AALBORG UNIVERSITY

MASTER'S THESIS

The European Commission's Delegated Act on RNFBOs

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Insights into Costs, Facility Setup, and Renewable Power Purchase Strategies

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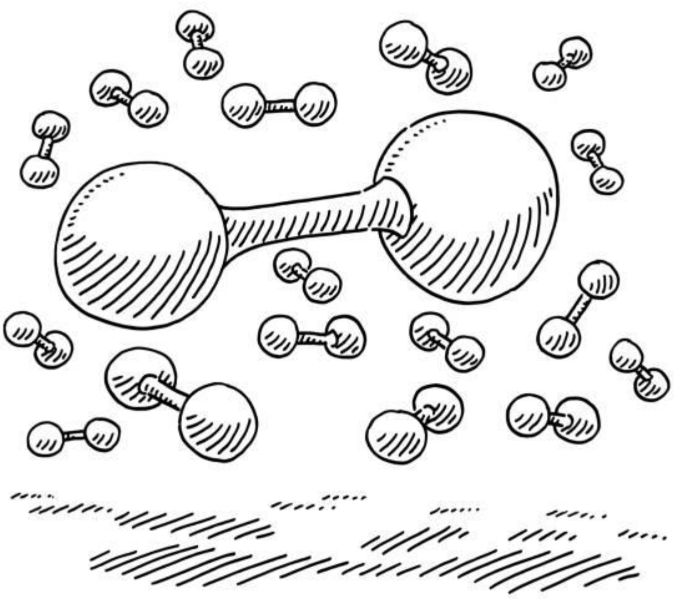
M.Sc. Sustainable Cities



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STUDENT REPORT

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Synopsis:

Background: In February 2023, the European Commission published a delegated act defining how Renewable Fuels of Non-Biological Origin could be claimed. The provisions break with the current practices of accounting for corporate emissions. The following research question was examined:

How will the European Commission's delegated act on RNFBOs impact the production of RNFBOs?

Methods: A qualitative analysis using desk study and semi-structured interviews. Then a quantitative analysis was conducted using linear optimisation and EnergyPRO.

Conclusion: The DA's influence extends beyond electricity supply and electrolysis, encompassing various project-specific factors. The GO scheme enables granular tracking and accounting of renewable electricity, supporting compliance and avoiding double claiming. The DA's impact on the design of renewable PPAs for RNFBO production involves a shift towards pay-as-produced structures and the potential use of combining PPAs to increase full-load hours. Shaped PPA structures are likely achieved by combining multiple pay-as-produced PPAs with different generation technologies, such as wind and solar. However, this approach carries the risk of over-procurement. Further, the impact of the DA on production costs and facility setup is relatively insignificant, with greater sensitivity observed in utilisation rates rather than the transition from monthly to hourly matching. Pay-as-produced PPAs and derogations help mitigate economic differences between monthly and hourly matching.

Abstract

Renewable/green hydrogen has had a prominent role in the public debate, and policymakers have often pointed to renewable hydrogen as a key to decarbonising industry. Renewable hydrogen can be obtained by using renewable electricity to split water into hydrogen and oxygen, and in the EU referred to as Renewable Fuels of Non-Biological Origin (RFNBO). The EU has a target of consuming 20 million tonnes of renewable hydrogen by 2030 as part of REPowerEU. In February 2023, the European Commission published a Delegated Act (DA) that defines under which conditions hydrogen or hydrogen-based fuels can be considered an RFNBO. To understand the implications of this act, it is crucial to examine its impact on the production of RNFBOs. Therefore, the research question of this thesis is:
How will the European Commission's delegated act on RNFBOs impact the production of RNFBOs?

The present thesis will contribute to a comprehensive understanding of the regulatory landscape surrounding RNFBO production and evaluate the DA's impact on production cost and facility setup. The research focuses on the provisions regarding temporal correlation requirements tying the renewable electricity production to the RNFBO production on a monthly basis and after 2030; hourly. In addition, the DA includes derogations for claiming grid electricity mix as renewable, which also will be assessed, as this has been neglected in the literature. The DA prescribes that the grid-sourced electricity must be covered by renewable Power Purchase Agreements (PPAs). This is likewise the centre of attention. The research was designed by conducting a qualitative analysis and then a quantitative analysis.

The qualitative analysis uses desk study and semi-structured interviews to gather empirical data. Six semi-structured interviews were conducted with RNFBO producers, consultancy bureaus, Danish Energy Agency, and finally, Energinet and EnergyTAG to get insights into granular renewable energy certificates. The quantitative analysis builds on the qualitative by creating likely RNFBO setups comprising an electrolyser and a renewable electricity supply contracted via renewable PPAs. The renewable electricity supply was identified using linear optimisation in Excel for setups at monthly and hourly matching and when introducing a fixed monthly hydrogen demand. The PPAs were structured as pay-as-produced and were assess using an off-site and behind-the-meter approach. The RNFBO production was then simulated using the simulation software EnergyPRO.

The present thesis demonstrates that the DA's influence extends beyond electricity supply and electrolysis, encompassing various project-specific factors. The GO scheme enables granular tracking and accounting of renewable electricity, supporting compliance and avoiding double claiming. The DA's impact on the design of renewable PPAs for RNFBO production involves a shift towards pay-as-produced structures and the potential use of combining PPAs to increase full-load hours. Shaped PPA structures are likely achieved by combining multiple pay-as-produced PPAs with different generation technologies, such as wind and solar, to improve the utilisation rate. However, this approach carries the risk of over-procurement, necessitating the sale of excess electricity in the Day-ahead market. The hourly matching requirements especially drive this.

The impact of the DA on production costs and facility setup is relatively insignificant, with greater sensitivity observed in utilisation rates rather than the transition from monthly to hourly matching. Pay-as-produced PPAs combined with the derogations help mitigate economic differences between monthly and hourly matching. The impact of the DA ultimately depends on geographical context, as the DA's provisions are determined by the renewable electricity penetration in the grid to which the RNFBO production facility is connected.

Preface

This thesis was carried out by Jeppe Høstgaard Poulsen during the 4th semester of the master's programme *Sustainable Cities* at Aalborg University. The thesis was conducted over a period of four month; 01.02.23 to 02.06.2023. The thesis covers 30 ECTS credits.

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To my friends and family, thank you for your unwavering support and encouragement. Your belief in me has been a constant source of motivation.

Thank you all for your contributions.

Reading Instructions

References follow the reference style APA. For this reason, in-text references refer to the author's last name and publication date. The complete reference list can be found at the conclusion. The abbreviations can be found following the tables of content.

Furthermore, the appendices are placed at the end of the thesis, following the order they are introduced. Additionally, an Excel file containing the technical and financial prints from EnergyPRO is submitted separately at Digital Exam.

Commas (,) are used as thousand separator and periods (.) as decimal separator.

