imbalances in the system can vary greatly, e.g. in Denmark the TCR has a dominant role, whereas in Germany the SCR is utilised to much larger extend than in Denmark [38]. With increasing wind power in the energy system, the SCR and TCR might see an increasing turnover, though other factors also plays a role here, such as the geographical size of the balancing areas and the time between actual delivery and deadline for the wholesale markets [45], and as such, it is difficult to estimate future utilisations of these balancing reserves. Currently, the Danish market for TCR is part of the Scandinavian TCR balancing reserve, where in the period of 2013-2015 an average of about 1.68 TWh/year was activated for upward regulation and an

[2] In markets using the pay-as-bid principle, each winning participant is settled according to that participant's bid.
[3] The organisation and utilisation of balancing reserves in Denmark differ between the western and eastern part of the country, with the western part being everything west of the Great Belt. Western Denmark is part of the continental European rules for balancing reserves, while eastern part is part of Nordic rules.

average of about 2.45 TWh/year was activated for downward regulation, where about 80% of activations occur in Norway or Sweden (based on data from [46]). For comparison the total electricity consumption in the Nordic area was 380.5 TWh in 2013 and 375.7 TWh in 2014 [47].

As the organisation and utilisation changes from balancing area to balancing area, and will change over time, the following takes its departure in the ENTSO-E guidelines. However, the current organisation and utilisation for the balancing area of western Denmark is included for the purpose of comparison. The potential for electrolysers to deliver balancing reserves is based on the electricity consumption capacity, and as such, the assessment will focus on this aspect of the electrolysers.

3.2. The operation of electrolysers in energy system

Operation of electrolysers on hourly basis both in a 2020 and a 2035 energy system model was investigated. In the 2020 BAU model, the capacity of 411 MW electrolysis was tested, which is the required capacity to meet the 10% renewable energy goal for transport if the fuel demand is met with electrofuels. The installed electrolysers are standard alkaline as they are the commercially most established technology. As fast regulation of alkaline electrolysers is very difficult [48] and is expected to drastically reduce their technical lifetime [49], this type of electrolyser is not expected to be relevant for participation in balancing reserves. Pressurized and higher temperature alkaline electrolysers are available that would be more suitable for fast regulations [50], but these were not investigated as they are not largely present on the market. It is not expected that electrolysers will participate in the balancing reserves in 2020, as it is assumed that only alkaline electrolysers will be installed before and in 2020.

Table 1. Regulation abilities and start-up time for alkaline and SOEC electrolysers. Adapted from [50]

		Alkaline electrolysers		SOEC
Production of		H_2		H_2 CO Syngas
Available from		**2012**	**2020–2030**	**2020–2050**
Start-up time	*Hours*	Depends on the system, can have rapid response		0.2
Regulation ability				
Fast reserves	*MW per 15 min.*	Full capacity	Full capacity (in 10 min.)	Full capacity
Regulation speed	*% per second*	0.001	0.004	3 down / 0.1 up
Minimum load	*% of full load*	10–20	10–20	3

In the 2035 scenario SOEC electrolysers are used. The total capacity of SOEC electrolysers installed is ~1,500 MW, where the produced hydrogen from the electrolysis is used for biomass hydrogenation and further conversion to electrofuel (same as in the 2020 scenario). The capacity was determined according to the potential of substituting oil with electrofuels. For the purpose of being able to operate the SOEC electrolysers flexible, hydrogen storage with a total capacity of 121 GWh is also included.

If kept at the operating temperature of 800°C, SOECs are expected to be able to ramp down with 3% of max load per second and ramp up with 0.1% per second (see Table 1). As it is expected that SOEC electrolyser systems will be based on a number of individual modules, ramping will to a large extend be possible by shutting down or activating individual modules. If they are not in operation the operating temperature of 800°C can be achieved with an external heat source. If, however, they are in a cold idle state the start-up time could be several hours. The minimum operating load is expected to be 3% of full load [50].

Based on these considerations and the current ENTSO-E guidelines for balancing reserves, three potential operational situations for SOEC electrolysers can be identified:

1. When already in operation, SOEC electrolysers can regulate fast enough to participate on all balancing reserves. For participation on the PCR the ramp up regulation of 0.1% per second sets the limit, as even though the ramp down regulation is faster, the SOEC electrolysers will need to adjust back fast enough to continuously deliver the offered balancing reserve. As such, based on the expected ramping speed alone, it is expected that SOEC electrolysers can deliver PCR with up to 3% of its installed capacity. For SCR and TCR, SOEC electrolysers can deliver up towards 90% of the installed capacity based on the expected ramping speeds, depending on the specific rules in the given markets. This regulation can both be offered as downward and upward regulation, depending on the actual operation and the corresponding not utilised capacity at the given period, e.g. if already operating at full load only upward regulation can be offered. However, it should be noted that the rules for SCR often requires that part of the delivered regulation comes from units already in operation.
2. When not already in operation but kept at the operating temperature, SOEC electrolysers are able to participate in the balancing reserves to the same extend as in operational situation 1, though it is only possible to offer downward regulation in this state.
3. When not already in operation and in a cold state, it is not possible for SOEC electrolysers to participate in any balancing reserve. It is unclear how long after being in operation or kept at the operational temperature that SOEC electrolysers will cool down to this operational state.

It should be noted that in these three operational situations only the expected regulation speed of the SOEC electrolysers is considered. Further analysis is done only for 2035 as this is the scenario that uses SOECs.

Considering the three operational situations, in hours of full operation the SOEC electrolysers can participate in balancing reserves with upward regulation by reducing the operation capacity, where up to about 44 MW can be provided as upward regulation in the PCR or up to about 1,312 MW as upward regulation in either the SCR or the TCR. If kept at the operating temperature when not in operation, the SOEC can provide up to about 44 MW downward regulation in the PCR or up to about 1,312 MW downward regulation in either the SCR or the TCR. For comparison the current size of the PCR in western Denmark is about 23 MW in both directions and the SCR is about 100 MW in both directions [51]. In the period 2013-2015 an average of 227 GWh/year was activated as upward regulation in the TCR and an average of 177 GWh/year was activated as downward regulation (based on data from [46]). However, as the TCR for western Denmark is traded on a Scandinavian market, the demand for activations in the TCR in western Denmark does not equal the activations within this balancing area.

The balancing reserves are market based and this means that activation of technologies mostly is chosen based on the cost of utilising them for balancing. This means that the utilisation of the SOEC electrolysers in 2035 will not only depend on the cost of utilising the SOEC electrolysers for balancing reserves and the organisation of the specific balancing reserves, but also on the cost of utilising alternative technologies, such as power plants, electric boilers, pumped hydro or heat pumps. In order to estimate an expected utilisation of the SOEC electrolysers for balancing reserves it would be relevant to compare the cost of participation in balancing reserves for different competing technologies. However, this was not further investigated. It should be noted that the 2035 scenario also includes a number of technologies relevant for utilisation in the

balancing reserves, such as 900 MW_e electric boilers and 700 MW_e compression heat pumps in district heating systems. Likewise, wind power has proven to be able to be utilised in balancing reserves [52]. As such, though SOEC electrolysers most likely can deliver a significant part of the needed balancing reserves in the 2035 scenario, it is unclear whether they will deliver balancing reserves and whether they will actually be required to.

Alkaline electrolysers are technically not suitable for the fast regulation required for participation in balancing reserves. It is expected that SOEC electrolysers will be installed in 2035. The SOEC electrolysers can participate in the balancing reserves, as these electrolysers technically are able to regulate sufficiently fast to participate in balancing reserves. However, it is expected that a number of flexible technologies also will be installed that also can be used for participation in balancing reserves, and as such, the SOEC electrolysers are most likely not required to deliver balancing reserves from a system perspective. The actual utilisation of SOEC electrolysers in the balancing reserves will depend on their cost for providing balancing reserves compared with other participating technologies. In general, the balancing markets represent only 2-3% of the total turnover volume of wholesale markets [53], and the investments in the technology should not be driven with the aim of participating in these markets. Furthermore, the optimal utilisation capacity of electrolysers in the energy system [16] is not fitting with the current market structure that prefers constant operation, which entails that there is a need for market restructuring as we go towards 100% renewable energy systems .

4. Short-term role of electrolysis 2020

All analyses carried out in this chapter are based on business-as-usual Danish energy system model for 2020 where more than 50% of electricity is supplied by renewable energy sources. The model is designed according to the projection of the Danish Energy Agency for 2020 and based on the data from projection documentation [54,55]. Details on the model are available from [56]. Key parameters relevant for the analysis are presented in Table 2.

Table 2. Key parameters of BAU 2020 Danish energy system scenario

	Unit	BAU 2020
Demands		
Electricity	TWh/year	31.5
DH demand	TWh/year	36.2
Individual heating	TWh/year	23.2
Transport	TWh/year	59
Primary energy supply		
Wind (on-shore&off-shore)	TWh/year	18.9
Solar PV	TWh/year	1.1
River hydro	TWh/year	0.02
Coal	TWh/year	15.4
Oil	TWh/year	76.8
Natural Gas	TWh/year	28.7
Biomass	TWh/year	59.6
Excess electricity production	TWh/year	2.3
Conversion capacities		
On-shore wind	MW_e	3539
Off-shore wind	MW_e	2430
PV	MW_e	1750
River hydro	MW_e	9
CHP	MW_e	7412
Power plant	MW_e	841
Heat pumps	MW_e	0

Electrolysers are introduced to the system in the transport sector and the produced hydrogen is directly used for hydrogenation of gasified biomass (biomass hydrogenation) in order to produce electrofuels or more precisely bioelectrofuels. The biomass used for the fuel production is straw. The total transport liquid and gaseous fuel demand in the system is 210 PJ while the remaining 2 PJ is met by electric trains and EVs. In the 2020 scenario only alkaline electrolysers are used with 63.7%$_{LHV}$ efficiency [17]. This is because alkaline electrolysers are present on the market and expectations that commercialization of SOECs is going to happen in the period post 2020. Cost data for both alkaline and SOEC electrolysers are given in Table 3. In terms of electricity production, the system with no electrolysis has 20.75 TWh of intermittent renewable electricity at the starting point and 2.3 TWh of forced export[4]. Furthermore, the system with the highest electrolyser capacity tested (411 MW) has 2.93 TWh of additional electricity demand for electrolysis in comparison to the system without electrolysis.

