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100 MW GREEN HYDROGEN PRODUCTION IN A REPLICABLE AND SCALABLE INDUSTRIAL HOSTING ENVIRONMENT

Deliverable D1.4 ‘Hydrogen applications for grid balancing’

This project has received funding from the European Union’s Horizon 2020 research and innovationprogramme under grant agreement No 101036935 (GreenHyScale).

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Participant responsible:	Imperial College London
Main authors:	Luis Badesa, Hossein Ameli, Goran Strbac
Website:	https://www.greenhyscale.eu/

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R	Document, report (excluding the periodic and final reports)	X
DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	

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PU	Public, fully open, e.g. web	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

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PROJECT SUMMARY

This report is part of the deliverables from the project "GreenHyScale" which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036935.

Hydrogen is crucial for overcoming anthropogenic CO2 emissions and to transit to a renewable energy system, and that is why hydrogen is included in the European long term decarbonisation strategy. However, the technology today is only available at multi-MW scale. In addition, the EU offshore renewable energy strategy stresses the need for offshore hydrogen production.

The overall objective of GreenHyScale is thus to pave the way for large scale deployment of electrolysis both on-shore and offshore in line with both EU strategies. GreenHyScale will demonstrate minimum 100 MW of green electrolysis based on a novel multi-MW electrolyser platform operated in a unique hosting environment at GreenLab Skive (GLABS), and capable of replication across Europe with the associated economic growth and job creation. The project will show the benefits of green electrolysis, in a replicable business model, accelerating the new green economy throughout Europe and worldwide.

Moreover, as the link between offshore wind and electrolysis is unavoidable due to electrical transmission grid limitations, and offshore electrolysis is necessary to achieve the EU offshore renewable energy strategy, as it is impossible to build large enough wind and solar farms on land due to social acceptance and other issues. Thus, an upgraded high-pressure 7.5 MW electrolysis module for offshore use will be developed and tested at GLABS. The GreenHyScale project will form new complete European green value chains that support the transition to a renewable energy system by overcoming both technical upscaling and scommercialisation barriers, paving the way towards GW-scale electrolyser plants.

More information on the project can be found at https://www.greenhyscale.eu.

OBJECTIVE AND EXECUTIVE SUMMARY

Work Package 1 (WP1): The experiences from hydrogen demonstration projects and the requirements for upscaling consists of four tasks and will have four deliverables and two milestones. The experiences, upscaling challenges, and hydrogen applications overview will provide guidelines towards the development of the 100 MW green hydrogen demonstration plant using 6MW alkaline water electrolyzer modules. The main objectives are the following: (i) Reviewing experiences and lessons learned from selected electrolyser plants and from the partners of GreenHyScale; (ii) Defining requirements for the 100 MW electrolyser demonstration plant; (iii) Identifying new hydrogen customers and preparation of the offtake plan for the demonstration; (iv) Addressing applications for grid balancing services. WP1 provides important inputs to all the technical work packages (WP2-WP6) and links WP activities with the replicability and exploitation work package (WP8), that is looking towards GW-scale deployment in Europe.

This deliverable 1.4 (D1.4) presents the main results from Task 1.4 Hydrogen applications for grid balancing services during the first year of GreenHyScale (from the project starting in October 2021 to September 2022).

This report provides core evidence related to the role and value of the green hydrogen alkaline electrolysers of GreenHyScale for providing grid balancing services to the Danish electricity system. As explained in D1.1., there is empirical evidence that electrolysers can provide these services, for example, in the HyBalance facility, which can react to a contingency in less than 10 seconds (a requirement for participating in the Frequency Containment Reserve (FCR) market in Europe) [1]. A simulation tool for modelling the operation of a national electricity grid developed by Imperial College London (ICL) has been enhanced to include a model of electrolysers, that can contribute to a frequency-containment service via demand alleviation (i.e., reducing the power consumed in the event of a contingency in the grid). This model simultaneous considers the role of electrolysers for balancing in short-time scales (seconds) and mid-time timescales (hours, days), while quantifying additional economic and carbon benefits of different deployment levels of electrolysers. Therefore, the simulations carried out for this report also focus on analysing how green hydrogen can be produced via electrolysers during *high-renewable and low-demand* periods, thereby minimising the curtailment of renewable energy.

Different scenarios have been considered, notably on the future levels of inertia in the Continental Europe synchronous area, as well as on the installed capacity and frequency-response capabilities of electrolysers. The key insight from the results of these simulations demonstrates that electrolysers can bring net benefits to the system: even though demand for electricity would increase for hydrogen production, balancing services from electrolysers can bring significant benefits to future highly renewable electricity grids. A 100 MW capacity of electrolysers installed in the Danish grid would decrease overall operating costs and carbon intensity compared to the case of no electrolysers installed, if these 100 MW electrolysers contribute to the Frequency-Containment Reserve (FCR) service defined in Continental Europe (CE).

Given the results obtained from Task 1.4, the main conclusion is that considering hydrogen as a tool for grid balancing could be a major value of GreenHyScale, and therefore should be analysed from a more applicative perspective for the Skive demonstration site in Task 2.4. The results will provide insights for Task 3.2 and Task 3.5 for design, implementation, and validation of power electronic technologies in integration of the demonstration project. Furthermore, the results of Task 1.4 will be provided as input for Task 6.4, for designing trials for assessing the performance of the electorlysers. The simulations carried out for this report show that a 100 MW electrolyser able to provide FCR equal to 100% of its capacity would bring benefits to the CE area of more than €50m per year, given current inertia levels in CE (around 1,500 GVAs). For projected inertia levels in CE by 2030 (around 500 GVAs), the benefit increase to more than €100m per year. These results consider that the electrolyser operates at a minimum annual load factor of 75%, meaning that 657GWh (~19,500 tonnes) of hydrogen would be produced.

LIST OF PARTNERS

N°	Name	Short name	Country
1	GREENLAB SKIVE	GLABS	Denmark
2	GREEN HYDROGEN SYSTEMS	GHS	Denmark
3	ENERGY CLUSTER DENMARK	ECD	Denmark
4	LHYFE	LHYFE	France
5	SIEMENS GAMESA RENEWABLE ENERGY	SGRE	Denmark
6	EQUINOR ENERGY	EQUINOR	Norway
7	TECHNICAL UNIVERSITY OF DENMARK	DTU	Denmark
8	IMPERIAL COLLEGE LONDON	ICL	United Kingdom
9	EVERFUEL	EFUEL	Denmark
10	QUANTAFUEL	QUANT	Norway
11	EUROQUALITY	EQY	France

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1. INTRODUCTION

This report analyses the value of electrolysers in providing balancing services in low-carbon electricity grids. First, it is important to understand two critical characteristics of the operation of future grids on the road to decarbonisation: low inertia levels and the need to accommodate variable renewable sources.

A main stability challenge of the low-carbon grids is due to the decreasing levels of inertia. Historically, the main power sources in the electricity system were large rotating generators and turbines. The inertia of these large machines prevented the grid from rapidly changing frequency when there is an imbalance in the grid. This inertia of the rotating masses stores kinetic energy as it rotates to produce electric power, therefore it is a valuable energy buffer that helps maintain the grid in balance after an unexpected contingency, such as the loss of a large power plant. By contrast, renewable generators are connected to the grid via power electronic converters, therefore this decoupling implies that they do not contribute to the physical inertia of the grid. As coal- and gas-fired power plants are decommissioned or operate with lower load factors due to the increasing penetration of non-synchronous renewables (wind turbines and solar photovoltaic), this valuable energy buffer is reduced, potentially being close to zero during times of very high renewable power output. This presents a risk of instability in the future zero-carbon electricity grid.

New alternatives are needed to counteract the future low inertia, and an enormous opportunity is created by new types of loads, notably electrolysers: these could provide the necessary grid support and, up to a degree, replace inertia in keeping the balance of the grid. After a contingency, the power balance in the grid is restored in the short term through frequency-proportional response, in which generators' control systems measure the local frequency and respond with a power increase in proportion to the frequency decrease. Conversely, electrolysers could provide an equivalent service by applying the opposite strategy: as a frequency drop is measured, the control system in an electrolyser can reduce power consumption, which has the same net effect as the power injection provided by synchronous generators.

Furthermore, electrolysers can also provide balancing services on the timescale of hours and days. The future European grid will be dominated by weather-driven Renewable Energy Sources (RES), notably offshore and onshore wind, and solar photovoltaic. Given that the power output of these technologies is variable, driven by weather conditions, flexible demand assets will be needed to be complementary to these non-dispatchable generators. While storage capacity will certainly increase in the future, both from batteries and from other conventional storage types such as pumped hydroelectric storage, it is expected that RES power will still have to be curtailed at times of very high output, as storage capacity will be insufficient to cover this RES output peak. Electrolysers can play a significant role in reducing RES curtailment, by increasing their power consumption during times of excess RES output (which will coincide with low energy prices, therefore benefitting the electrolysers' business case).