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Abbreviations

BPP	Blue Power Partners (Consultancy Bureau)
DA	Delegated Act
ETS	(European) Emission Trading Scheme
EUA	The price of emissions allowances traded on the ETS
GHG	Greenhouse Gas
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
LOCH	Liquified Organic Hydrogen Carriers
PtX	Power-to-X
RES	Renewable Energy Source
REDII	Renewable Energy Directive 2018/2001 (EU)
RNFBO	Renewable Fuels of Non-Biological Origin
TSO	Transmission System Operator

1 Introduction

Renewable/green hydrogen has had a prominent role in the public debate, and policymakers have often pointed to renewable hydrogen as a key to decarbonising industry. Renewable hydrogen can be obtained by using renewable electricity to split water into hydrogen and oxygen, and in the EU referred to as Renewable Fuels of Non-Biological Origin (denoted RNFBO) (European Commission, n.d.; European Commission, DG ENER, 2023, p. 16). 16 European countries have adopted national hydrogen strategies, which together amount to 40 GW electrolyser capacity by 2030, or 5.6 million tonnes of hydrogen (European Commission, 2023a, p. 1). This still leaves a gap as the EU has a target of consuming 20 million tonnes of renewable hydrogen by 2030 as part of REPowerEU, aiming to produce 10 million tonnes of renewable hydrogen within the EU and import the residual 10 million tonnes (European Commission, n.d.). Currently, 8 million tonnes of hydrogen is consumed annually within the EU, which is almost exclusively produced from natural gas using steam methane reformation, so-called ‘grey hydrogen’, which is mainly used for oil refining, ammonia (European Commission, 2023a, p. 3; IEA, 2019). Hence, a monumental transition of the current hydrogen supply lies ahead.

Renewable hydrogen is targeted to directly substitute grey hydrogen or used in fuel cells or as feedstock for synthetic fuels substituting, fossil-based fertilisers, diesel or jet fuel, or natural gas to decarbonise hard-to-abate sectors (European Commission, DG ENER, 2023, p. 15). In addition, introducing electrolysers into the energy system can enable high penetration of variable renewable energy sources, i.e., wind and solar. Electrolysers can operate flexibly and rapidly adjust the load and, in this way, help balance supply and demand (Stöckl et al., 2021). Thus, large-scale electrolysers can provide system services and reduce the curtailment of renewables which becomes increasingly pertinent as the penetration of renewables increases (Stöckl et al., 2021).

The European Union has been missing a definition of *renewable hydrogen* and *RNFBOs,* causing some frustration in the industry (Hydrogen Europe & Renewable Hydrogen Coalition, 2023; Simon, 2022). In 2023, the European Commission published two long-awaited delegated acts (denoted DA) setting standards for the production of RNFBOs. The first DA defines under which conditions hydrogen, hydrogen-based fuels or other energy carriers can be considered as an RFNBO, and the second DA provides a methodology for calculating life-cycle greenhouse gas emissions for RFNBOs, relevant for carbon-based fuels (European Commission, 2023b). The process leading up to the publication of the DAs illuminated disputes between member states and EU institutions and the heavily nested industry interests in defining RNFBOs (Kurmayer, 2023; Simon, 2022).

The present thesis will focus on the first DA defining under which conditions hydrogen, hydrogen-based fuels or other energy carriers can be considered as an RFNBO, as the DA includes a comprehensive set of requirements regarding the renewable electricity sourced by the RNFBO production facility, where the renewable electricity generation plant must be located, and further the correlation between production and consumption, etc. The comprehensive set of requirements was put in place as the current standards of accounting for GHG emissions were perceived insufficient to safeguard that RNFBOs were a zero-emission product and would result in greenhouse gas (denoted GHG) emission reductions when replacing the fossil alternative.

The present thesis aims to assess how the first DA will impact the production of RNFBOs.

2 Problem Statement

This chapter uncovers the current standards for accounting for GHG emissions related to energy consumption in companies. It explores the requirements set out by the DA for claiming electrolytic hydrogen or synthetic fuel as an RNFBO and examines the literature on regulating RNFBO production. Addressing these areas aims to provide insights into GHG emissions accounting, criteria for RNFBO classification, and the existing literature concerning regulating RNFBO.

2.1 Tracing and Accounting Renewable Electricity via Renewable Energy Certificates

It is essential to understand the current standards for accounting for GHG emissions as a company, as the DA published by the EU Commission breaks with the current practice.

The Greenhouse Gas Protocol plays a key role in defining how companies account for GHG emissions resulting from their energy consumption and activities and how they can account for renewable energy in their GHG inventory to reduce GHG emissions. The Greenhouse Gas Protocol Corporate Standards issued by the World Resources Institute guide companies to account for emissions related to scope 1, 2, and 3 (Sotos, 2015). A company's scope 2 covers 'indirect' emissions and goes beyond the 'direct' scope 1, which covers GHG emissions from sources directly in control or owned by the company. Scope 2 covers the GHG emissions that are a consequence of the company's activities, or rather related to the energy purchased or consumed by the company (Sotos, 2015, p. 33). So, the GHG emissions related to the electricity consumed by an RNFBO production facility would, in most cases be reported under scope 2.

The standards, further, differ between two different methodologies for accounting scope 2 emissions: 1) the location-based method and 2) the market-based method. Using the location-based method, the company quantify the emissions based on average electricity generation emission factors for defined geographic locations (Sotos, 2015, p. 26). On the contrary, using market-based, the company reports based on the GHG emissions emitted by the generators from which the company contractually purchases electricity with contractual instruments, such as Renewable Energy Certificate (REC) or Guarantees of Origin (GO) used in the U.S. and EU, respectively (Sotos, 2015, pp. 6–26). Both methods account for energy consumption on an annual basis, meaning that a company can report 0 GHG emissions from electricity consumption in a calendar year if the consumed volume of electricity is balanced by an equal volume of renewable electricity via bundled or unbundled power purchases (Sotos, 2015, p. 50). Bundled and unbundled power purchases mean that the electricity is sold with or separate from the attributes, hence, if unbundled, the power and renewable certificate are sold separately. The important takeaway here is that the current practice balances renewable electricity production and electricity consumption on an annual basis disregarding the actual electricity generation by the renewable energy source (denoted RES) plant. Renewable energy certificates play an essential role in this regard. Therefore, it is instructive to understand the use of renewable energy certificates in the EU: Guarantees of Origin and how it relates to the GHG protocol.

GOs are legally bound by the Renewable Energy Directive's Article 19, adopted in 2018 (hereafter REDII), which is currently subject to revision (Council of the EU and the European Council, 2023; *Renewable Energy Directive 2018/2001*, 2018). The EU introduced GOs to monitor member states' compliance with renewable electricity targets by obligating energy suppliers to disclose information about the supplied electricity and, via

GOs, verify the content of the disclosure. The GOs are defined in REDII's Article 2(12), a GO *"means an electronic document which has the sole function of providing evidence to a final customer that a given share or quantity of energy was produced from renewable sources".* Though GOs can also be issued from non-renewable energy sources if the member state allows (*Renewable Energy Directive 2018/2001*, 2018, Article 19(2)). They can thus be disregarded in the context of RNFBOs. REDII mandates energy producers to further outline that GOs are issued by producers of renewable energy with a standard size of 1 MWh, and a GO is valid for 12 months after the production of the energy unit (Article 19). The GOs can be traded and transferred independently of the electron it relates to (Recital 55). This case is referred to as an unbundled certificate. Hence, the electricity consumed by the offtaker is no different from the electricity they would have otherwise received from the grid as the electricity and the renewable attribute are separated. However, the offtaker can claim the renewable origin of the electricity consumed. This aligns with the market-based method issued in the Greenhouse Gas Protocol Corporate Standards (Sotos, 2015, p. 46). A bundled power purchase means that the renewable attribute and power are sold together, this can for example be via a power purchase agreement (PPA) from a renewable generation asset, this can be from both new and existing assets.