[4] The forced export is defined as electricity that cannot be used in the system and must be exported independently of whether the excess electricity is from renewable energy sources or other electricity producers.

Table 3. Cost data for alkaline and SOEC electrolysers (2012 prices). Adapted from [3,50]

		Alkaline		SOEC		
		2012	**2020–2030**	**2020**	**2030**	**2050**
Investment costs	*M€/MW*	1.07[5]	0.87[3,6]	0.93[7]	0.35[4]	0.28[4]
Fixed O&M costs	*% of inv./year*	4	4	3	3	3
Variable O&M costs	*€/MWh*	-	-	-	-	-
Lifetime stack	*Operating hours*		<90,000	<90,000	<90,000	<90,000
Lifetime system	*Years*	20–30	25–30	10–20	10–20	10–20

4.1. Renewable energy integration analysis

In order to investigate the potential of integrating intermittent renewable electricity in the system, all the analyses are carried out by varying the installed capacity of electrolysis from no electrofuels in the system (electrolysis capacity of 0 MW) to 10% of transport fuel demand met with electrofuels (electrolysis capacity of 411 MW). Furthermore, a step with 205 MW electrolysis installed is referring to newest regulative *Directive (EU) 2015/1513* for meeting the transport renewable goal that instructs double counting – *"considered to be twice their energy content"* – for fuels that are based on feedstocks such as straw [57].

EnergyPLAN is chosen for the analyses as the model can simulate both gaseous and liquid fuel production with electrolysis and provides the overview of the energy system's interaction with the technology. The model also includes many variables so different types of analyses can be carried out. The model is based on an hourly approach for a one-year period that enables precise modelling of hourly fluctuations in demand and supply, which is important for system with high shares of intermittent renewable energy sources. Seven different electrolyser capacities were tested in the system and for every each step energy system model was created. With varying electrolyser capacity, hydrogen storage was adjusted accordingly, followed by changing the needed biomass demand for gasification in order to produce bioelectrofuel that can be used in the transport sector. Bioelectrofuel is modelled as a substitution for diesel, so the fuel output assumed is dimethyl ether (DME). Transport fuel demand for diesel was reduced with efficiency factor of substitution so that the total transport fuel demand is always kept same. The efficiency factor is based on data on energy consumption per type of vehicle for 2020 provided by Danish Energy Agency [58]. In each created model, set of calculations were done with different off-shore wind capacities in order to get the results for all steps. Overall, in each of seven models representing different electrolyser capacity installed, five main parameters were changed followed by 10 step calculations for different off-shore wind capacities.

The focus of the first analysis was to investigate the option of lowering the forced export in order to cope with the situations where Denmark will not be able to export. Not being able to export can be due to the weather patterns similar to neighbouring countries that we are trading electricity with, leading to high wind power production occurring at the same time. This can further cause congestion in transmission lines or if transmission capacity is available to decreasing or even negative pricing of electricity as reported in IDA's Energy Vision 2050 [15]. Overall, the less correlation between wind power production from connected countries the better the power exchange between them and more benefits for both countries. Monforti *et al* [55] identified correlation factors of wind production in different countries around Europe, showing that

[5] Including costs associated with grid connection (66,000 €/MW for large plants).
[6] Cost for large alkaline pressure electrolyser with a capacity of 1500 Nm^3/h.
[7] Average cost for period of 2030–2050, including improvements in grid connection, of €66,000/MW for large plants.

countries in the middle of Europe connected to many other systems will suffer the most from increase in wind power, while countries in the periphery of Europe such as Denmark and Sweden show more complementary wind production towards the rest of EU. However, Germany as a main connection for Denmark towards Europe is a potential bottleneck and electricity should be better used in the domestic system itself by connecting it to the heat and transport sectors, but also traded on international electricity markets when favourable conditions are present.

Figure 2 illustrates the critical excess electricity production (CEEP)[8] in the system with different electrolyser capacities and an increasing share of intermittent renewable electricity. The share of intermittent renewable electricity was varied by changing the off-shore wind capacity only and keeping the other RES capacity constant. Off-shore wind capacity was varied from 0 to 3200 MW corresponding to 0 to 17.9 TWh. The analysis was done by using technical simulation in EnergyPLAN to get the least fuel consuming system operating to minimized import/export of electricity. As this simulation optimizes the operation of the system rather the cost minimization it reflects the technical potential and need for this technology in the system.

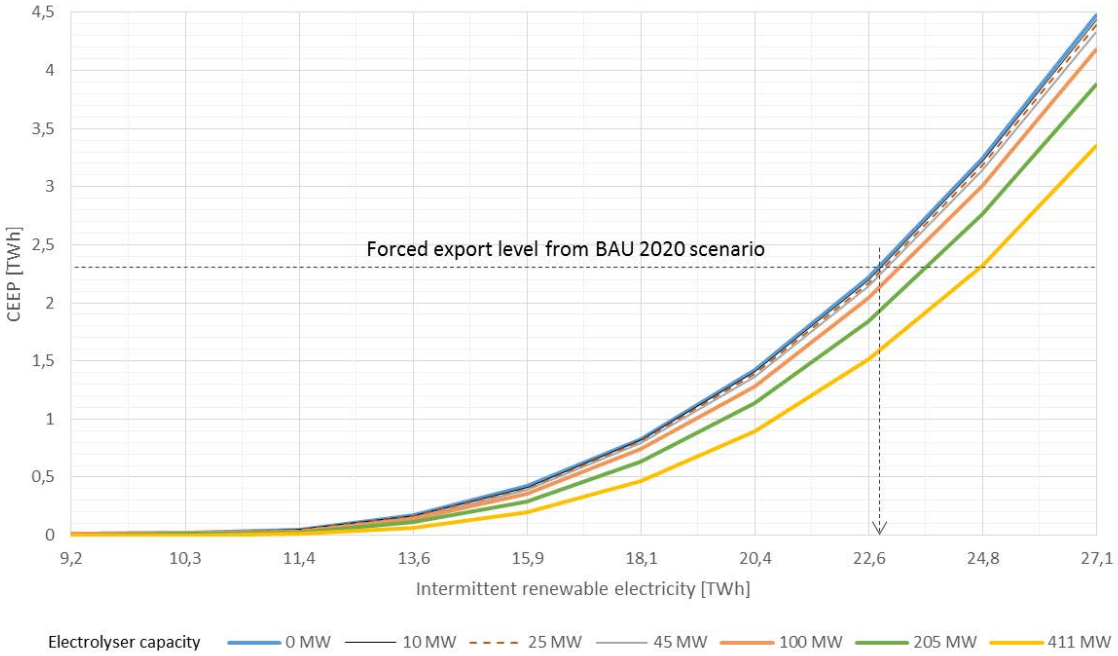

Figure 2. Critical excess electricity production for different electrolysis and intermittent renewable electricity capacity for 2020 energy system

It can be seen from the graph that there is a potential to reduce excess electricity production up to 30% in the system with the same amount of intermittent renewable electricity but with higher electrolyser capacity in comparison to BAU 2020 scenario. The results indicate that per MW of installed electrolyser capacity it is possible to reduce forced exports by 17 GWh going from no electrolysis installed to 411 MW electrolysers. This also reflects the wind integration potential, where we can integrate up to 370 MW more off-shore wind by installing electrolysers in the system and maintaining the same forced export from BAU 2020.

The primary energy supply is also illustrated to see how electrolyser capacity influences the supply. Figure 3 shows that the lowest primary energy supply changes depending on the installed electrolyser capacity. This

[8] The amount of energy that is exceeding the electricity needs and the transmission line capacity.

diagram can be interpreted as fuel efficiency of the system. We can see that systems with higher electrolyser capacity are the most fuel efficient with higher share of intermittent renewable energy, but more electrolyser capacity reduces the efficiency overall. For example if we compare point A and B, where both the system without electrolyser and one with 411 MW installed have same wind penetration, the system without electrolysers shows lower primary energy supply, directly implying that the system is more efficient. Furthermore, if we compare C and B points, we can see that the system without electrolysis can integrate more wind power more efficiently in the system by keeping almost the same levels of primary energy supply.

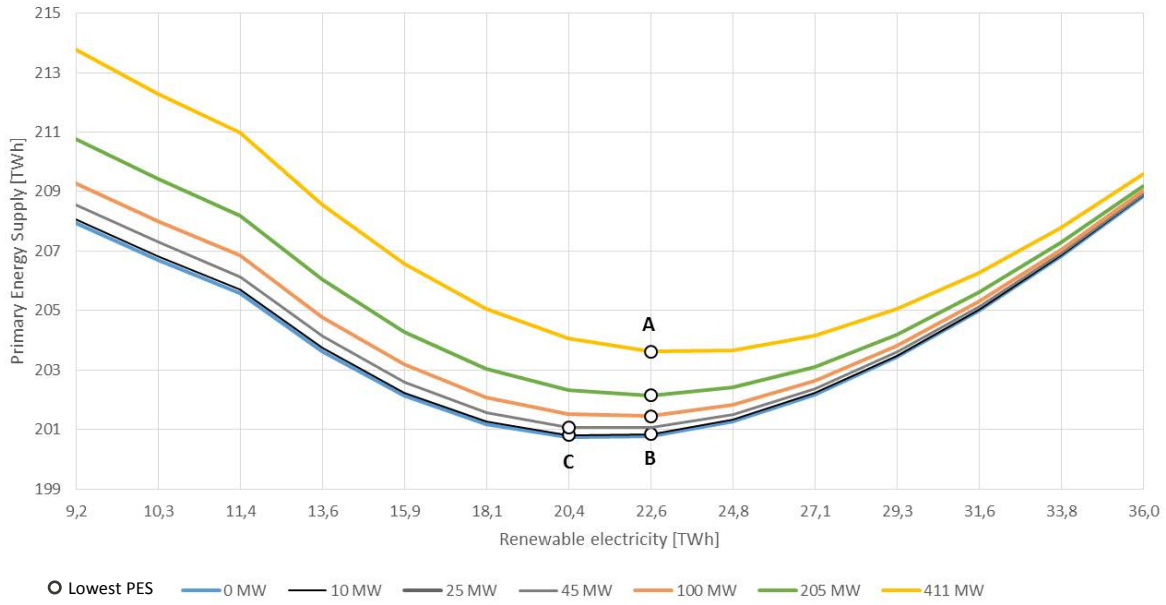

Figure 3. Primary energy supply (PES) in 2020 energy system with different electrolysers and renewable electricity capacities

Increase in electrolysis capacity allows for integration of more renewable energy in the system by around 2% from 0 to 411 MW of capacity installed (Figure 4). However, we can also see that the systems with electrolysers are more inefficient and have higher biomass consumption due to the electrofuel production if compared with system without electrolysis but with the same intermittent renewable energy levels.