A model which represents the operation of an electricity grid on a national level, developed by Imperial College London, has been used here to analyse the value of electrolysers (i.e., described in Appendix 1). This model is referred to in this report as the 'Stochastic Unit Commitment' (SUC). The SUC model has been enhanced during this Work Package 1, including an electrolyser model for providing balancing services. The electrolyser is modelled as a flexible load that must consume a certain volume of energy throughout the year, with flexibility on when to consume it. For the results presented in this report, a minimum load factor of 75% was used for all simulations (i.e., the electrolysers must be used for an equivalent of at least 75% of the time in the year operating at full capacity). Note that the SUC model considers a balance between generation and demand on a national scale and with hourly resolution, while the power output of some RES generators such as wind fluctuates intra-hourly. These intra-hour power fluctuations could be relevant for electrolysers drawing power directly from a RES facility, such as electrolysers co-located with offshore wind: given that electrolysers might not be able to perform continuous load-following, it would be relevant to analyse RES curtailment in this scenario. Intra-hour fluctuations in RES output are however out of the scope of this work.

Regarding the capabilities of the electrolyser for contributing to frequency-containment services, a sensitivity assessment is carried out on the percentage of electrolyser capacity that can contribute to these services. There is empirical evidence that electrolysers can provide these services, for example, as demonstrated in the HyBalance facility, which can react to a contingency in less than 10 seconds (a requirement for participating in the Frequency Containment Reserve (FCR) market in Europe) [1].

The following sections in this report focus on explaining the main parameters used as inputs in the SUC model (all values are based on current and future projections for the European electricity system), as well as discussing the modelling evidence related to the role and value of the green hydrogen alkaline electrolysers of the GreenHyScale paradigm in: 1) providing balancing and frequency regulation services to the Danish electricity system; and 2) enabling larger penetration of renewable energy sources.

2. BALANCING SERVICES IN LOW-CARBON ELECTRICITY GRIDS: PROBLEM AND OPPORTUNITY

A key operational requirement of an electricity grid is to balance the power being fed into the grid with the power consumed at all times. The magnitude that reflects imbalances of power in the grid is frequency: a frequency deviation from the nominal value of 50Hz implies that generation and demand do not exactly match. While frequency deviates from this nominal value constantly, as small random imbalances occur all the time, the main concern is large frequency deviations that follow a large disturbance, such as a large generator suddenly tripping off the system. In these cases, power must be rebalanced quickly, so that the grid remains operating within defined performance boundaries to avoid further disruption and customer load loss. Otherwise, if frequency kept dropping, under-frequency load shedding relays would trip, which are the last resort to bring the grid back into balance by disconnecting some demand. To avoid reaching this point, frequency response services are used, which typically take the form of part-loaded generators that use their headroom to increase power injected to the grid in the event of a contingency.

Here we discuss the main frequency-related operational requirements in the European system, which are used as inputs to the SUC model. The level of inertia in the current and future European grid is also discussed, since this is a key magnitude affecting post-contingency frequency excursions.

2.1. REFERENCE INCIDENT AND FREQUENCY LIMITS IN CONTINENTAL EUROPE

An important parameter in the SUC model is the largest power infeed loss in the system, which in Continental Europe (CE) is referred to as the 'reference incident'. The size of the reference incident is relevant because it sets the volumes required for frequency-containment services, since the network must be operated at all times with sufficient services to withstand a contingency equal to or smaller to the reference incident.

The current reference incident in CE (as well as the projected value for the foreseeable future) is of 3,000MW, corresponding to a double outage of two large generators, and determined by Article 153 (2b.i) of [2].

The frequency limits that must be respected at all times are: 1) the maximum Rate-of-Change-of-Frequency (RoCoF), and 2) the lowest admissible value for frequency, i.e. the frequency nadir.

The maximum admissible RoCoF in CE is of 1Hz/s [3]. During the "inertial response" period after a generation outage in the grid, the frequency drops very rapidly, therefore the derivative of frequency (the RoCoF) is at its highest point. The kinetic energy stored in the rotating machines of the synchronous generators (the inertia) is released to the grid during the first few instants following the contingency. The RoCoF, or rate at which the overall system frequency drops, is proportional to the imbalance of power (the size of the contingency) and inversely proportional to the inertia carried in the system. Therefore, for the reference incident (the largest contingency planned for), RoCoF cannot exceed this maximum value of 1Hz/s. This is the RoCoF limit enforced in all the SUC model simulations included in this report.

It is key to respect this RoCoF limit, as otherwise, system protection devices would disconnect generation units, as specified in the connection network codes [4]. RoCoF-sensitive relays are placed in the grid for disconnecting generation during islanding conditions, however after a frequency drop caused by a large contingency in the grid, the action of these relays would actually exacerbate the problem, as the power imbalance would be even higher.

The other operability boundary applied in the grid is related to the frequency nadir, which must not go below 49.8Hz in CE [3]. If frequency goes below this value, the 'limited frequency sensitive mode at underfrequency' is activated [5], meaning that the frequency-dependent load defence system in France is activated, disconnecting 1,300MW of interruptible loads that are under contracts to provide this service [6]. Therefore, the limit of 49.8Hz is used here for all SUC model simulations, as one of the goals of these simulations is to quantify the necessary volume of frequency-containment services, and all generators must have exhausted their headroom by a frequency deviation of 200 mHz [7].

More details on the methodology for including the frequency limits within the SUC model are included in Appendix 1, while the interested reader is advised to refer to [11] and [12] for a full mathematical formulation.

2.2. FREQUENCY RESERVES REQUIREMENTS IN DENMARK AND CONTINENTAL EUROPE

Certain frequency reserves are needed to comply with the frequency limits defined in Section 2.1. In Europe, the service used in the first few seconds after a contingency to contain the frequency drop is called Frequency Containment Reserve (FCR), and system operators of several countries procure this service in a common market. A diagram illustrating the frequency limits that must be respected, and the timescale for activation of FCR, are included in Figure 1.

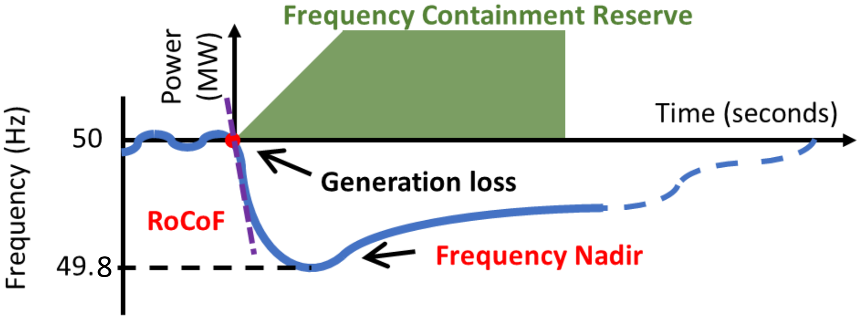

Figure 1: Illustrative diagram for a frequency drop following a generation loss in the grid, and activation of the FCR service.

All system operators in the Continental Europe synchronous area share the responsibility for procuring sufficient FCR to secure the reference incident, therefore the total amount of FCR that must be available in CE is of 3,000 MW. West Denmark participates in a joint market with Austria, Belgium, the Netherlands, France, Germany, Switzerland and Slovenia [8]. The share that each system operator is responsible for is determined by the generation and consumption in that operator's region, relative to the total generation and consumption in CE. Given the relatively small size of the Danish system, the Danish operator (Energinet), was responsible for procuring only 21 MW in 2020 [9]. However, this requirement will increase to 127 MW in 2023, as reported by Hybrid Greentech. Therefore, the total minimum of 3,000 MW for CE, and the minimum of 127 MW for DK were enforced in all SUC simulations carried out for this report. FCR needed to cover the loss of generation of 3GW (corresponding to the 'reference incident') is considered in this report, the opposite service used to cover losses of demand is not modelled.

Note that a significantly higher volume of secondary frequency response, named Frequency Restoration Reserve (FRR) in Europe, is procured in Denmark. The volume of FRR must cover the loss of the largest unit in Denmark, currently the COBRAcable HVDC connection with the Netherlands, setting a requirement of 684 MW [9]. However, given that the analysis here focuses on the challenge introduced by the declining levels of inertia due to the integration of RES, electrolysers are modelled in the SUC simulations contributing only to the FCR service. This is because FRR requirements remain unaffected by lower inertia, as the activation of FRR is not contained within the timescales of the highest RoCoF and frequency nadir shown in Figure 1.