This method of accounting for renewable electricity and associated GHG emission reductions has been subject to criticism. Bjørn et al. (2022, pp. 543–545) and Hamburger (2019, pp. 493–495) point to the risk of double-counting emission benefits of renewable electricity generation, and the use of non-additional certificates such as GOs, meaning they claim emissions reductions without contributing to system-level reductions by adding new renewable generation capacity. The literature state that GOs do not drive investments in new renewable generation capacity due to the low cost of "renewable electricity" as the market is flooded with GOs from existing capacity, e.g., from Norwegian, Swiss, and Austrian hydropower (Hamburger, 2019, pp. 496–497). Further, this way of accounting for GHG emissions disregards the physical electricity flows (Hamburger, 2019, pp. 500–501). Balancing supply and demand on an annual basis only results in decarbonising 40 to 70 pct. of the offtaker's electricity consumption due to the temporal mismatch, which leaves a significant gap to be 100 pct. decarbonised as claimed (Energinet, n.d.-a; LDES Council & McKinsey, 2022, p. iii).

EU Commission's long-awaited published standards for electrolytic hydrogen production break with this current approach of company accounting of GHG emissions by balancing either bundled or unbundled GOs on an annual basis. The following chapter will unfold the DA's requirements for RNFBO production.

2.2 Defining of RNFBOs: A Challenging Journey

REDII urged the European Commission to publish two delegated acts regarding renewable hydrogen. The European Commission was tasked to supplement REDII with 1) a delegated regulation establishing the threshold for low-carbon hydrogen used in transport, amending Article 27(3) and 2) a delegated regulation creating a methodology to ensure that RNFBOs used in transport contribute to lowering greenhouse gas emissions and is based on renewable electricity, amending Article 25(2) and 28(5) (*Renewable Energy Directive 2018/2001*, 2018). In short, the first DA defines the circumstances under which hydrogen-based fuels or other energy carriers can be considered an RFNBO. And the second DA provides a methodology for calculating life-cycle greenhouse gas emissions for RFNBOs, which is useful when producing carbon fuels. The delegated regulations are likely to be expanded to encompass all sectors, even if the delegated acts only mention RNFBOs used in transportation (Brauer et al., 2022, p. 2).

REDII further defined regulatory dimensions to be considered when developing the first DA on RNFBO production with electricity sourced from the grid. The EU co-legislators agreed on three aspects for consideration to ensure a reliable methodology:

"That methodology should ensure that there is a temporal and geographical correlation between the electricity production unit with which the producer has a bilateral renewables power purchase agreement and the fuel production. […] Furthermore, there should be an element of additionality, meaning that the fuel producer is adding to the renewable deployment or to the financing of renewable energy."
(*Renewable Energy Directive 2018/2001*, 2018 Recital 90)

The co-legislators agreed on 'temporal correlation', 'geographical correlation', and 'additionality' as essential aspects to consider for reliability.

1. A *temporal aspect* to ensure correlation between the production of renewable electricity and the production of RNFBOs, in other words tying the RNFBO production profile to the RES generation profile,
2. a *geographical aspect* to enable the renewable electrons to reach the RNFBO production facility by considering grid congestion and connectivity in the legislation, and lastly,
3. *an element of additionality* to ensure new RES production capacity is added to the grid to avoid diverting and cannibalising the existing renewable electrons in the grid.

The long-awaited delegated act was published on February 20, 2023, exceeding the original deadline of January 1, 2021, as agreed in 2018 (*Renewable Energy Directive 2018/2001*, 2018 Article 27(3)). This happened after a lengthy debate between policymakers, industry, and non-governmental organisations covering several different versions of the delegated act, which has been leaked or published as part of a public consultation by the European Commission (Hydrogen Europe & Renewable Hydrogen Coalition, 2023; Kurmayer, 2023; Simon, 2022). Industry and NGOs urged the European Commission to adopt the delegated act to provide regulatory certainty. While the NGOs emphasised the importance of maintaining high environmental integrity, the hydrogen industry was worried about slowing the deployment if strict standards were adopted (Hydrogen Europe & Renewable Hydrogen Coalition, 2023; Transport & Environment et al., 2022). At the submission of the present thesis, the DA has yet to be finally adopted following the European Parliament and Council of the European Union scrutiny period (European Commission, 2023b).

Before uncovering the content of the first DA on RNFBOs, it is necessary to understand the regulatory dimensions of RNFBO production. The following subsection will elaborate on the three regulatory dimensions.

2.2.1 Regulatory Dimensions of RNFBO Production

This subsection delves into the regulatory dimensions surrounding RNFBO production, what aspects of the production can be regulated – and how - to ensure RNFBOs reduce emissions when substituting a fossil counterpart. The focus is on electrolytic hydrogen production and disregards the potential for further processing and conversion to a synthetic fuel, and carbon source, which the second DA covers.

Brauer et al. (2022) depict the three main regulatory dimensions in Figure 1.

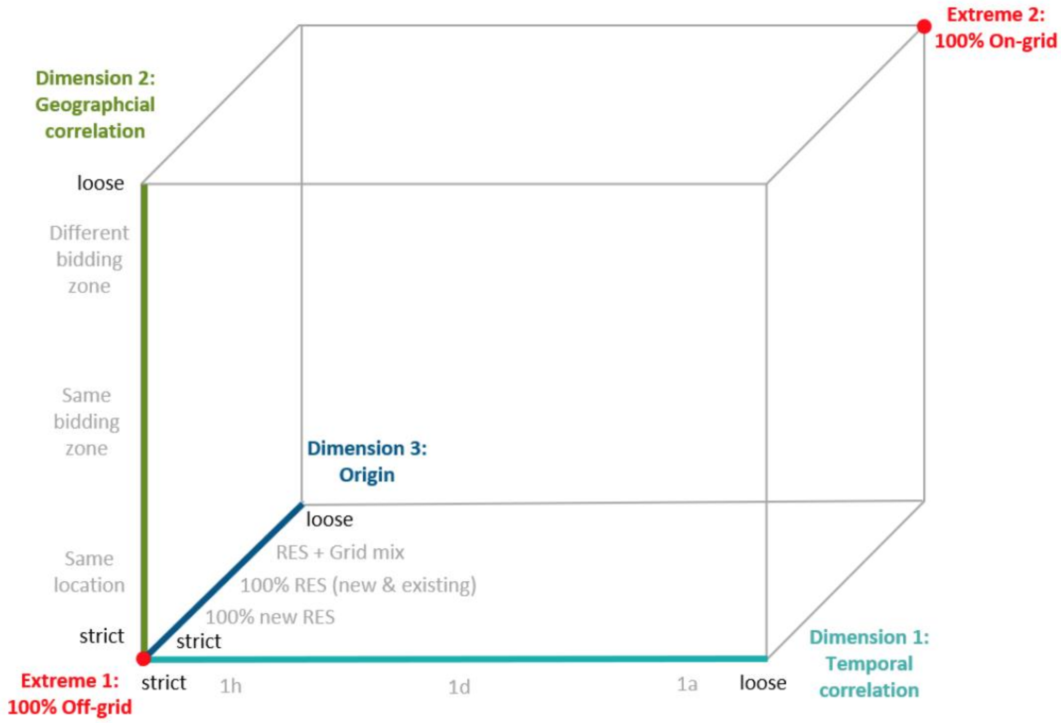

Figure 1 Regulatory Dimensions of Electrolytic Hydrogen Production

Notes The figure illustrates the three regulatory dimensions of hydrogen production. X-axis: Temporal correlation, y-axis: geographical correlation, z-axis: origin. The two extreme cases represent the strictest and most relaxed combination of the three.