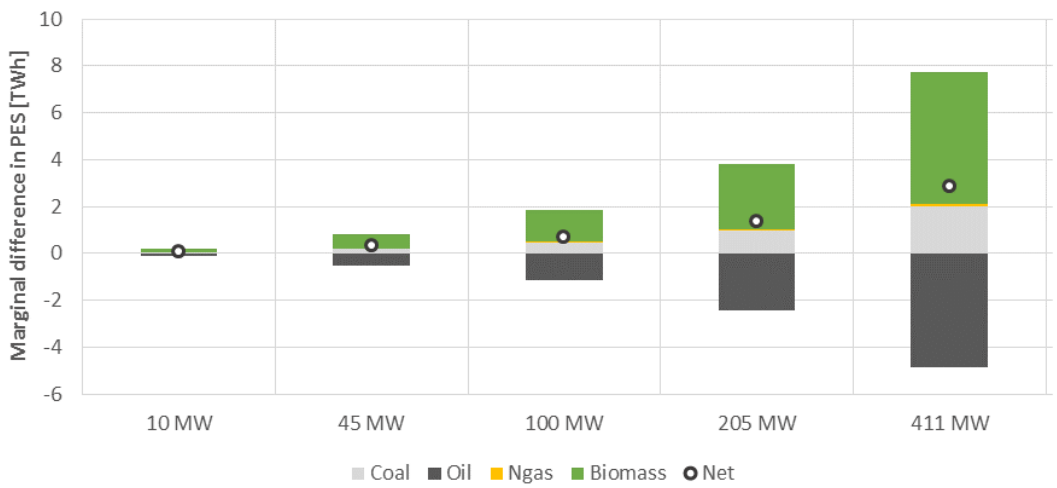

Figure 4. Marginal difference in primary energy supply between system without electrolysis and for different electrolyser capacities

The difference is present as the displace of oil with electrofuels is lower than biomass needed for fuel production due to the efficiency loss between diesel and DME vehicle and therefore fuel demand. Overall, the fuel savings are limited or non-present depending on which fuels are displaced. It can be seen from the results that electrolysers have a good ability to reduce the excess electricity production from intermittent renewable sources, but by doing so, it will decrease the efficiency of the system (point B is better than point A in Figure 3).

Table 4. Fuel costs by fuel type excl. distribution costs to the place of consumption

2015 - €/GJ	Crude oil	Coal	Natural gas	Fuel oil	Diesel fuel / Gas Oil	Petrol / JP	Straw / Wood chips	Wood pellets (general)	Energy Crops	$/barrel crude oil
Low	9.5	2.2	6.3	6	11	12	4.6	10	5.7	62
Medium	14	2.8	8.3	11.5	16	16.3	6	10.9	6.8	105
High	18.5	3.5	10.4	17	21	20.8	7.3	11.9	8	148

It is important to investigate the economical perspective of electrolysis, the analysis of market simulation with external market electricity price of 45 €/MWh and medium fuel price levels (see Table 4) was conducted. It can be seen from Figure 5 that systems with electrolysers are more expensive (point A) than systems without (point B), due to investments in the electrolysis capacity and fuel production components. We can also see that with 1200 MW off-shore wind capacity in the system without electrolysis is the cheapest (point C).

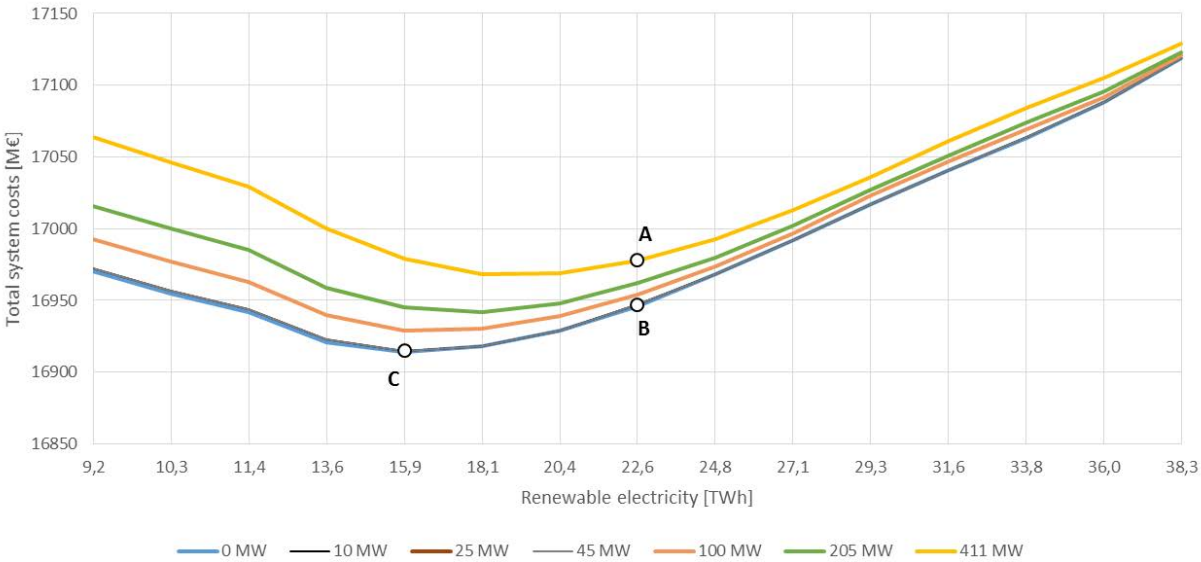

Figure 5. Total system cost for 2020 energy system with market electricity price of 45 €/MWh and medium fuel price level

Electrolysers can provide more flexibility for the system at higher costs but this can also be achieved without electrolysis (point B) in a more efficient way. However, the increase of 0.32% in total system costs is negligible while at the same time transport demand is met with renewable energy rather than oil, which is connected to drop in system's CO_2 emissions. It is important to be noted that the total system costs are changing from fuel intensive to investment intensive, as fuel costs are dropping with increased electrolyser capacities but technology investments are higher (see Figure 6).

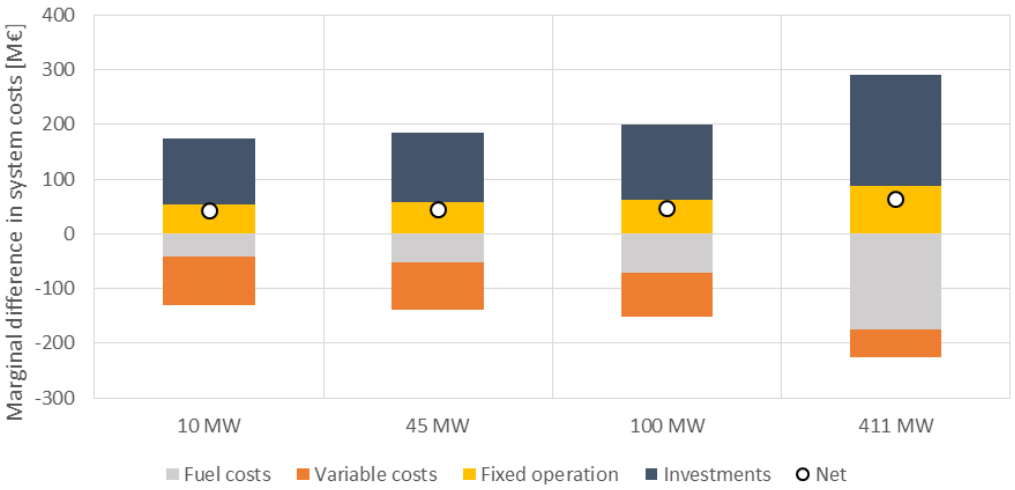

Figure 6. Marginal difference in total system cost for systems with different electrolyser capacities in comparison to system without electrolysis for medium fuel price level and 45 €/MWh external market electricity price

Figure 7 illustrates the total system costs for different external market electricity prices (10, 45, 80, 115 and 150 €/MWh), with different intermittent renewable electricity and electrolysis capacities in the system. The variations in costs occur due to the variations in electricity exchange and the implied consumption of fuels in the system. The systems with higher electricity price than 80 €/MWh have lower system costs than systems with lower electricity prices, due to the relatively large income from electricity exchange, with an exception of very low price of 10€/MWh where similar trend occurs. With electricity price of 10 €/MWh and 45 €/MWh, the total system costs are increasing with a higher renewable electricity production in the system (18.1 to 24.8 TWh). The electricity prices above 80 €/MWh have opposing trend of decrease in system costs with higher share of renewable energy in the system.