2.3. CURRENT AND PROJECTED LEVELS OF INERTIA IN CONTINENTAL EUROPE

Inertia is a key magnitude that significantly influences the frequency deviation after a contingency. Inertia is essentially a measure of the kinetic energy available in the system, which provides a few valuable seconds to contain a generation-demand imbalance following a contingency, before other sources of support such as FCR are activated. The levels of inertia seen in the Continental European synchronous area in 2019 are included in Figure 2.

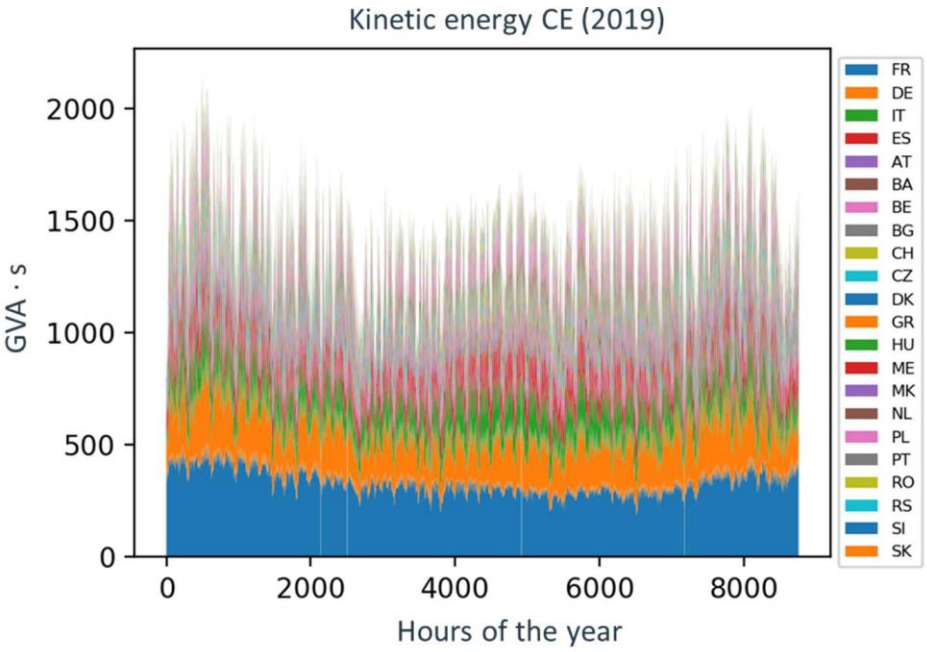

Figure 2: Inertia in the Continental Europe synchronous area throughout year 2019, as reported in [10]

Figure 2 shows that the peak of inertia was just above 2,000 GVAs in winter, when electricity demand in Europe is also highest and therefore, the fleet of synchronous generators is used at close to capacity. The diagram also shows the important baseline of inertia provided by the French nuclear fleet.

However, inertia levels are expected to significantly decrease in the coming years, as European countries decarbonise their power generation fleets to comply with the carbon targets set by governments and the European Commission. The projections by ENTSO-E for different future scenarios of the CE system are included in Figure 3.

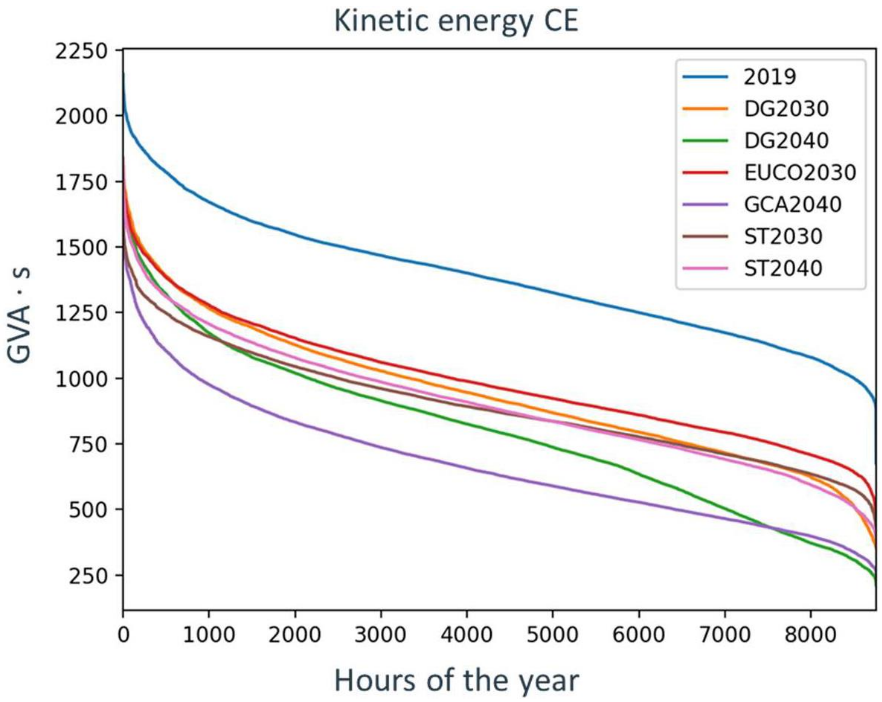

Figure 3: Projected inertia levels in CE in the different ENTSO-E TYNDP scenarios, as reported in [10]

The projections in Figure 3 correspond to the different scenarios for 2030 and 2040 included in ENTSO-E's 10-year network development plan (TYNDP). While in the analysis carried out for the present report the focus is on the operation of the Danish system, it is critical to consider the future inertia level sin the wider Continental Europe synchronous area, given that Denmark is synchronously connected to all countries in CE. Therefore, CE is modelled as an equivalent synchronous machine, as will be explained in Section 3, while a sensitivity on the inertia in CE is considered: both values of 1,500 GVAs and 500 GVAs are considered, as these values roughly correspond to the highest and lowest values for the 2030 scenarios included in Figure 3.

3. VALUE ASSESSMENT OF BALANCING SERVICES FROM ELECTROLYSERS IN THE FUTURE DANISH SYSTEM

In this section, the results from applying the SUC model to quantify the value of electrolysers for providing balancing services in the Danish system are presented. First, the most relevant system parameters used within the SUC model are defined, and then the detailed results from simulations considering several key sensitivities are discussed.

The methodology used for carrying out the value assessment of balancing services from electrolysers is based on two separate runs of the SUC mode, with and without any electrolyser capacity, to understand the differences in system operation and cost (i.e., reduction in fuel costs needed to run the grid in a stable manner). Benefits are quantified in terms of cost reduction and reduction in RES curtailment, while several sensitivities are considered, including different levels of inertia in CE, different values of installed capacity of electrolysers, as well as different degrees of flexibility from the electrolysers to provide the frequency-containment service.

3.1. BASE CASE FOR CHARACTERISTICS OF FUTURE DANISH ELECTRICITY GRID BY 2030

Key inputs to the SUC model include an electricity demand profile, RES capacity installed of the different types, and storage capacity installed. Furthermore, other relevant parameters include the size of the reference incident that the system must be secured against, and the characteristics of the thermal generation fleet. The value for these parameters is explained in detail in the next section.

3.1.1. DK FUTURE GENERATION MIX AND DEMAND

A scenario representative of the 2030 DK system was considered as the base case, regarding the future generation mix and electricity demand. This scenario is consistent with projections in ENTSO-E’s 10-year network development plan (TYNDP).

Electricity demand in DK was considered to be of 31.5TWh annually, with a peak of 4,800MW. A time series of hourly demand, including daily and seasonal trends was used within the SUC-model simulations carried out for this report. This time series has been used in several of Imperial College’s previous modelling works.

The characteristics of the thermal generation fleet are included in Table 1. The capacity for biomass and CCGT is slightly higher than in ENTSO-E's TYNDP projections; given that the focus of the modelling is on the operation of the Danish grid, this extra capacity is added to reflect typical power imports from neighbouring countries such as Norway and Sweden. Note however that, since the SUC is an operational model (meaning that a given generation mix must be used as an input, and therefore investment costs are not considered), this extra thermal generation capacity does not make a significant impact in the simulations results.

Furthermore, the focus of the analysis carried out for this report is on the cost of securing the future DK and Continental Europe electricity grids against unexpected contingencies, and not on the future energy costs of the system.

Table 1: Generation mix of thermal units for the 2030 scenario used in the SUC model

Thermal generation type	Installed capacity (MW)	Inertia constant (s)	Commitment time (h)	Fuel costs (€/MWh)
Bioenergy	1,500	5	4	25
Gas CCGT	1,500	5	4	46
Gas OCGT	200	5	0	200

This generation mix considers only the main technologies, as the goal of the simulations is to understand the future need for ancillary services, therefore, the level of inertia and primary frequency response from synchronous generators is the main variable to be considered.