Source Copied from Brauer et al. (2022).

The stringency of the regulation can vary in each dimension and can be combined in numerous ways, with two extreme cases representing the most strict and relaxed combination of the three dimensions: Temporal correlation, geographical correlation, and origin.

Temporal correlation (x-axis) defines the period within which the RNFBO producer must balance the electricity consumption with electricity production. The strictest temporal correlation is either immediate, sub-hourly, or hourly balancing and up to the most relaxed case where the volumes are to be balanced annually as the GHG Protocol Standards prescribe. *Geographical correlation* (y-axis) determines the relative location of the RES electricity generation plant to the RNFBO production facility. The strictest case mandates them to be in the same location, e.g., directly connected, while the most lenient case allows the RES electricity generation plant to be located in a different bidding zone. *Origin* of the electricity (z-axis) specifies where the electricity sourced originates. The strictest case mandates the electricity to be sourced from new (additional) RES electricity assets, while the most lenient case allows sourcing the grid electricity mix.

Relaxing the standards in either of the three dimensions reduce the chance of which the RNFBO is produced by renewable electrons, while this, of course, disregards the fact that individual electrons in the grid cannot be tracked.

The following subsection will unfold the published DA in relation to the three regulatory dimensions.

2.2.2 European Commission's final Delegated act on RNFBOs

The final publication happened after several events and frustrations from industry and politicians, starting with the first draft published for consultation in May 2022 (European Commission, 2022; Simon, 2022). From May 2022 to February 2023, some aspects were relaxed, e.g., the initial transitional phase was prolonged, entry into force was delayed, and several exemptions were added, such as derogations from additionality. However, the temporal matching requirements were preserved: Monthly in short-term and hourly in the long term (*Commission Delegated Regulation C(2023) 1087 Final*, 2023).

The DA include various requirements depending on 1) the RES generation asset and RNFBO directly connected and 2) the RES penetration in the electricity grid to which the RNFBO facility is connected. If the RES generation asset and RNFBO production facility are directly connected, the RES generation asset must be additional, meaning that the RES generation asset came into operation not earlier than 36 months before the RNFBO production facility. Second, the temporal correlation requirements must be met: Monthly before 2030 and then hourly matching, however, in the case of a direct connection, the electricity is likely consumed immediately.

Furthermore, if the RES generation asset is to be considered additional, it must not have received investment or operating aid. However, it can be if the aid is repaid or received in the case of repowering (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 5(b)).

With a grid-connected RNFBO facility, it becomes more complex (see blue box). The RNFBO producer must conclude RES PPAs that generate a volume equal to the amount consumed from the grid. The DA further specify the renewable power generation technologies with which PPAs can be concluded by referring to REDII Article 2(1) (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 2(3)). The definition of renewable generation technologies includes onshore and offshore wind, solar, wave, biogas, biomass, etc., however, the DA explicitly exclude electricity based on biomass. The generated and consumed volumes must be balanced monthly before 2030 and hourly after 2030, and the RES electricity generation assets must meet the additionality requirement stated above. Further, the RES electricity generation asset must be located in the same bidding zone, an interconnected bidding zone with lower or equal electricity prices, or an interconnected offshore bidding zone.

If the electricity grid has a RES share higher than 90 pct. in a calendar year, the grid electricity mix can be accounted as renewable in the following five years (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 4(1)). Though, the maximum number of full load hours must not exceed the RES %-share times hours in a year. If the RNFBO installation is connected to a grid with a greenhouse gas intensity lower than 18 gCO_2/MJ on an annual average, corresponding to 65 gCO_2/kWh. In that case, the additionality requirement is scrapped compared to a *general grid* case (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 4(2)).

Disregarding the RES penetration in the grid, the RNFBO producer can in all cases, account grid electricity as renewable if it is consumed in periods with a Day-ahead price lower than 20 €/MWh or 0.36 times the price of an emissions allowance (denoted EUA) traded on EU's Emission Trading Scheme (denoted ETS)[1], and in addition, periods where RES generation was dispatched downwards (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 4(3)). Figure 2 summarises the conditions under which RNFBOs can be produced.

1 The price of emissions allowances (EUA) (1 tonnes CO_2), traded on the European Union's Emissions Trading System (ETS).

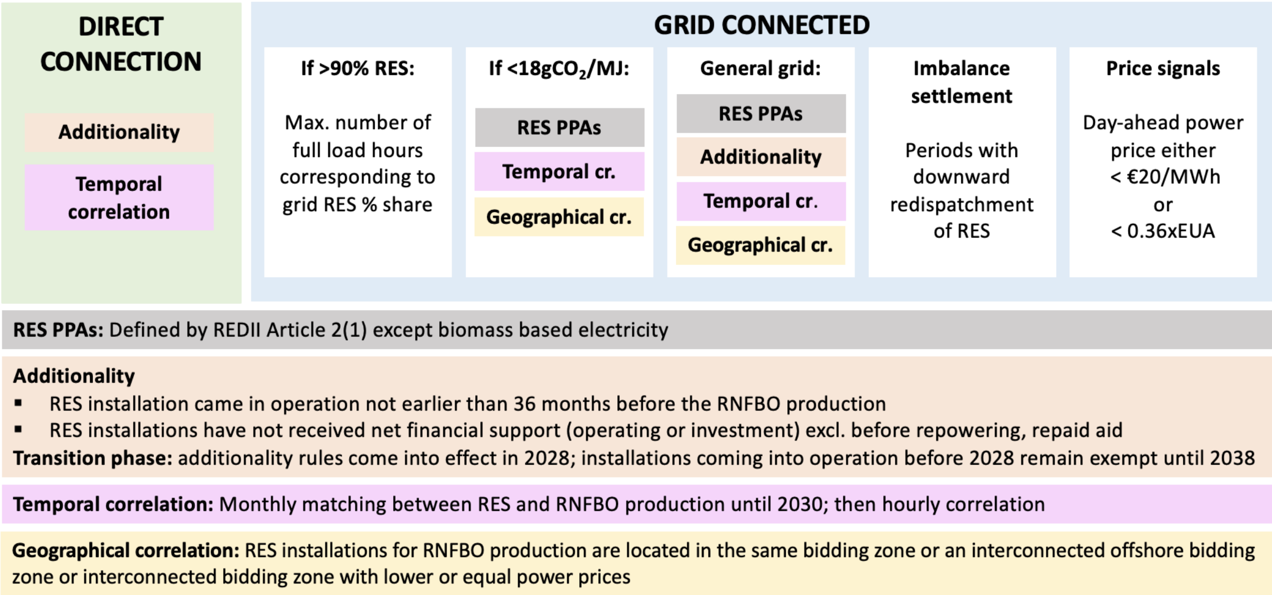

Figure 2 Overview of the European Commission's DA on RFNBOs

Notes Illustrates under which conditions RNFBOs can be produced with a production facility grid connected or directly connected to the RES generation asset. The requirements are elaborated in the boxes with the same colour. RES generation assets that have benefited from financial support do not comply, this excludes repowering, and financial support for land, and grid connections.
EUA is short for Emissions Allowances traded on the European Union Emissions Trading Scheme (ETS)

Sources (Commission Delegated Regulation C(2023) 1087 Final, 2023) with inspiration from Agora Energiewende.