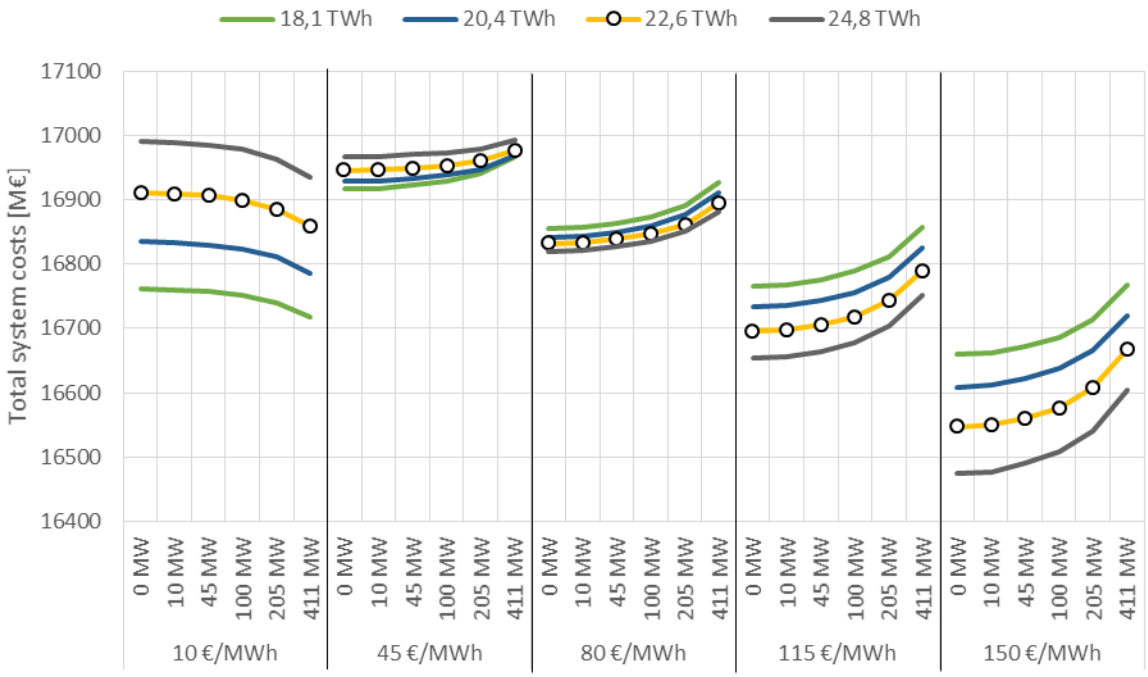

Figure 7. Total system costs for different external electricity market prices, electrolyser capacities and increasing renewable electricity production

If we compare the yellow lines that show a renewable electricity level of 22.6 TWh, we can see that the decrease in costs occur with higher electrolyser capacities for electricity price of 10 €/MWh, as the savings in fuel costs in the system are higher than the annual investments in wind and electrolyser technology. For electricity prices between 45 and 150 €/MWh, the system costs increase for all electrolyser capacities as the investments are higher than cost savings on the fuel side. The most likely electricity prices are between 45 and 80 €/MWh as this corresponds to the current electricity prices and long-term marginal costs of electricity price from off-shore wind turbines (66€/MWh according to [59]). We can see that for these electricity prices difference in investments in electrolysis and wind do not differ by much total system costs.

4.1.1. Electrolysers versus other renewable energy integration and alternative fuel technologies

The 2020 BAU energy system does not have many flexible technologies integrated in the system. Therefore, we could see how the integration of electrolysis influences the system. The regulating assessment of electrolysers participation in balancing reserves (Section 3) concludes that alkaline electrolysis based on their performances is not suitable for this purpose. Also from results in this section, we can see that electrolysis can enable wind integration but this results in less efficient (Figure 3) and more expensive system (Figure 5). Many technologies could be used for integration of renewable energy and previous studies have evaluated their potential. For example, it has been shown previously that heat pumps have best performances and can also result in reduction of socioeconomic costs as well as significantly reduce the fuel consumption [56,60–62]. As previously indicated, electrolysers can be used to reduce excess electricity production but the fuel savings and costs associated are limited and higher than other alternatives as reported by Mathiesen and Lund [60].

Therefore, it was to investigate, what should be the role of electrolysis in energy system. Electrolysis was model in all scenarios for electrofuel production and comparison with other transport alternatives was made. All of the alternatives in Figure 8 assure the 10% renewable energy goal in transport is met, with 2G bioethanol, biogas and electrofuels being accounted with factor of two and EVs with factor of 5 for the share of renewable electricity in the supply [57].

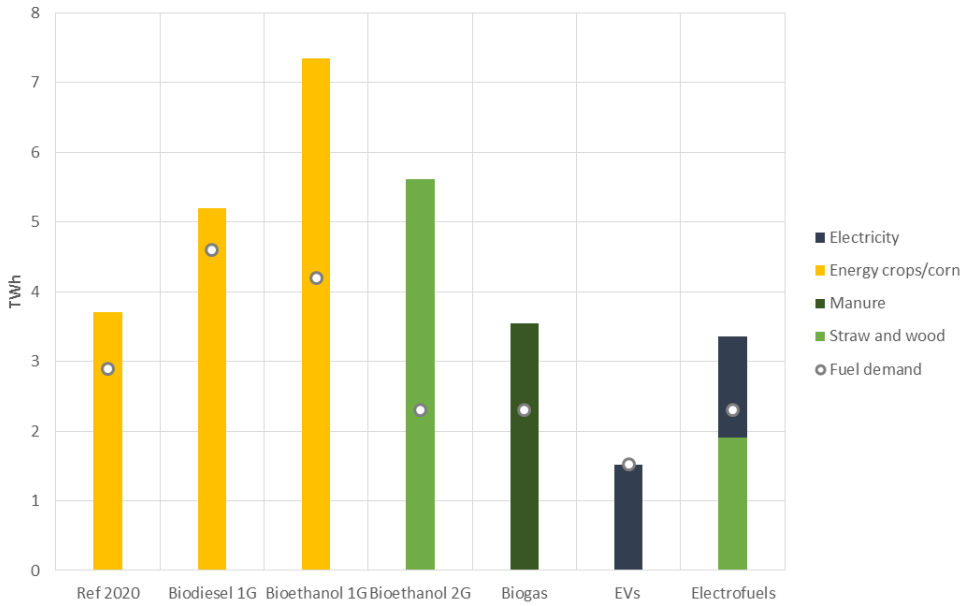

Figure 8. Energy used per TWh for fuel production including type of biomass used

The figure shows that in comparison to other transport fuel alternatives, which can meet the heavy-duty transport demand, electrofuels can offer a significant reduction in biomass demand and lower energy demand in total per fuel produced. For example, the 2G bioethanol is currently using ~65% more biomass per fuel produced in comparison to biomass based electrofuel. These results confirm that the investments in electrolysis should be driven by the need for meeting the transport fuel demand, as their biggest contribution is for fuel production rather than for integrating renewable electricity. This should be seen as an additional benefit from electrolyser integration.

5. Long-term role of electrolysis 2035

The long-term role of electrolysis was tested in the Danish energy system in 2035 (DK 2035), based on the IDA Energy Vision 2035 model [15]. The system was adapted so electrolysers are used only for bioelectrofuel production with no additional syngas in the system. All analyses were done using solid oxide electrolysis cells (SOEC) with an efficiency of 73%$_{LHV}$ for steam electrolysis that includes 10% energy losses in the production and 5% extra losses for gas storage [50]. Total installed electrolyser capacity in the reference system is 1458 MW_e with 121 GWh of hydrogen storage. Key parameters relevant for the analysis are presented in Table 5.

Table 5. Key parameters of the 2035 Danish energy system scenario

	Unit	DK 2035
Demands		
Electricity	TWh/year	30.2
DH demand	TWh/year	38.1
Individual heating	TWh/year	15.7
Transport	TWh/year	43.9
Primary energy supply		
Wind (on-shore&off-shore)	TWh/year	31.7
Solar PV	TWh/year	3.8
Wave power	TWh/year	0.07
Coal	TWh/year	0.6
Oil	TWh/year	28.9
Natural Gas	TWh/year	8
Biomass	TWh/year	59.2
Excess electricity production	TWh/year	0.22
Conversion capacities		
On-shore wind	MW_e	3875
Off-shore	MW_e	4300
PV	MW_e	3127
Wave Power	MW_e	176
CHP	MW_e	5526
Heat pumps	MW_e	700

Each analysis includes 10 different electrolyser capacities with 200 MW steps, from 0 to 1800 MW. Similar to the 2020 analyses five parameters were adjusted: electrolyser capacity, hydrogen storage, biomass for gasification, electrofuel demand and diesel demand creating 10 different models with step inputs. Off-shore wind capacities were varied in each model from 0 to 9000 MW corresponding to 0 to 40.3 TWh.

5.1. Electrolysis for renewable electricity integration

The analysis for 2035 shows similar trends as the 2020 system in terms of grid balancing and renewable energy integration. We can see from Figure 9 that the system with 1800 MW electrolysis has the same level of forced export as the DK 2035 scenario, of 0.22 TWh, when there is almost 10 times lower critical excess in comparison with system with no installed electrolyser capacity. However, this is depending on the level of forced export chosen, therefore results may vary. Furthermore, if we take the same level of force export, the system with high electrolyser capacity (point B) can integrate almost 2500 MW more offshore wind than the

system without electrolysis (point A). However, this comes with lower system efficiency and higher system costs as shown in previous section.

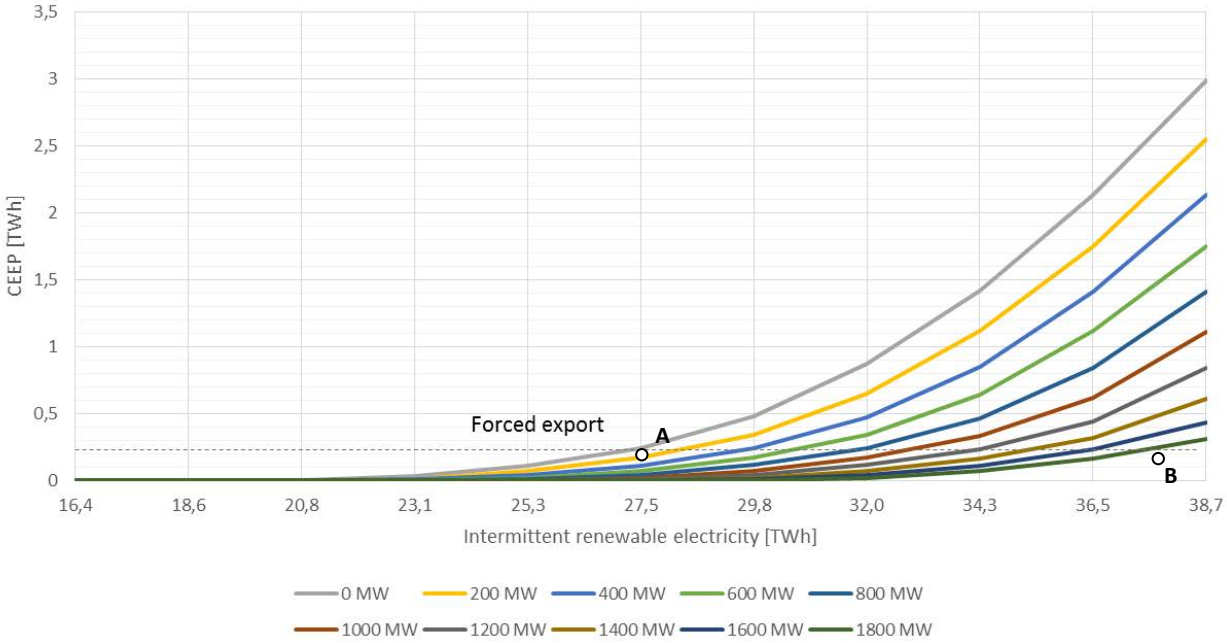

Figure 9. Critical excess electricity production for different electrolysis and intermittent renewable electricity capacity for 2035 energy system

Additional analysis on associated CO_2 emissions on the system level was conducted to see the benefits of integrating electrolysis from a carbon reductions perspective. Analysis shows that investments in electrolysis results in 28% emission reductions in case that 41.3% of the transport liquid fuel demand (that is not suitable for electrification) is met by electrofuels (see Figure 10).