The capacity of Renewable Energy Sources (RES) installed and associated load factors, are as follows:

Table 2: Renewable Energy Sources (RES) capacity installed in the 2030 scenario considered

RES type	Installed capacity (MW)	Average capacity factor (%)
Wind onshore	4,300	26%
Wind offshore	3,500	36%
Solar PV	2,000	11%

The time-series of load factors used within the SUC model corresponds to the year 2019, and the data was obtained from the open datasets in renewables.ninja.

Finally, the storage assets considered in the base case are included in Table 3.

Table 3: Battery Energy Storage Systems (BESS) included in the 2030 scenario

Storage type	Installed capacity (MW)	Duration (h)
Battery (BESS)	280	1

Battery Energy Storage Systems (BESS) are considered to provide up to 50 MW of primary frequency response, of the total requirement of 127 MW enforced for DK. Note that BESS can only provide FCR is sufficient headroom is available: if the BESS is charging, then all its FCR capacity is available, as this service would be delivered by suddenly stopping charging and even swiftly changing to discharging (a very rapid change from charging to discharging is possible in most battery storage technologies); however, if the BESS is discharging, only the available headroom at any given time can contribute to the FCR service.

3.2. RESULTS CONSIDERING CURRENT INERTIA LEVELS IN CE

This section presents the SUC model results while considering a value of inertia in CE roughly corresponding to current levels, i.e. 1,500 GVAs. The fleet of synchronous generators in CE is modelled as an equivalent inertia of 1,500 GVAs in this case, with no capability to produce power, as only the demand in DK is considered (which is covered by the thermal plants and RES described in Table 1 and Table 2, respectively). An FCR service is also made available in the CE area (outside DK), at a cost of €200/MW. This value is consistent with the cost of curtailing RES power for accommodating the minimum-stable generation of synchronous units to provide headroom, as explained in [11] and [12].

First, we analyse the cost of operating the system for different cases of electrolyser capacity and support for balancing services. The figure below displays the sum of annual system costs in DK and system costs for FCR in the Continental Europe synchronous area (given that DK is part of the CE synchronous area, the services to contain a frequency drop are coupled with those of other countries). The results on the left-hand side correspond to a SUC simulation where frequency-security constraints are not included, therefore this is an 'energy-only' optimisation with no guarantee that sufficient FCR is available to secure the reference incident. By comparing this result with the second bar from the left, tagged 'No electrolyser' within the category 'Inertia CE = 1,500 GVAs', the increase in system costs due to enforcing FCR requirements can be obtained (as all simulations within the category 'Inertia CE = 1,500 GVAs' do include the RoCoF and frequency nadir limits discussed in Section 2.1).

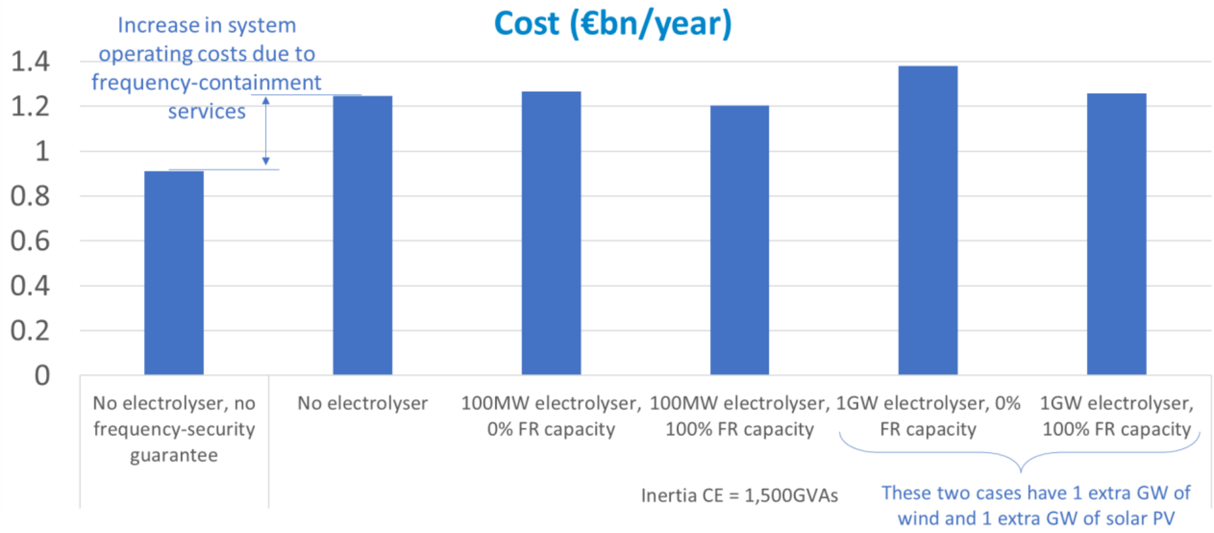

Figure 4: Annual cost of operating the DK system within CE, for several different cases with and without electrolysers, varying levels of electrolyser capacity installed, and different capabilities of the electrolysers to contribute to frequency reserve (FR)

Figure 5 includes a zoom-in for the frequency-secured results included in Figure 4, which are the cases corresponding to a realistic operation of the system, as the grid must always be secured against the reference incident. These results show that including a 100 MW electrolyser in the Danish grid, which does not contribute to the FCR service would actually increase system costs, given that this electrolyser increases the electricity consumption of the national system. However, for the case when 100% of the capacity of this electrolyser actually contributed to FCR, costs are reduced by more than €50m per year in the CE area, and the system costs in this case are even lower than for the case with no electrolyser at all. This implies that providing balancing services from the electrolyser brings a net benefit to the system, overcompensating the increased electricity consumption needed to produce hydrogen. If the FCR capacity of the electrolyser was below the 100% (e.g. 35% of rated power), benefits would reduce but still contribute to support grid operation.

Note that a competitor to electrolysers for providing the FCR service is battery storage, therefore higher BESS capacity would imply that the cost reduction brought by electrolysers providing FCR would diminish. However, these results already consider 280 MW of BESS capacity installed, and demonstrate that the balancing services from electrolysers are highly valuable. Furthermore, synthetic inertia from wind turbines could also reduce the requirement for FCR, although not completely remove it, since inertia and FCR are different services which both help contain frequency excursions in a different manner. Synthetic inertia has not been considered in the simulations carried out for this report.

The high system benefits from FCR provision by electrolysers are even more significant for the cases with additional electrolyser capacity of up to 1 GW, where the benefits of the FCR service from electrolysers are over €100m/year. Note that additional RES capacity has been included in cases with 1 GW electrolyser capacity, as explained within Figure 5, as otherwise the generation capacity installed in DK would be insufficient to cover the demand needs of this significant capacity of electrolysers.

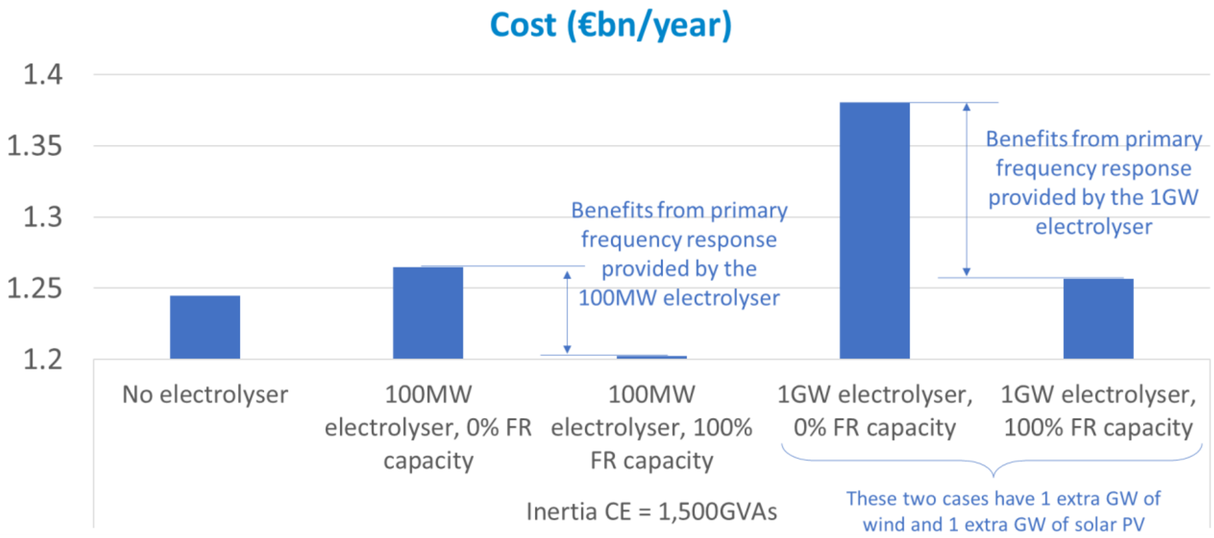

Figure 5: Annual cost for the frequency-secured cases included in Figure 4 (y-axis has been scaled)

The results for renewable energy curtailed, for the same cases as in the figures above, are reported in Figure 6. This figure shows that renewable curtailment increases due to enforcing frequency-security requirements, as some thermal plants are needed for this service, and their energy output must be accommodated, leading to some RES curtailment. A close-up on these results is given in Figure 7, focusing only on the frequency-secured cases.