The European Commission proposal breaks with the current practice of accounting for renewable electricity by increasing the temporal correlation granularity from annual to monthly and hourly.

Obligating RNFBO producers to comply with temporal matching, geographical, and origin requirements will unquestionably impact the operation and economic viability of RNFBO production.
On the one hand, policymakers count on RNFBOs, i.e., electrolytic hydrogen, to reduce GHG emissions contributing to the short- and long-term climate targets, which rely on large-scale investments and deployment. On the other hand, too strict standards could hurt and slow down investments, such trade-off between environmental integrity and economic viability is identified in the literature (Brauer et al., 2022, p. 21; Schlund & Theile, 2022, p. 11). The following subsection will unfold the existing literature on regulating RNFBO production and the potential magnitude of the political dilemma.

2.3 Literature Review: Implications of Regulating RNFBO Production:

Several recent reports and studies have been published assessing the impacts on cost and GHG emissions when imposing temporal, geographical, and/or origin requirements. The studies assess an electrolyser system, disregarding the potential for later processing to synthetic fuels. The recency of the studies highlights the prevailing interest in this topic (Brauer et al., 2022; Perner & Peichert, 2021; Ricks et al., 2023; Ruhnau & Schiele, 2022; Schlund & Theile, 2022; Zeyen et al., 2022). The main findings of the studies will briefly be unfolded in relation to requirements set out by DA, thus, focusing on monthly and hourly correlation, origin and additionality, and geographical dimension. Therefore, an in-depth analysis of similarities and differences will not be provided, as the studies highly differ concerning methodology, historical and geographical settings, RES generation and storage technologies included, system or business economic focus, and last but not least, the number of regulatory dimensions included.

It is challenging to assess the impact on renewable hydrogen when introducing new regulations as only vague estimates of an equilibrium price exist for renewable electrolytic hydrogen since the industry is still in its infancy and no market exists (Schlund & Theile, 2022, p. 2). Though, the U.S. Department of Energy has recently published estimates on the willingness to pay across sectors for renewable hydrogen, highlighting the heterogeneity of such a market (U.S. Department of Energy, 2023, p. 4). Thus, it is difficult to assess the exact impact on the economic viability when constraining the production of RNFBOs and additionally accounts for the potential demand elasticities, which is also why inelastic and fixed demand is often assumed in the literature (Brauer et al., 2022; Ruhnau & Schiele, 2022; Zeyen et al., 2022). By contrast, Ricks et al. (2023, p. 2) model electrolytic hydrogen production in the U.S. when applying temporal matching using a flexible demand but with a high off-take price, taking advantage of the production tax credit introduced in the Inflation Reduction Act. So, most studies identified assume demand as a constant to isolate the production costs in different scenarios, disregarding the economic viability.

The following subsection will uncover how the literature assess the impacts on cost and GHG emissions given different regulatory scenario. It should be emphasised that the literature does not consider the published version of the DA specifically but instead different regulatory scenarios of electrolytic hydrogen and its potential effects.

2.3.1 Production Costs

The Production costs are highly dependent on capital investment costs, variable production costs, and the potential market price of renewable hydrogen, while the variable production costs are highly determined by the electricity price (Glenk & Reichelstein, 2019, p. 219; IEA, 2019, pp. 47–48).

Zeyen et al. (2022, pp. 6–7) investigate combinations of fixed and flexible demand combined with various storage facilities at annual, monthly, and hourly matching showing that the production costs highly depend on the RNFBO installation design, e.g., storage availability and hydrogen demand. The importance of installation design and regulatory context is highlighted by Ricks et al. (2023, p. 12), who find a significantly lower cost premium at hourly matching than Zeyen et al. (2022, p. 10) at seemingly comparable setups. This can be explained by the flexible hydrogen demand, instead of a fixed, and access to Inflation Reduction Act subsidies. This indicates a little opportunity to generalise results across geography, context, and project, given its case-specific nature. However, Zeyen et al. (2022, p. 7) identify a cost premium in almost all cases when going from annual to hourly matching, though this premium can be reduced by over-procuring RES capacity creating an additional profit by selling electricity. This is likewise found by Ricks et al. (2023, p. 11). A cost premium is the percentage or numerical value by which a product's selling price exceeds (or falls short of) a benchmark price.

Brauer et al. (2022), Schlund & Thiele (2022), and Zeyen et al. (2022) downgrade the significance of this cost premium when compared to the environmental benefits and overall uncertainty. While Ruhnau & Schiele (2022, p. 20) argue that strict temporal matching results in over-procurement of RES capacity, which contributes to reducing GHG emissions at the system level, the authors consider this an undue cost burden for hydrogen producers. In general, the literature identifies a cost premium when imposing more granular temporal matching requirements, the highest are found in the strictest case, hourly matching. However, most of the studies downgrade the significance of hourly temporal matching requirements as the impact can be reduced

by over-procuring RES generation capacity and when compared to the associated environmental benefits, though the size of the cost premium highly depends on the off-take profile, if fixed or flexible (Zeyen et al., 2022, pp. 10–11).
Only Brauer et al. (2022) and Zeyen et al. (2022) include monthly matching. Zeyen et al. (2022, p. 8) briefly assess monthly matching in Germany by 2025, finding a slight cost increase of 3-5 pct. at monthly matching relative to annual. Brauer et al. (2022, p. 17) identifies an increase in the cost of around 14 pct., which can be considered a substantial increase.

Brauer et al. (2022, p. 17) find that the spatial dimension can have a significant cost impact if they are only allowed to be located on-site of the RNFBO production, though this is not deemed an issue as the DA allow off-site location.

None of the studies includes the DA's derogations allowing accounting grid electricity as renewable when Day-ahead prices are lower than 20 €/MWh or 0.36 times EUA.

2.3.2 Environmental integrity

The requirement to install additional RES generation capacity to the grid is highlighted as the most critical requirement for reducing the attributional GHG emissions of electrolytic hydrogen production (Brauer et al., 2022; Ricks et al., 2023; Ruhnau & Schiele, 2022; Schlund & Theile, 2022; Zeyen et al., 2022). Further, Ruhnau & Schiele (2022, pp. 22–23) recommend that strict additionality requirements ought to be combined with loose temporal matching requirements to provide flexibility and curb costs. Zeyen et al. (2022) argue to introduce both strict additionality requirements and hourly matching requirements or, alternatively, annual matching with limited capacity factors as long as the grid is dominated by fossil power generation. To recap, the literature finds additionality pivotal to ensuring the high environmental integrity of electrolytic hydrogen, however, different combinations of additionality and temporal matching are identified.