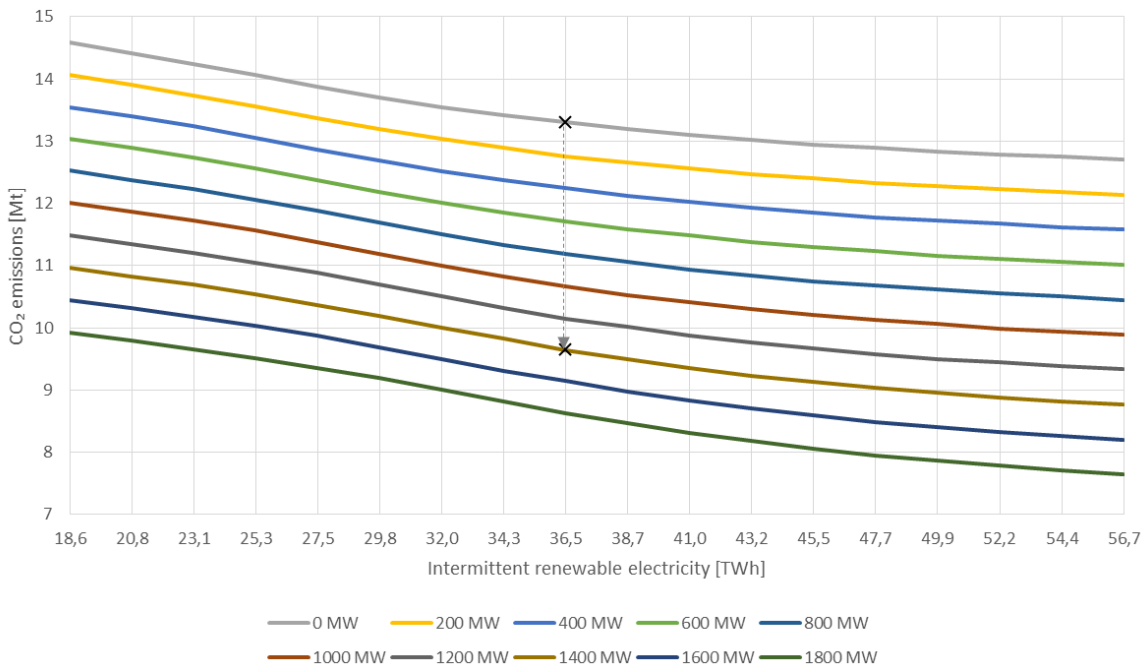

Figure 10. CO_2 emissions reduction for increasing electrolysis and wind capacity in the system

The reductions are associated with using biomass as a resource fuel for electrofuel production and its displacement of oil in transport sector, furthermore due to the more wind in the system with higher electrolyser capacities, less fuel is used in CHPs which also contributes to lower CO_2 emissions.

5.2. Electrolysis for gas grid balancing

As the median product for electrofuel production is always syngas that can be methanized to natural gas quality and injected to the grid, investigation of the consequences of electrolysers' integration on the gas market was carried out. The analysis included six different electrolyser capacities 0, 200, 400, 1000, 1400 and 1800 MW_e and off-shore wind capacity was varied from 0 to 5000 MW_e in 11 steps corresponding to 0 to 22.36 TWh. It is assumed that all natural gas demand in the system is met with imported gas, so gas production from electroysers will displace imported natural gas.

As we introduce more wind capacity in the system, CHP power production is reduced accordingly (see Figure 11) as there is more electricity coming from intermittent renewable energy (i.e. offshore wind power). This clearly leads to a lower fuel demand. Combined heat and power plants in the system are consuming both natural gas and biomass. We can see from Figure 12, how the fuel demand for power and heat production is reduced for 0 and 1800 MW of electrolysis installed of which approximately 1/3 is natural gas consumption.

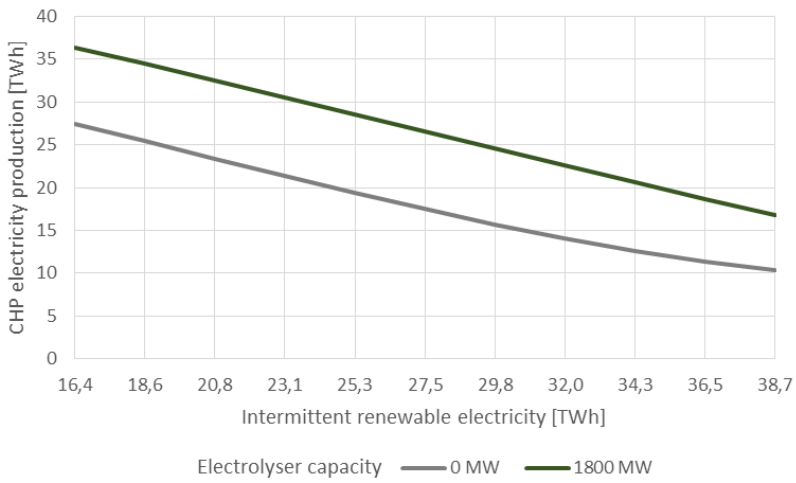

Figure 11. CHP electricity production according to increase intermittent renewable electricity in the system for 0 and 1800 MW of electrolyser capacity installed

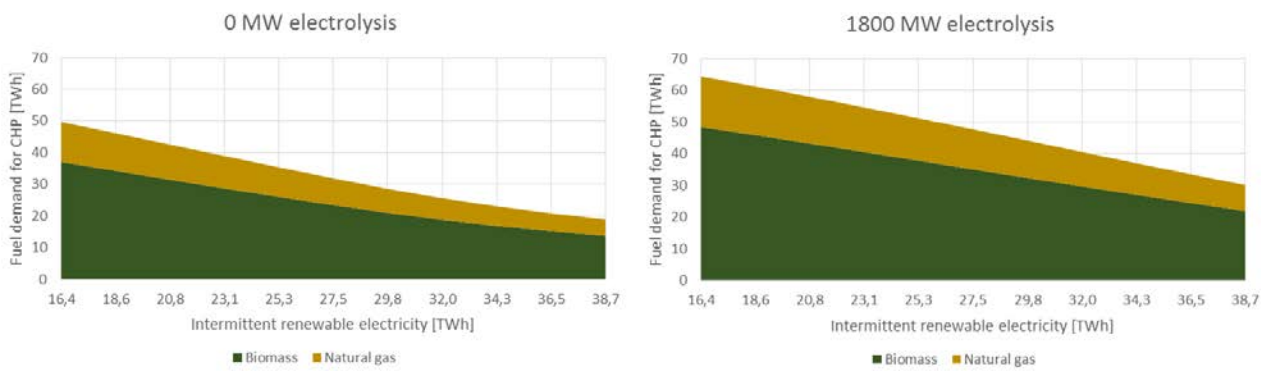

Figure 12. Fuel demand for CHP for 0 and 1800 MW electrolysis capacity installed

There are two other operational scenarios investigated here:

A. Gas produced by mixing hydrogen from electrolysis and biomass gasification is used for transport fuel (in form of liquid fuel)
B. Gas produced by mixing hydrogen from electrolysis and biomass gasification is used for gas-grid injection (in form of methane)

If we have a scenario A where gas produced is directly used for transport fuel, reductions in natural gas imports are only due to the decrease in CHP operation as a consequence of more wind in the system (see Figure 13). Therefore, introducing electrofuels enables more wind power to be integrated onto the Danish electricity network, since it creates additional flexibility in the energy system (due to hydrogen and gas storage). This additional wind power reduces the demand for gas in the CHP plants, so the gas demand is reduced since it is possible to integrate additional wind power rather than by replacing the natural gas in CHP plants with electrogas. This implies that electrolysis has no real influence on gas trading or gas balancing in the system, as the domestic gas production is directly utilised for further fuel synthesis.