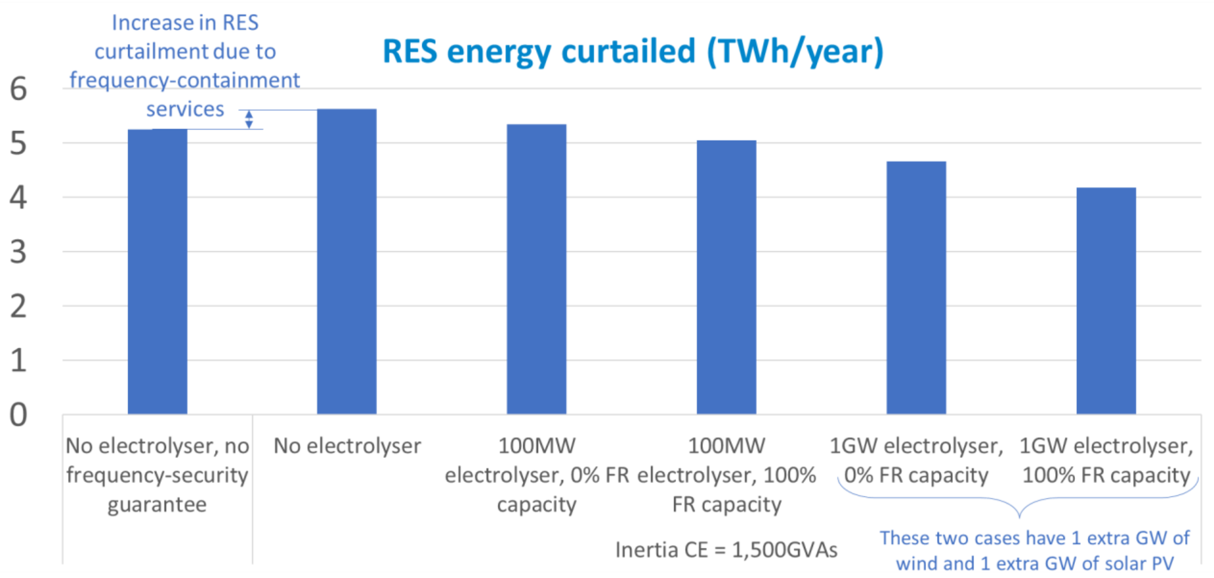

Figure 6: Annual renewable energy curtailed in the DK system, for all the cases considered.

The reduction in RES curtailment is due to two reasons: first, electrolysers are chosen to consume energy primary during periods of excess RES power, when the cost of electricity is lowest. This effect can be seen by comparing the first and second columns in Figure 7, as the electrolyser in the second column is not contributing to the FCR service and therefore all the extra RES accommodated is solely due to power consumption from the electrolyser during times of curtailed RES. The second reason for the reduction in RES curtailment is the provision of FCR from demand-side assets like electrolysers: if FCR available is only from the thermal generator, these generators have a minimum-stable generation limit that must be respected, therefore they displace some RES power due to frequency-security reasons. On the other hand, electrolysers could contribute to the FCR and not replace any RES power, which further reduces RES curtailment. The comparison of the second and third columns in Figure 7 shows this second contribution towards accommodating RES power due to the electrolysers. The effect on reducing RES curtailment is even more significant for increasing values of electrolyser capacity (i.e. fourth and fifth columns in Figure 7).

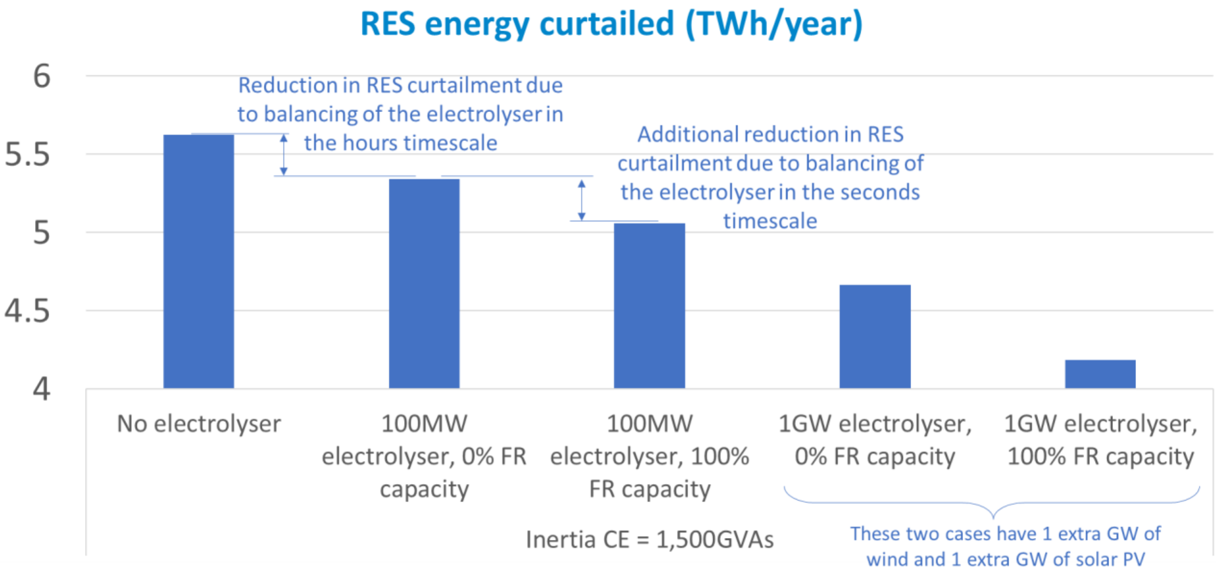

Figure 7: Annual RES curtailment for the frequency-secured cases included in Figure 6 (y-axis has been scaled)

Finally, the carbon intensity of the DK system is included in Figure 8. The carbon intensity of the Danish system does increase when frequency-containment services are enforced in the optimisation, as thermal generators with headroom are the main providers of the FCR service. Battery storage systems can also provide this service, but the need for FCR is higher than the capabilities of the BESS projected to be installed in DK by 2030, which is the reason why some thermal plants are still needed for FCR.

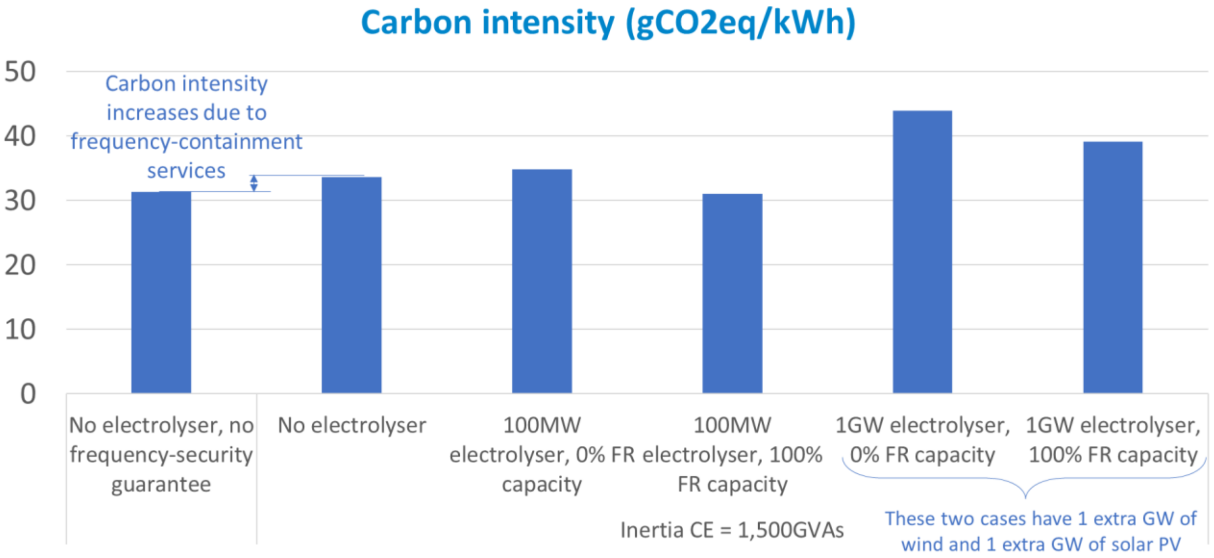

Figure 8: Carbon intensity of the DK grid, for all the cases considered

Figure 9 shows a close-up of the frequency-secured results in Figure 8. Carbon intensity does increase slightly when a 100 MW electrolyser is installed, compared to the case with no electrolyser: although the results in Figure 7 showed that the 100 MW electrolyser decreased RES curtailment compared to the case with no electrolyser, these results in Figure 9 demonstrate that some energy from thermal plants is still required for the electrolyser to maintain a load factor of at least 75% (which is enforced in all simulations, as explained in Section 1). However, when the same electrolyser does provide frequency response (third column in Figure 9), the carbon intensity of the DK grid reduces compared to the case with no electrolysers, as fewer thermal plants are needed for frequency-containment purposes. These same trends can be observed for the cases with 1 GW electrolyser capacity (fourth and fifth columns in the graph).