Regarding the attributional GHG emissions from hydrogen production, hourly matching reduces emissions substantially when compared to annual and monthly matching. However, the extent varies between studies as different accounting methods are applied: marginal or average emissions factors, attributional or consequential GHG emissions accounting (Brauer et al., 2022, pp. 19–20; Ricks et al., 2023, p. 12; Ruhnau & Schiele, 2022, p. 20; Zeyen et al., 2022, p. 5). It is important to note about the GHG emissions that the studies use different time horizons, hence, the renewable penetration of the system varies. Schlund and Thiele (2021) model the current power system, whereas Zeyen et al. (2022) model 2025, Brauer et al. (2022) and Ricks et al. (2023) the year 2030. Only Brauer et al. (2022) and Zeyen et al. (2022) assess monthly matching, concluding that monthly matching does not lead to a substantial reduction in GHG emissions by 2025 or 2030 when compared to annual matching and the reductions achieved at hourly matching.

Strict spatial requirements do neither result in beneficial economic nor optimal environmental outcomes (Zeyen et al., 2022, p. 25), the published delegated act is in line with this finding and does not impose strict geographical requirements. Several studies point to hourly matching as desirable in the long term, as it ensures high environmental integrity at a limited cost premium, hence, downplaying the significance of the identified trade-off between economic viability and environmental integrity in the long term (Brauer et al., 2022, pp. 22–23; Ricks et al., 2023, p. 12; Zeyen et al., 2022, p. 12). This is except for Ruhnau & Schiele (2022, pp. 22–23), who argue to relax the temporal matching requirements and instead introduce a strict additionality requirement.

To summarise, the literature finds:

1) Hourly matching leads to an increase in production costs, while its significance is downgraded by most studies and can further be mitigated by over-procuring RES generation capacity. Additionally, monthly matching results in an increase in cost when compared to annual matching, though, only two studies assessed monthly matching.
2) Additionality is identified as the most crucial element to ensure the high environmental integrity of RNFBOs, which the DA requires in most cases.
3) Hourly matching similarly provides a significant reduction in the GHG emission intensity of the end-product. In contrast, monthly matching does not entail a substantial drop when compared to annual matching.
4) Strict geographical correlation does neither result in beneficial economic nor optimal environmental outcomes, which is neither the case in the DA.

Since the studies were published before the publication of the DA, the present thesis will examine the cost impacts of imposing monthly and hourly temporal matching requirements, as monthly matching only was assessed in two studies (Brauer et al., 2022; Zeyen et al., 2022). Further, the two derogations for accounting grid electricity mix as renewable is not considered. Zeyen et al. (2022) and Brauer et al. (2022) optimise the costs on a national level by optimising the RES supply and RNFBO production capacities incl. storage, to meet a defined demand. This approach disregards the heterogeneity of RNFBO production and the varying production setups, as the DA render possible. Thus, it can be of value to assess the impact at various RNFBO setups and further examine the decisions made by RNFBO developers in the light of the DA.

3 Research Design

The European Commission's DA on RNFBOs presents a significant regulatory development in the renewable energy sector. To understand the implications of this act, it is crucial to examine its impact on the production of RNFBOs. Therefore, the research question of this thesis is:

How will the European Commission's delegated act on RNFBOs impact the production of RNFBOs?

By investigating this research question, the aim is to gain insights into the specific changes, challenges, and opportunities that arise from the implementation of the DA. The present thesis will contribute to a comprehensive understanding of the regulatory landscape surrounding RNFBO production, informing stakeholders, policymakers, and industry about the potential effects on production costs and processes and RNFBO production facility setup. The DA not only raises the overarching research question of how it will impact the production of RNFBOs but also introduces two essential subquestions that warrant further investigation:

1. *How can renewable electricity be traced and accounted for on a granular basis, and how will the delegated act impact the design of renewable PPAs for RNFBO production?*
2. *How will the delegated act on RNFBOs impact the production costs and production facility setup?*

Firstly, the report will delve into the first subquestion of how renewable electricity can be traced and accounted for on a granular basis, as well as examine the impact of the delegated act on the design of renewable PPAs concluded by RNFBO producers. This subquestion aims to shed light on the mechanisms and requirements for ensuring transparency and accurate tracking of renewable electricity sources, to enable compliance with the multifaceted requirements imposed by the DA. The first subquestion further aims to improve the understanding of how the delegated act influences the contractual arrangements regarding PPAs between RNFBO producers and electricity suppliers. The research will be based on semi-structured interviews with professionals working with granular renewable energy certificates and developers of RES generation projects and RNFBO production facilities. The insights gained from the designs of renewable PPAs for RNFBO producers will be used as the foundation for RNFBO setups to answer the second subquestion where the impact on cost is assessed.

Secondly, the report will address the second subquestion of how the delegated act on RNFBOs will impact production costs and the design of RNFBO production facilities. This subquestion focuses on the economic and operational aspects of RNFBO production, assessing the potential cost implications resulting from the DA's requirements. Additionally, it aims to explore the potential adjustments and modifications needed in the setup to comply with the DA's provisions. The potential cost impacts are assessed by focusing on the supply side, hence, renewable PPAs as prescribed by the DA, and further the temporality requirements of matching supply and production on a monthly and hourly basis. This is done by using linear optimisation in Excel and drawing on the first analysis's findings. The operation of electrolytic hydrogen production is then simulated using the energy modelling software EnergyPRO to comply with the temporal matching requirements imposed by the DA. The levelized cost of producing one unit of hydrogen was used as a metric to compare the production costs across different RNFBO setups. The reasoning and method are elaborated on in *Chapter 5.4.*

By examining both subquestions, this report will provide a comprehensive analysis of the multifaceted impacts of the DA on the production, setup, and contractual aspects of RNFBOs in the renewable energy sector, thus, enabling to answer the research question of how the DA will impact the production of RNFBOs.

To foster an understanding of the introduction of RNFBOs in the existing energy system, the theoretical framework: *Choice Awareness Thesis* by Lund (2014a) serves to grasp the dimensions of a technology such as electrolysis and conceptualise the challenges of introducing *radical technological changes*. Choice Awareness provides a theoretical perspective helpful to do exactly that. Further, Lund (2014a) argues that technology cannot be understood or interpreted as an isolated entity or artefact but only as part of a context and system, why the present thesis will apply a broader focus by drawing on the multiple constituents defining technology as presented by Lund (2014a). *Choice Awareness* serves as an underlying analytical framework to assess the DA's impact on RNFBOs, which will further be unfolded and discussed in Subsection 8.4, illustrated by the green box in Figure 3.