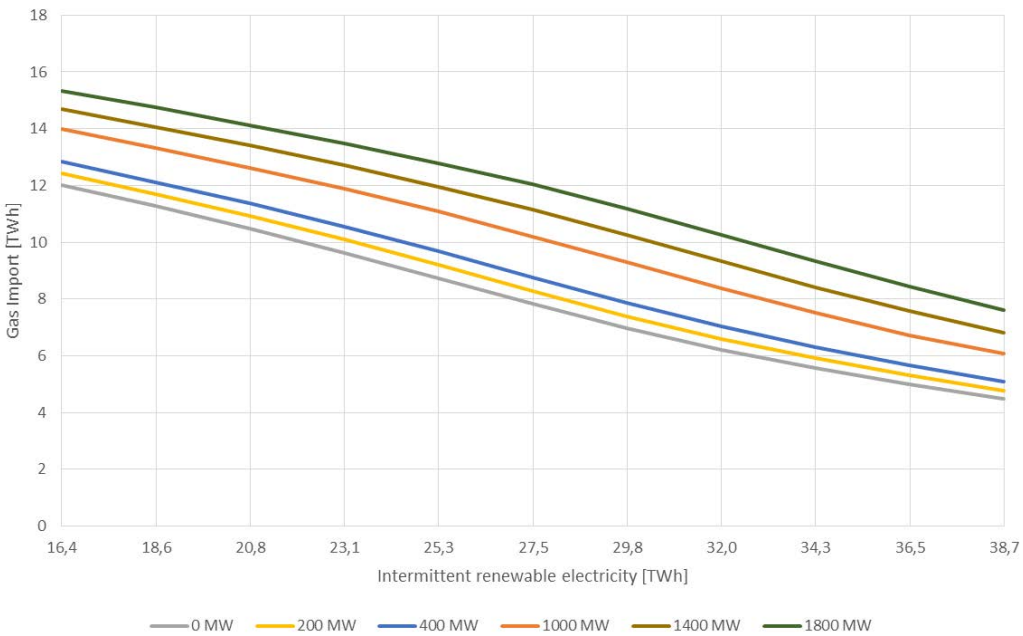

Figure 13. Gas import for electricity and heat production if electrolysis is used for electrofuel production (scenario A)

However, if the domestically produced gas is not used for transport but rather sent to the gas grid (scenario B), we can see that the system starts exporting gas already with 1000 MW_e electrolysis capacity (see Figure 14). This is a consequence of the double effect that occurs in this system. With an increase in wind production, combined heat and power production is reduced, leading to, as previously showed, lower fuel demand for heat and power sector. Furthermore the more domestically produced gas from electrolysis is sent to the gas grid, as a result of increasing electrolyser capacity, but the generated gas in the system is not needed resulting in reduction of import and with increased electrolyser capacity even gas export. Overall, this results in reduction of fossil fuels in the system, lower dependence on import and higher domestic fuel security.

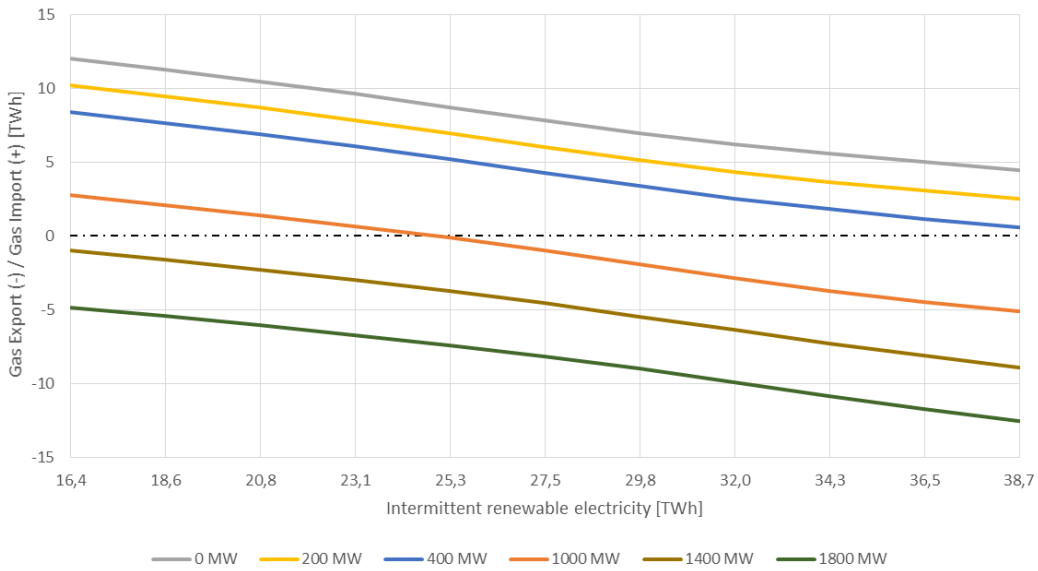

Figure 14. Electrolysis used for gas production via biomass hydrogenation that is send to the grid

These analyses were interesting to look at, as they offer an insight of the consequences for the system if the gas is used for gas grid balancing or for production of liquid fuels that can be stored and later used when needed. In both system electrolysers are used for domestic gas production that reduces gas import, but only if the gas produced in the system is send to the gas grid there is a direct influence on gas trading. The domestic gas production from electrolysis system makes only sense if we the wind is used for providing power to electrolysis, as wind integration also directly reduces fuel demand for CHP.

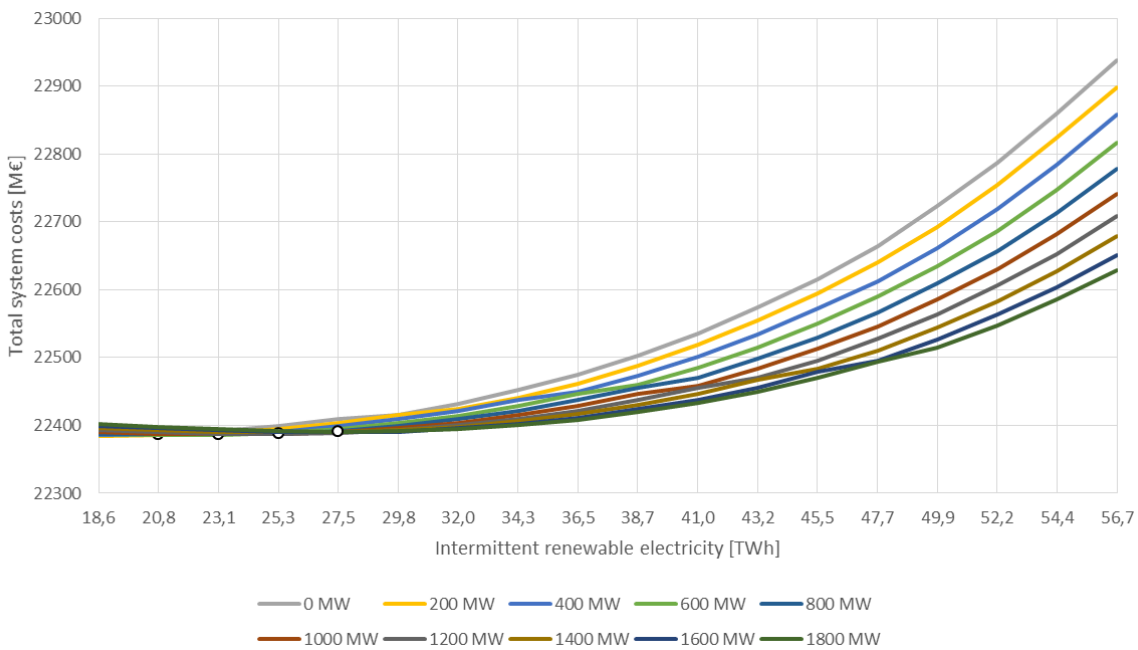

Figure 15. Total system costs for electrofuel production with different electrolyser capacity and increasing wind capacity

From an economic point of view, a system that uses gas directly for fuel production (Figure 15) is cheaper than the system that uses it for gas-grid injection (Figure 16). Furthermore, we can see from the graph that the trend in cost curves are reciprocal with the system that uses gas directly for electrofuel production gets

cheaper with higher electrolyser capacity, while the one that trades gas gets more expensive. This is as the incomes from the gas exporting are still lower than costs for domestic gas production. It is therefore very important to stress that the gas that is produced by converting electrons from intermittent renewable sources should not be converted back to electricity as a strategy for balancing renewable electricity as for the round trip losses of such conversion. This once again supports that the role of electrolysis should be for transport fuel production.

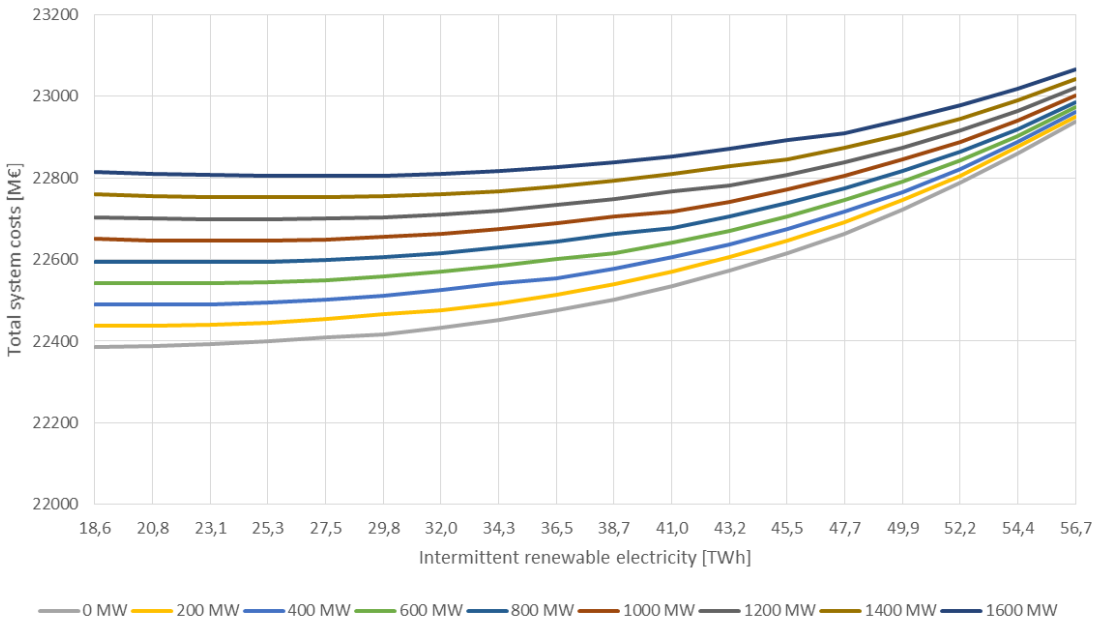

Figure 16. Total system costs for system where in-system methane produced is supplied to grid with different electrolyser capacity and increasing wind capacity

5.3. Nordic and European electricity market trading

In order to test the role of electrolysis in the Nordic and European electricity market context, an analysis with different electricity market prices that are expected to occur in 2035 [63] was conducted. The prices predicted in the most recent Nordic Energy Technology Perspective of 50-70 €/MWh were in the analysis replaced by 45 and 85€/MWh to get a bigger span. Furthermore, additional sensitivity factors were added by illustrating costs for medium and high fuel prices (see Table 4).