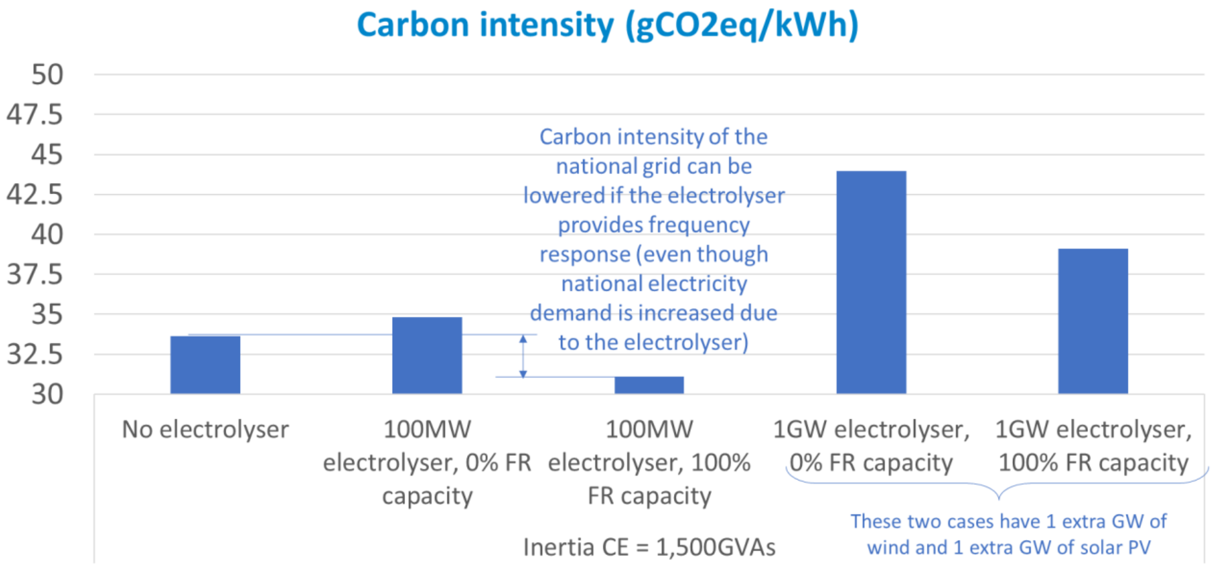

Figure 9: Carbon intensity for the frequency-secured cases included in Figure 8 (y-axis has been scaled)

3.3. RESULTS CONSIDERING FUTURE INERTIA LEVELS IN CE

The case studies shown in the previous section were repeated for a value of 500 GVAs in the CE synchronous area, consistent with the lowest values projected by 2030 from ENTSO-E. The results are presented in Figure 10 through Figure 15.

Figure 10 shows a much more significant impact of frequency-containment services than the results reported in Section 3.2. The first case on the left does not include the frequency limits in the SUC simulation. The main result is that system costs increase significantly by including the frequency-security constraints for the RoCoF and nadir discussed in Section 2.1, i.e. the system operating costs double due to enforcing the security requirements. Note that this cost of ancillary services corresponds to CE as a whole.

This very significant impact on system costs can be explained by considering the volume of FCR that is shown in Figure 10, compared to the cases in Section 2.1: the average volume of PFR in the ‘1,500 GVAs inertia in CE’ cases reported in Section 2.1 is slightly above 3,700 MW, while in the cases with 500 GVAs, the necessary volume of FCR in the SUC is above 11,000 MW. This significantly higher volume of FCR justifies the much higher costs included in Figure 10, as a significantly higher capacity of thermal plants is needed to operate at minimum-stable generation to provide the required headroom for the FCR service. In turn, the reason why such a high volume of FCR is required is due to the frequency nadir constraint: as explained in [11], low levels of inertia imply that this situation must be compensated by significantly high volumes of FCR.

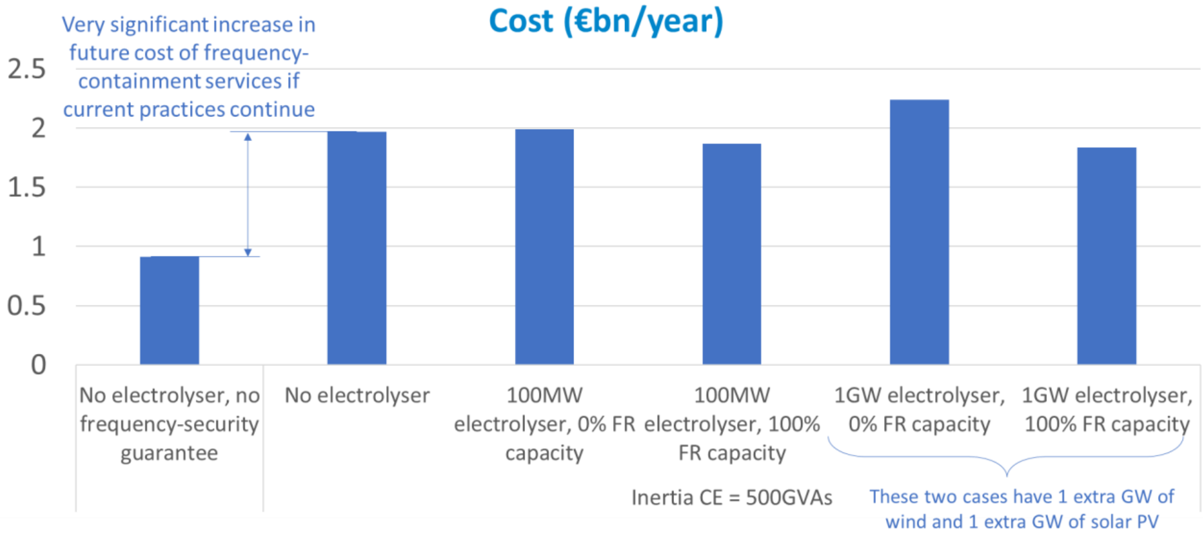

Figure 10: Annual cost of operating the DK system within CE, for several different cases with and without electrolysers, varying levels of electrolyser capacity installed, and different capabilities of the electrolysers to contribute to frequency reserve (FR)

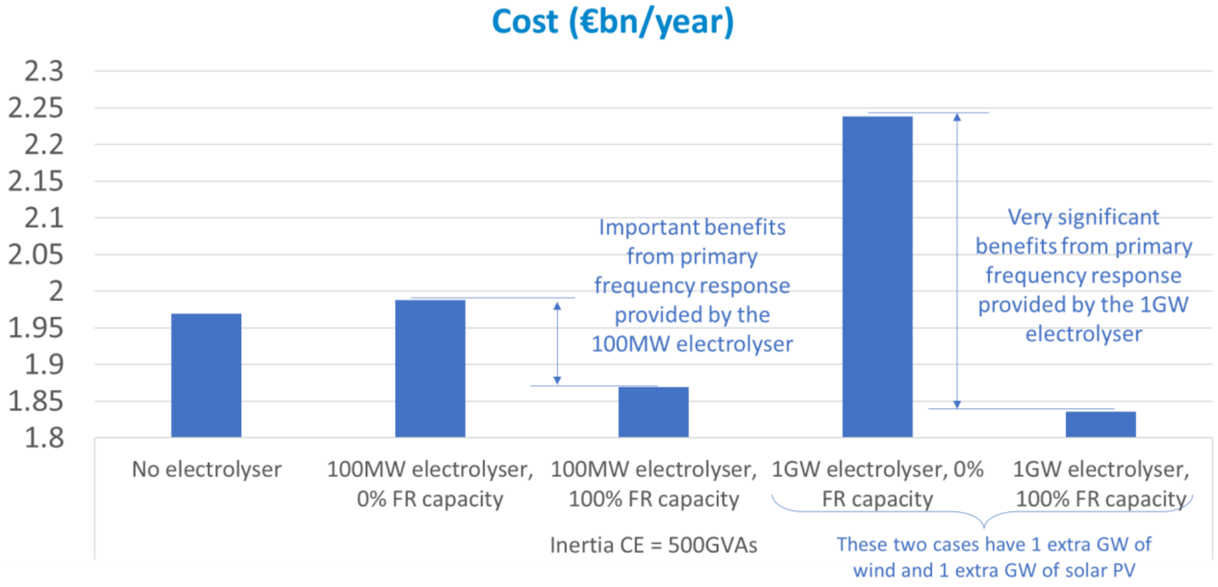

Figure 11: Annual cost for the frequency-secured cases included in Figure 10 (y-axis has been scaled)

Regarding the impact on RES curtailment and carbon intensity in DK (presented in Figure 12 to Figure 15), the main comparison with the previous results presented in Section 3.2 is that the trends are equivalent, although more prominent in some cases: introducing electrolysers in the grid can have net-benefits if these assets contribute to FCR services, given that they would then reduce the need for keeping thermal generators online for the single purpose of providing headroom.