The design of the present thesis follows a mixed-methods approach by combining both qualitative research in the form of semi-structured interviews and quantitative research in the form of linear optimisation and energy system modelling. The research design is inspired by Creswell's (2009, p. 193) Sequential Exploratory Design, which consists of two phases: a qualitative and then a quantitative. The qualitative data is collected and then analysed, followed by the collection of quantitative data which is then analysed, and lastly, the research is evaluated (Creswell, 2009, p. 195). In the present thesis, the quantitative analysis will build on the findings made from the qualitative research, so the semi-structured interviews together with desk study will be used as the foundation to define the quantitative analysis assessing the DA's impact on cost. This is illustrated in Figure 3.

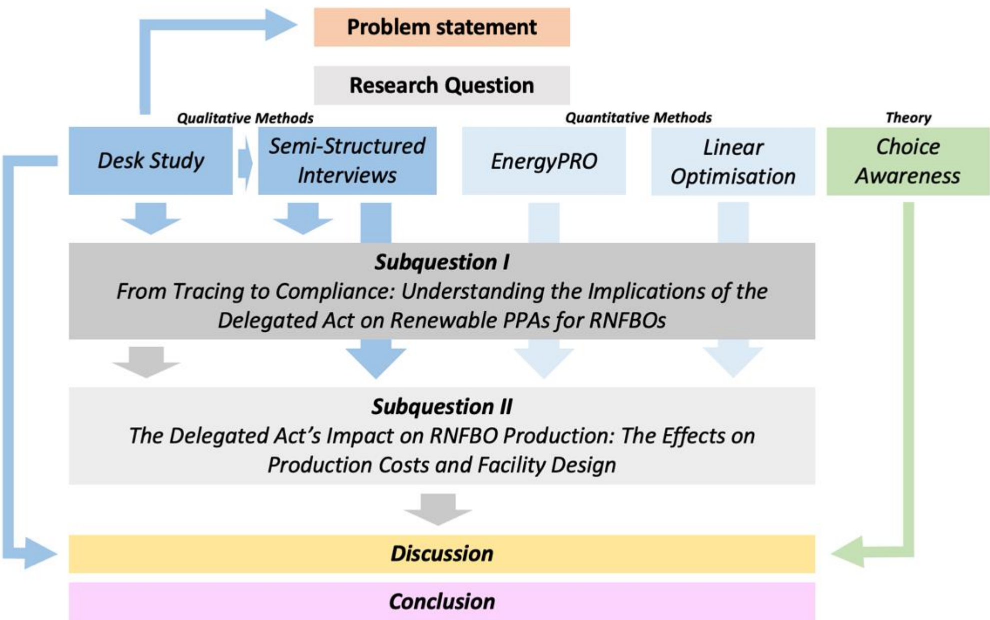

Figure 3 Illustrative Research Design and Application of Theory and Methods

Notes The structure of the report is illustrated together with the connections between the chapters. The figure further shows where the theory and methods are applied.

Source Own figure.

3.1 Theory of Science – Critical Hermeneutic Theory

Critical Hermeneutic Theory provides the foundation for the scientific research in the present thesis. Juul and Pedersen (2012) define Critical Hermeneutic Theory as a critical approach to knowledge creation and the role of science in society.

This is important to state explicitly as the research design and the findings must be interpreted in light of this. Further, being explicit about the foundation increases the reliability and validity of the research, as this helps both the researcher to reflect on their position but also the recipient to understand the origin of the research (Juul & Andersen, 2012). According to critical hermeneutic theory, research is invariably historical and context-dependent; there is no universal truth or interpretation. As a result, the findings will always be constrained and influenced by the historical context (Juul & Andersen, 2012).

The researcher is not an impartial observer removed from society but rather one who is entangled and prejudiced due to information obtained from previous experiences, cultural background etc. (Juul & Pedersen, 2012). Prejudices play an active part in research and should be viewed as a benefit since they allow the researcher to ask pertinent questions and hypothesis (Juul & Pedersen, 2012). Furthermore, research should contribute to society rather than just explain a research object or phenomenon, which is why the initial motivation for this thesis was to uncover the potentially fatal impacts of regulating RNFBO production as claimed by, e.g., industry. The research is further motivated by a sincere desire to contribute to the implementation of the DA, why the present thesis also focuses on the implementation and possibilities for compliance to mitigate GHG emissions. These circumstances have influenced the direction of the present thesis.

4 Theory: Choice Awareness

This chapter will present the theoretical framework of the present thesis. The theoretical perspective provides a systematic approach to a phenomenon, which in this case is the impact of regulating RNFBO production (Creswell, 2009, p. 60). The present thesis will apply the *Choice Awareness Theses* by Lund (2014a) as presented in the book *Renewable energy systems - a smart energy systems approach to the choice and modelling of 100% renewable solutions* published in 2014. *Choice Awareness* consists of several components, though the present thesis will draw on *Radical Technological Change,* how technology can be defined and, further, how radical changes can be analysed. The delimitation from the other components of the theory is due to their limited relevance and application to the present thesis' focus and methodology.

Shifting from an energy system relying solely on fossil fuels and nuclear to renewable energy systems requires changes at all levels of society. Some changes are minor adjustments while some require a fundamental change in not only technology but also existing institutions and organisations (Lund, 2014b). Lund (2014b) presents *Choice Awareness* addressing first how the energy system can be transformed to 100 pct. renewables from a technological perspective, and second how society can implement such radical technological changes (Lund, 2014a, p. 1). Introducing RNFBOs in energy systems requires a technological shift in how hydrogen is produced, shifting from natural gas as the main feedstock to electrolysers using electricity. Furthermore, decarbonising hard-to-abate sectors can also result in technological changes at the end-use, unless the RNFBO can substitute the fossil fuel without major changes e.g., renewable ammonia replacing fossil fuel-based ammonia or e-kerosene replacing Jet A-1 aviation fuel (European Commission, DG ENER, 2023, p. 14). This theory will contribute to understanding how the deployment RNFBOs can be comprehended and how such a technological change must be analysed with respect to the existing energy system and organisational structures. A component of the transition towards 100 pct. renewable-based energy systems.

Lund (2014b, p. 20) defines technology as a combination of five constituents:

1) Technique,
2) Knowledge,
3) Organisation,
4) Products, and
5) Profits.

The five dimensions are essential to consider when analysing a specific technology or changes from one technology to another. Thus, technology cannot be understood or interpreted as an isolated entity or artefact but only as part of a context and system. Lund (2014b, p. 20) argues, that a change in one dimension will lead to changes in at least one of the others and continues, a fundamental technology change cannot happen without changing knowledge and/or organisation, as the initial change will be then be abandoned over time (Lund, 2014b, p. 20). Hence, a radical change is defined as a change affecting more than one dimension.

In the case of RNFBOs, producing electrolytic hydrogen substantially differs from grey hydrogen regarding technology, however, this might not consider a radical technological change from an offtaker's perspective as the product delivered is identical. Yet, it might be regarded as a radical change from an off-taker's perspective if, e.g., the price of the product increase or production flow changes, as the characteristics of the production are substantially different. So, a radical change at production level is not necessarily regarded as a radical change at system level (Lund, 2014b, p. 21).