The results indicate that the costs differences for different electricity and fuel prices levels are negligible ~1% as shown in Figure 17, but associated CO_2 emission savings are rather high (Figure 10). We can also see that likely variations in fuel prices have bigger influence on total system costs than likely variations in electricity prices

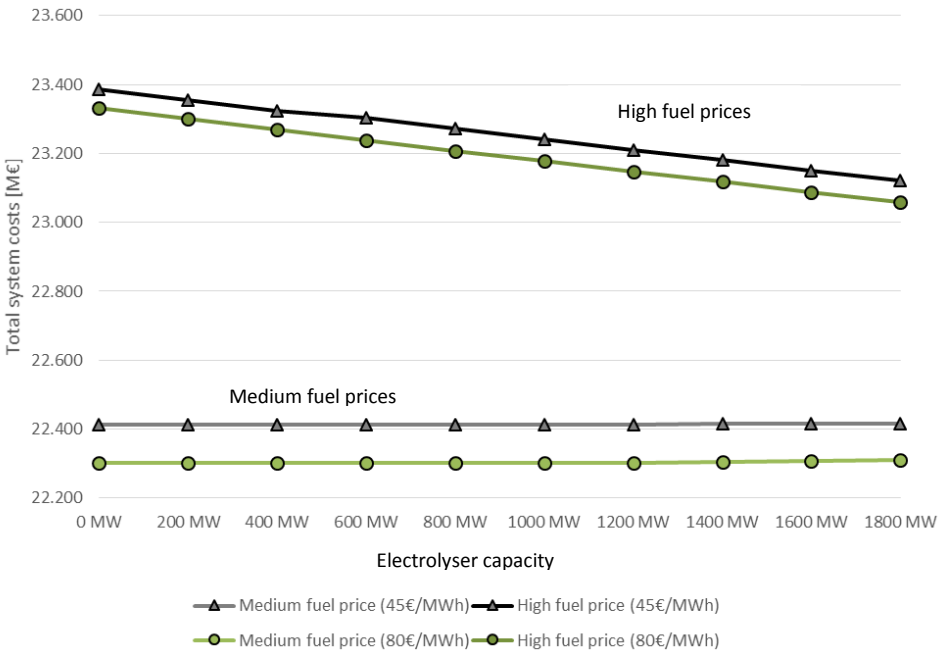

Figure 17. Total system costs for different fuel price and electricity market price level with different electrolyser capacities in the system

5.4. SOEC vs. alkaline electrolysers

Due to the uncertainty of commercializing SOEC and the necessity for this technology, comparison with alkaline electrolysis was conducted based on data listed in Table 3. The utilisation of alkaline electrolysis in comparison to SOECs causes a negligible cost increase. However, due to the lower process efficiency using alkaline electrolysis with the same installed capacity as SOECs results in 10% less fuel produced.

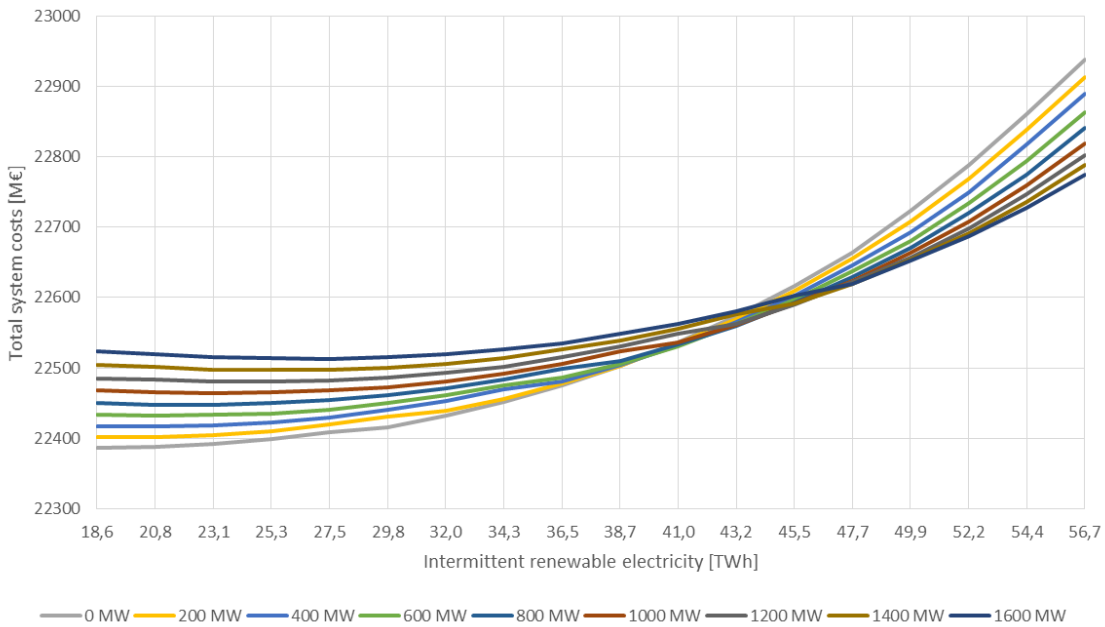

Figure 18. Total system costs for electrofuel production with different alkaline electrolyser capacities and increasing wind capacity

Increase in alkaline electrolysis capacity in the system also shows reduction in system costs with higher wind capacities (Figure 18) but with lower wind integration, systems with no electrolysis are cheaper. The SOECs show competitiveness already with low capacities (Figure 15) as there is almost no price difference between system with and without electrolysis even with low wind integration.

This entails that investments in alkaline should be made to start the transition, the capacity investments are more expensive but the increased costs are negligible on the system level. This can later on lead to a transition to SOECs if they become commercialized and maintain the predicted costs.

6. Concluding remarks

The short- and long-term role of electrolysis for grid balancing was investigated in this report, followed by an analysis on the feasibility of implementing electrolysis in the energy system and their potential for gas market balancing. The report starts with a literature review on state-of-the-art knowledge on electrolysis for grid balancing and it is followed by a regulative assessment of electrolysers participating in balancing reserves based on electrolysers' operation in energy system models for 2020 and 2035. This is followed by set of different analyses on potential for renewable energy integration, feasibility of electrolysis in energy systems and their potential for gas grid balancing.

The literature review showed that there are many different ancillary services that electrolysers can support the grid system with, however not all electrolyser types are suitable for providing these. Furthermore, there is also a lack of field demonstrations that can confirm the benefits of real-time grid connection especially with newer types of electrolysers. With the current regulation in place, it is not economically favourable to use electrolysers for grid balancing and it is expected that higher revenues could be achieved with using electrolysis for different purposes such as fuel or feedstock production.

As the objective of this report was to investigate alkaline and SOEC application for grid balancing it can be concluded that standard alkaline are not suitable for participating in the balancing reserves but SOECs participation is possible. The analysis took departure in European Network of Transmission System Operators for Electricity (ENTSO-E) guidelines as the organisation and utilisation changes from balancing area to balancing area will most probably change over time. SOEC electrolysers can regulate fast enough to continuously deliver balancing reserves if they are in operation, however if the units are not in operation, but kept at the operating temperature they will be able to participate with downward regulation only or if they are in a cold state it is not possible for SOECS to participate in any balancing reserves. Therefore, it is possible to use SOECS for participation in balancing reserves, but their participation will most likely not be required as there are a number of other flexible technologies with a better performance and lower costs that could be used instead. Moreover, in comparison to the other market timeframes, the balancing reserve markets are very limited and investments in the technology should not be prioritized according to it.

Electrolysers have a good ability to reduce excess electricity production from intermittent renewable sources or in other words provide flexibility to the system, but the fuel saving potential of this technology is limited in comparison to other renewable energy integration technologies. However, as electrolysers can simultaneously be used for electrofuel production for transport, their role is twofold. With regards to the system costs, systems with electrolysers are more expensive due to investments in the electrolysis capacity and fuel production components, which entails that they provide more flexibility for the system at higher costs. Overall, with more electrolysis in the system, the total system costs division is switching towards more investment intensive rather than fuel intensive. If we compare electrolysis for electrofuel production with other transport fuel alternatives it shows that electrofuels can offer a significant reduction in biomass demand and lower energy demand in total per fuel produced. This also confirms that the investments in electrolysis should be driven by the need for meeting the transport fuel demand as they can provide the missing link between intermittent renewable energy, resource scarcity and dependence on high-density fuels. The flexibility they provide in terms of renewable energy integration should be seen as an additional benefit from electrolyser implementation.

As the system operation changes with integration of electrolysis and associated increase in wind power, CO_2 emissions in the system can be reduced by 33% emission if 43% of the transport liquid fuel demand (that is not suitable for electrification) is met by electrofuels.

The gas market analysis was carried out as electrofuel production has syngas as the intermediate product and if it is upgraded to methane as final fuel, it could be used for interacting with the gas grid. If electrolysers are not used for direct electrofuel production, that does not involve any grid interaction, but rather for production of methane that is sent to the grid it shows that the "overproduction" of the gas in the system causes export of the gas from the system. The overproduction occurs as with increased electrolysers capacity more domestically produced renewable gas is sent to the grid while at the same time due to the higher wind capacity in the system CHP operation is reduced implying the reduced gas demand in the system. This can also be seen as reduction of fossil fuels in the system, lower dependence on import and higher domestic fuel security. From an economic point of view, a system that uses gas directly for electrofuel production is cheaper that the system that uses methane for gas balancing purposes. It should be stressed that the gas produced by converting electrons from intermittent renewable sources should not be converted back to electricity due to the round trip losses but rather used directly for transport fuel production.

Lastly analysis of Nordic and European electricity market trading shows that the results are more sensitive to the fuel price increases than the electricity prices involved, but the costs differences are not significant. Furthermore, the utilisation of alkaline electrolysis in comparison to SOECs also results in a negligible system cost increase, but due to the lower process efficiency using alkaline electrolysis with the same installed capacity as SOECs results in 10% less fuel produced. Given that the costs difference are so small, it is important to start the investments in electrolysis technologies as soon as possible in order to help the transition of the transport sector towards more renewable energy and to help the integration of renewable electricity.