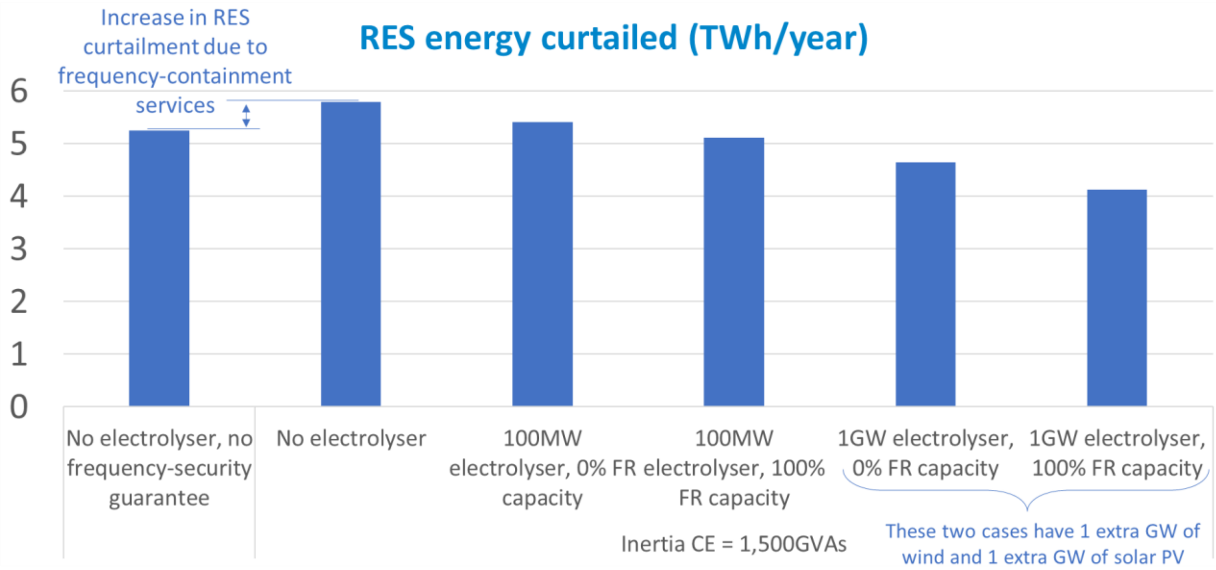

Figure 12: Annual renewable energy curtailed in the DK system, for all the cases considered.

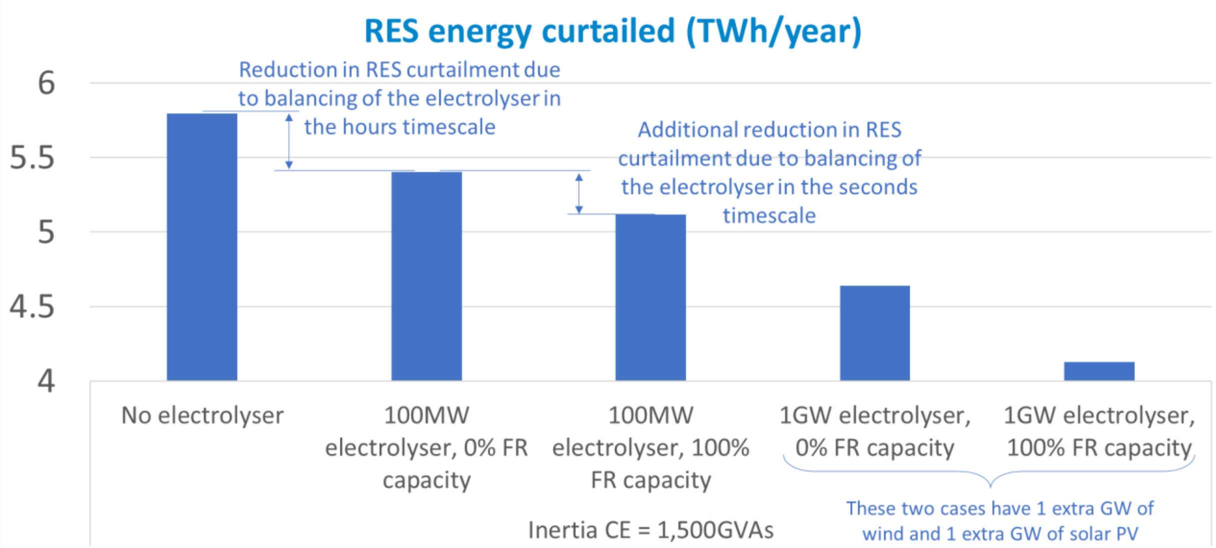

Figure 13: Annual RES curtailment for the frequency-secured cases included in Figure 12 (y-axis has been scaled)