References

[1] Denholm P, Ela E, Kirby B, Milligan M. The Role of energy storage with renewable electricity generation. 2010.

[2] Connolly D, Mathiesen B V., Ridjan I. A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system. Energy 2014;73:110–25. doi:10.1016/j.energy.2014.05.104.

[3] Ridjan I. Integrated electrofuels and renewable energy systems. Department of Development and Planning, 2015.

[4] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PAPA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[5] Jensen JO, Bandu V, Bjerrum NJ, Jensen SH, Ebbesen S, Mogensen M, et al. Pre-investigation of water electrolysis. PSO-F{&}U 2006-1-6287; 2008.

[6] Beckman K. World's first power-to-liquids production plant opened in Dresden 2014. http://www.energypost.eu/worlds-first-power-liquids-production-plant-opened-dresden/.

[7] Energiforskning.dk. Solid Oxide Electrolyser Technology. 2016 n.d. http://energiforskning.dk/node/8594.

[8] Energiforskning.dk. Power-2-electrolyser n.d. http://energiforskning.dk/node/7779.

[9] Energiforskning.dk. Energy Efficient Production of Pressurized Hydrogen n.d. http://energiforskning.dk/node/7795.

[10] Energiforskning.dk. Solid Oxide Cell Testing, Safety and Quality Assurance n.d. http://energiforskning.dk/node/7905.

[11] Energiforskning.dk. Towards solid oxide electrolysis plants in 2020 n.d. http://energiforskning.dk/node/8146.

[12] Energiforskning.dk. El-opgraderet biogas | Energiteknologiske forskningsprojekter 2013. http://energiforskning.dk/en/node/7155 (accessed March 10, 2015).

[13] BioCat Project. Power-to-gas via Biological Catalysis (P2G-BioCat) 2014. http://biocat-project.com/ (accessed October 29, 2015).

[14] HyBalance project 2016. http://hybalance.eu/ (accessed July 20, 2016).

[15] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050. Aalborg University; 2015.

[16] Ridjan I, Mathiesen BV, Connolly D, Hansen K, Wunsch JH. Applications of SOECs in different types of energy systems - German and Danish case studies. Copenhagen, Danmark: Department of Development and Planning; 2015.

[17] Ridjan I. Integrated electrofuels and renewable energy systems. Department of Development and Planning, 2015.

[18] L. Bird, M. Milligan DL. Integrating Variable Renewable Energy: Challenges. Golden: 2013.

[19] EC. The future role and challenges of Energy Storage. n.d.

[20] Investigating a Higher Renewables Portfolio Standard in California. 2013.

[21] Helman U, Loutan C, Rosenblum G, Guo T, Toolson E, Hobbs B. Integration of renewable resources: Updated analysis of operational requirements and assessment of generation fleet capability under a 20% RPS requirement. IEEE PES Gen Meet 2010:1–2. doi:10.1109/PES.2010.5590171.

[22] Eichman J, Harrison K, Peters M. Novel Electrolyzer Applications: Providing More Than Just Hydrogen. Golden: National Renewable Energy Laboratory(NREL); 2014.

[23] M. Melaina JE. Hydrogen Energy Storage: Grid and Transportation Service. Golden: 2015.

[24] NEAS. WP2 final report - Evaluation of the hydrogen production cost. To be published: Energinet.dk; 2016.

[25] Shivachev SI. Techno-economic assessment of integrating electrolysers in future energy systems. AAalborg Univerisity, 2015.

[26] Romaní Dalmau A, Martínez Pérez D. Application of Power to Gas (P2G) Systems in Danish Electric Distribution Networks. Aalborg University, 2015.

[27] Kiaee M, Cruden A, Infield D, Chladek P. Utilisation of alkaline electrolysers to improve power system frequency stability with a high penetration of wind power. IET Renew Power Gener 2014;8:529–36. doi:10.1049/iet-rpg.2012.0190.

[28] Kiaee M, Cruden A, Infield D, Chladek P. Improvement of power system frequency stability using alkaline electrolysis plants. Proc Inst Mech Eng Part A J Power Energy n.d.;227:115–23. doi:10.1177/0957650912466642.

[29] Hydrogenics website. Hydrogenics news release: “Hydrogenics successfully completesutility-scale grid stabilization trial with Ontario”s independent electricity system operator’ 2011.

[30] Pozzi LG. Harnessing the power of hydrogen: Economic feasibility of hydrogen-based electricity storage units applying price arbitrage in the Italian spot market and their potential grid applications. Aalborg University, 2014.

[31] Guinot B, Montignac F, Champel B, Vannucci D. Profitability of an electrolysis based hydrogen production plant providing grid balancing services. Int J Hydrogen Energy 2015;40:8778–87. doi:10.1016/j.ijhydene.2015.05.033.

[32] Jørgensen C, Ropenus S. Production price of hydrogen from grid connected electrolysis in a power market with high wind penetration. Int J Hydrogen Energy 2008;33:5335–44. doi:http://dx.doi.org/10.1016/j.ijhydene.2008.06.037.

[33] Institute SBCE. hydrogen based energy conversion 2014;2016.

[34] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[35] Eichman J, Townsend A, Melaina M. Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets. Golden: National Renewable Energy Laboratory (NREL) ; 2016.

[36] Ridjan I, Mathiesen BV, Connolly D, Duić N. The feasibility of synthetic fuels in renewable energy systems. Energy 2013;57:76–84. doi:10.1016/j.energy.2013.01.046.

[37] Market Observatory for Energy. Quarterly Report on European Electricity Markets - Volume 8. 2015.

[38] Sorknæs P. Bidding and operation strategies in future energy markets 2015.

[39] ENTSO-E. Continental Europe Operation Handbook -P1 – Policy 1: Load-Frequency Control and Performance [C]. 2009.

[40] NETefficien- Storage for life. Peak shaving and ancillary services in the market n.d. http://netfficient-project.eu/use-case-1/.

[41] Consentec GmbH. Description of load-frequency control concept and market for control reserves. Aachen, Germany: 2014.

[42] Energinet.dk. Ancillary services to be delivered in Denmark Tender conditions. Fredericia: 2012.

[43] Energinet.dk. Systemydelser til levering i Danmark - Udbudsbetingelser. 2016.

[44] Hedegaard K, Meibom P. Wind power impacts and electricity storage – A time scale perspective. Renew Energy 2012;37:318–24. doi:10.1016/j.renene.2011.06.034.

[45] Holttinen H, Tande JO, Estanqueiro A, Gomez-lazaro E, Lange B, Milligan M, et al. Summary of experiences and studies for Wind Integration – IEA Wind Task 25. Proc. WIW2013 Work. London, 22-24 Oct, 2013, 2013, p. 22–4.

[46] Nord Pool Spot. Historical Market Data n.d. http://nordpoolspot.com/historical-market-data/.

[47] NordREG. Statistical S umma ry of the Nordic Energy Market 2014. n.d.

[48] Chen L, Dong X, Wang Y, Xia Y. Separating hydrogen and oxygen evolution in alkaline water electrolysis using nickel hydroxide. Nat Commun 2016;7.

[49] Mathiesen BV, Lund H, Karlsson K. IDA´s klimaplan 2050 : Tekniske energisystemanalyser og samfundsøkonomisk konsekvensvurdering - Baggrundsrapport (IDAsClimate Plan 2050, backgroundreport in Danish and English). Copenhagen: 2009.

[50] Mathiesen B V, Ridjan I, Connolly D, Nielsen MP, Hendriksen PV, Mogensen MB, et al. Technology data for high temperature solid oxide electrolyser cells, alkali and PEM electrolysers. Denmark: Department of Development and Planning, Aalborg University; 2013.

[51] Energinet.dk. Introduktion til systemydelser. 2016.

[52] Sorknæs P, Andersen AN, Tang J, Strøm S. Market integration of wind power in electricity system balancing. Energy Strateg Rev 2013;1:174. doi:10.1016/j.esr.2013.01.006.

[53] ENTSO-E. Cross Border Electricity Balancing Pilot Projects 2016. https://www.entsoe.eu/major-projects/network-code-implementation/cross-border-electricity-balancing-pilot-projects/Pages/default.aspx (accessed August 1, 2016).

[54] Danish Energy Agency. Danmarks energi- og klimafremskrivning 2015 (Denmark's energy and climate projection 2015). Danish Energy Agency; 2015.

[55] Danish Energy Agency. Spreadsheet with national data 2015 - Basic projection (Regneark med National tal 2015 - Basisfremskrivningen). Danish Energy Agency 2015. http://www.ens.dk/sites/ens.dk/files/dokumenter/side/energiforbrug_national_metode_bf2015.xlsx (accessed April 20, 2016).

[56] Lund R, Dominkovic D, Mathiesen BV. Socioeconomic Consequences of Short-Term Decisions on Large

Heat Pumps and Biomass Consumption for Heat Strategies in Denmark. 11th Conf. Sustain. Dev. Energy, Water Environ. Syst. – SDEWES Conf., Lisbon, Portugal: 2016.

[57] European Commission. DIRECTIVE (EU) 2015/1513 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewabl. Official Journal of the European Union; 2015.

[58] Danish Energy Agency. Alternative drivmidler 3.0.2. Copenhagen, Danmark: 2016.

[59] Danish Energy Agency. Technology Data for Energy Plants. Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion. - certain updates made October 2013, January 2014 and March 2015. Copenhagen: 2015.

[60] Mathiesen B V, Lund H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. IET Renew Power Gener 2009;3:190–204.

[61] Hedegaard K, Mathiesen BV, Lund H, Heiselberg P. Wind power integration using individual heat pumps – Analysis of different heat storage options. Energy 2012;47:284–93. doi:http://dx.doi.org/10.1016/j.energy.2012.09.030.

[62] Meibom P, Kiviluoma J, Barth R, Brand H, Weber C, Larsen H V. Value of electric heat boilers and heat pumps for wind power integration. Wind Energy 2007;10:321–37.

[63] International Energy Agency IEA. Nordic Energy Technology Perspectives 2016. IAE Publications; 2016.

[64] Ridjan I, Mathiesen BV, Connolly D. Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: a review. J Clean Prod 2015. doi:10.1016/j.jclepro.2015.05.117.