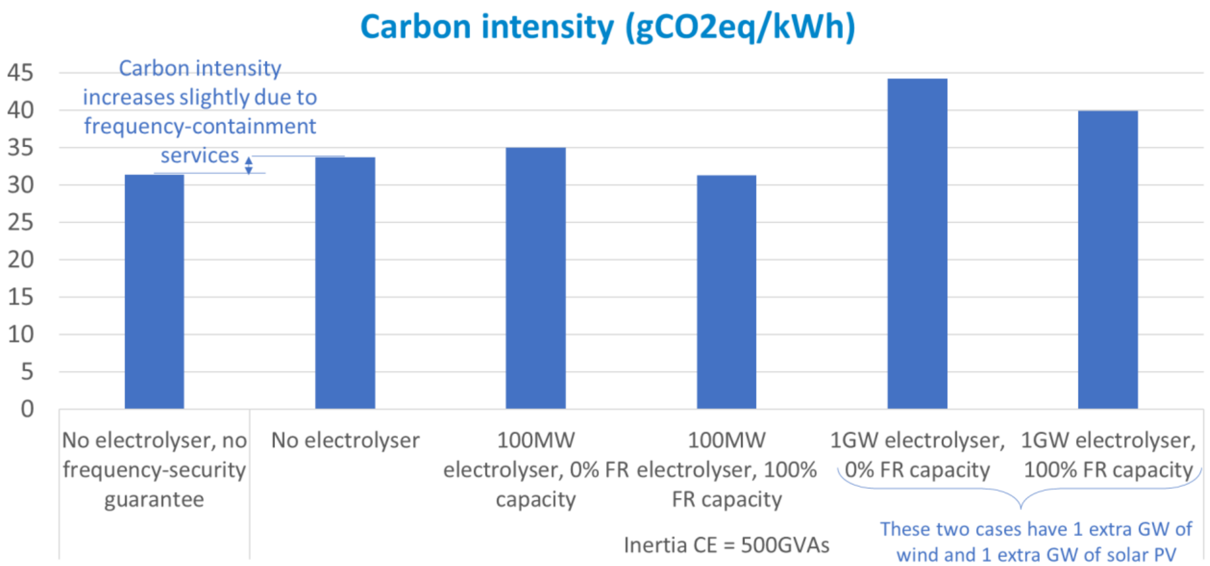

Figure 14: Carbon intensity of the DK grid, for all the cases considered

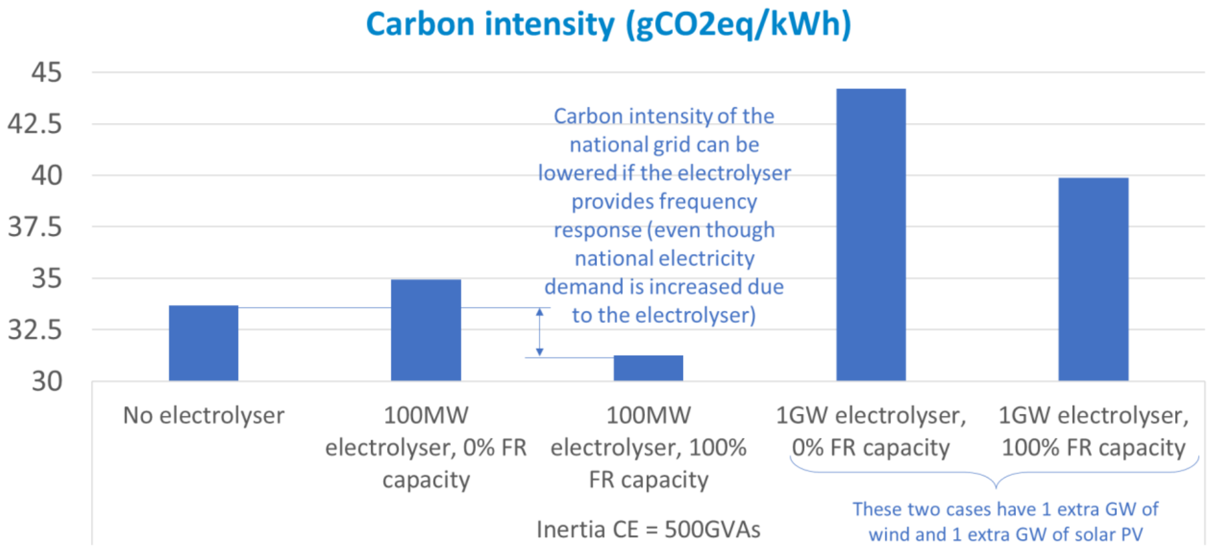

Figure 15: Carbon intensity for the frequency-secured cases included in Figure 14 (y-axis has been scaled)

4. CONCLUSION ON BENEFITS OF BALANCING SERVICES FROM ELECTROLYSERS

This report has summarised the main learnings from using the SUC model to quantify the value of electrolysers providing balancing services in the future Danish and Continental Europe electricity grids.

The main finding from the results presented in this report is that the future reduced inertia in Europe will significantly increase the challenge of keeping frequency within acceptable limits after a contingency. The cost of securing the system could be more than double compared to current inertia levels, if the traditional approach of using synchronous generators is still used to increase system inertia and frequency response. However, electrolysers bring very significant benefits to the system, both in terms of reducing this cost, but also in reducing renewable energy curtailment and reducing the carbon intensity of the national electricity grid. For the case of current inertia levels in Continental Europe (around 1,500 GVAs), a 100 MW electrolyser able to provide Frequency Containment Reserves equal to 100% of its capacity would bring benefits to the CE area of more than €50m per year. For projected inertia levels in CE by 2030 (around 500 GVAs), the benefit increase to more than €100m per year. These results consider that the electrolyser operates at a minimum annual load factor of 75%, meaning that 657GWh (~19,500 tonnes) of hydrogen would be produced. These benefits are mainly due to two reasons: 1) electrolysers prioritise electricity consumption during times of excess RES; and 2) reducing the need for thermal plants to be operated in the provision of headroom that contributes to the Frequency-Containment Reserves (this second reason only applies if the electrolysers do indeed contribute to the FCR service). The results will provide insights for design of the demonstrated project including the power electronic applications as well as design of trials to test/validate of the developed electrolysers in the project.

APPENDIX 1: FREQUENCY-SECURED STOCHASTIC UNIT COMMITMENT MODEL

Imperial College’s frequency-secured Stochastic Unit Commitment (SUC) model is a unique tool that includes frequency-containment services dynamics (with a timescale of sub-seconds) within the generation scheduling of a power grid (with a timescale of several minutes to an hour). This model simultaneously optimises energy and frequency-containment services, accounting for uncertainty in RES generation and finding the optimal volume of services needed for balancing generation and demand on a second-by-second basis. This is achieved by solving a stochastic optimisation problem with constraints for respecting the frequency regulation limits in the event of any credible contingency.

Frequency-containment services are considered within this model in a fully co-optimised manner, finding the optimal balance between the different types of services to achieve the lowest cost in operating the system. This means that complete coordination is achieved, as the SUC links the optimisation of inertia and Primary Frequency Response (i.e., the ‘Frequency Containment Reserve’ service in Europe) from different sources, such as thermal generators, storage devices, and demand-side assets like electrolysers. The model finds strategies to use the different assets in the most cost-effective way from a system perspective.

The structure of the model is represented by the schematic in Figure 16. Frequency dynamics are modelled through the ‘swing equation’, a differential equation that is solved to obtain the security constraints for the Rate-of-Change-of-Frequency (RoCoF) and nadir limits, which are later included in the Unit Commitment software. Uncertainty is modelled via the scenario tree on the right side of the diagram, built with several possible future realisations of RES power output. The Unit Commitment optimisation minimises the expected operation cost (i.e. fuel costs of thermal generators) for the next 24 hours while considering the probabilities of RES forecast error, and this approach is repeated for every hour within a whole year of operation of the national electricity grid. The detailed mathematical description of the frequency-secured model can be found in references [11] and [12]. This formulation has been enhanced for the GreenHyScale project to include an electrolyser model, represented as a flexible load that must consume a minimum volume of energy in the year, but with flexibility on the exact periods to consume.

Key outputs from this model include quantifying the value of different types of flexibility, as well as identifying the best operational strategies for low-inertia power systems.

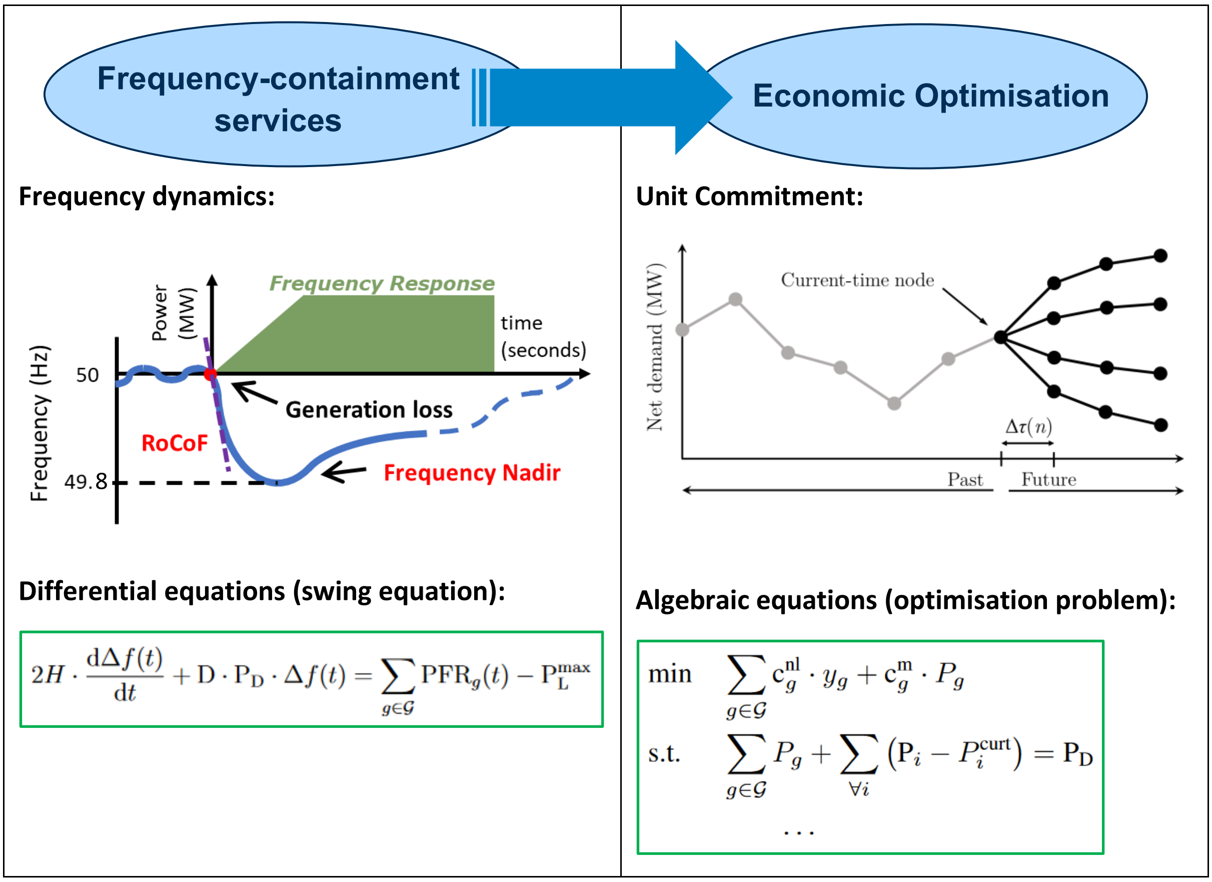

Figure 16: Schematic of Imperial College's frequency-secured Stochastic Unit Commitment (SUC) model. Frequency-containment services (with timescale of milliseconds) are mapped into economic optimisation (with timescale of hours).

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