In the context of RNFBOs, some studies argue that there potentially is a trade-off between environmental integrity and economic feasibility when regulating RNFBOs (Schlund & Theile, 2022, p. 10; Zeyen et al., 2022, p. 12). Imposing requirements of temporality and additionality can potentially slow down the deployment of RNFBO production facilities, thus pointing at several of the constituents of technology. Where a new regulatory framework is needed to deploy RNFBOs, which the DA provides, therefore this can inevitably impact the fifth element, profits. The present thesis aims to increase the level of knowledge regarding the impact of the DA by using the five constituents of technology as a theoretical framework to conceptualise the consequences. In addition, the understanding of radical technological change is helpful to apply when assessing the implementation of the DA and how fuel producers can comply. *Choice Awareness* serves as an underlying analytical framework in the present thesis when assessing the DA's impact on RNFBOs, which will further be unfolded and discussed in Section 8.4.

5 Methodology

The present report applies both quantitative and qualitative methodologies to supplement one another, this is also called a ‘mixed-methods approach’ (Brinkmann & Tanggaard, 2010a, p. 19; Creswell, 2009, p. 188). This chapter aims to display how the applied methods relate to and contribute to answering the research question. This is done by first describing the mixed methods approach followed by unfolding each method. The methods applied in the present thesis are:

1) desk study,
2) semi-structured interview,
3) linear optimisation, and
4) energy system modelling using EnergyPRO.

The desk study and semi-structured are considered qualitative research methods and will primarily contribute to answering the first subquestion: *How can renewable electricity be traced and accounted for on a granular basis, and how will the delegated act impact the design of renewable PPAs for RNFBO production?* While linear optimisation and energy system modelling are considered quantitative research methods and will primarily contribute to the second subquestion: *How will the delegated act on RNFBOs impact the production costs and production facility setup?* The quantitative research will build on the findings made from the qualitative research.

Each method will briefly be described using relevant literature. However, the emphasis is on 1) the selection of the methods, 2) the application of the method and contribution, and 3) the relation to the other methods and a critical reflection of the application. But first, a short introduction to qualitative and quantitative methods, and why a mixed methods approach is considered feasible to examine the research question.

5.1 Mixed Methods - Combining Qualitative and Quantitative Research

Qualitative research can both be considered as a specific epistemological tradition but also as a natural part of a research design and process, hence, it can be seen as an antithesis to quantitative research or more as one of many phases in research (Brinkmann & Tanggaard, 2010b, pp. 18–19). The present thesis does not regard qualitative and quantitative research as antitheses, but as supplementary approaches, hence, the focus is on the methods originating from qualitative research. The qualitative methods applied are desk study and semi-structured interviews to collect and produce empirical data. The desk study contributes to gathering existing literature on the topic, and semi-structured interviews are used to collect empirical data from professionals engaged on the subject.

The qualitative research is supplemented by quantitative analyses to quantify the impact of the DA to build and substantiate the results gained from the qualitative research. The Sequential Exploratory Design applied suits well to initially explore a phenomenon, hence, fits well to RNFBOs as the regulation defining under which conditions a fuel can be defined as an RNFBO, and further, the RNFBO production industry is still in its infancy (Creswell, 2009, p. 195).

The first phase of the research, the qualitative phase, aims to gather an in-depth understanding of the DA, which is expected to impact the strategic and operational decisions made by RNFBO producers. Further, the findings will actively be used to shape the second phase, the quantitative phase, and the RNFBO setups simulated in EnergyPRO. Thereby the qualitative phase substantiates the quantitative research and presumably increases the relevance.

5.2 Desk Study

Early in the research process, a desk study was conducted to identify literature relevant to the research undertaken in the present thesis. The literature review contributed to defining the direction of the present research by identifying gaps in the current literature (Creswell, 2009, p. 41). The literature review was initiated by identifying keywords and searching databases. When key studies were identified, the approach followed the snowball method, using reference lists and literature reviews to identify papers. The literature identified was mainly from the EU taking departure in the leaked and published versions of the DA from the European Commission and a U.S. context focusing on the IRA. The key studies in a European regulatory context are Brauer et al. (2022) and Zeyen et al. (2022) and in a U.S. context; Ricks et al. (2023). The identified literature in a European context was all published before the final publication of the DA on RNFBOs. The identified studies mentioned here and in the literature review Section 2.3 all investigate a stand-alone electrolyser system, disregarding the potential further processing of carbon-based RNFBOs.

Some of the papers were non-academic, hence, not subject to peer-review, this regards Brauer et al. (2022), which is defined as a working paper. Despite this fact, Brauer et al. (2022) are considered valid research from a reliable institution; The Florence School of Regulation.

The desk study contributes to scoping the research and further compares and discusses the present thesis's findings to relevant literature, which takes place in the Section 8.1-8.3.

5.3 Semi-structured Interview

The semi-structured interview was chosen to explore and gain an in-depth understanding of the impacts of the delegated act on RNFBOs from a developer perspective. Since the delegated act was only recently published little research was available on this specific topic, whereas most of it was quantitative assessments of the delegated act on costs and environmental integrity related to the various regulatory aspects. Minimal information was available on how developers of RNFBO production facilities perceived the final version of the delegated act, and how the regulation was mirrored in strategic decisions, RNFBO facility setup, i.e., technology, PPAs structure, compliance. Therefore, the semi-structured interview was chosen to gain knowledge and an understanding of the potential impacts on RNFBO production. Furthermore, the semi-structured interview was deemed useful to understand how RNFBO producers can disclose the needed information to comply with the DA’s provisions. The semi-structured interview is evident when having this objective in mind and will contribute to the examination of the first subquestion in Chapter 6.

The method (the *how*) was chosen after the objective of the present thesis (the *what*) was decided, this specific order of the *how* and *what* is essential when designing the research (Brinkmann & Tanggaard, 2010a, p. 37). That said, the semi-structured interviews played an active part in shaping the direction of the research, as prescribed by hermeneutic epistemology cf. Section 3.1. The research question and sub-questions were drafted before conducting the interviews and were adjusted after finalising the interviews. In this way, there was a clear direction and purpose for each interview, helping to select informants and designing the respective interview guide while enabling the researcher to gain knowledge and new insights throughout the research process. The semi-structured interview does equally will allow the interviewer to test hypotheses and pursue new information during the interview (Brinkmann & Tanggaard, 2010a, p. 38). The desk study was carried out before the interviews to improve the quality of the questions asked, hence, also improving the quality of the empirical data (Brinkmann & Tanggaard, 2010a, p. 37).

The following sub-sections will present how the semi-structured interviews were prepared and conducted, the selection of the informants, and lastly, the processing of empirical data collected.

5.3.1 Selection of Informants

Before contacting informants, it was made clear *what* kind of knowledge was needed to answer the initial research question and sub-questions and identify knowledge gaps in the literature via desk study. Based on this, developers of RNFBO production facilities were deemed essential, as they have first-hand knowledge of the strategic and technological considerations for short and long-term RNFBO production. RNFBO developers could provide relevant knowledge and experiences based on specific projects. To back and substantiate the developers' point of view, an interview was conducted with the consultancy bureau Blue Power Partners to obtain more general considerations based on a broad area of contact of Power-to-X projects. The developers are anonymised with respect to business-sensitive information. Further, as the focus of the present thesis is also on the sourcing of electricity, it was prioritised to contact RNFBO developers with a RES electricity generation portfolio.

Additionally, it was key to gather empirical data on how tracing and accounting RES electricity on a granular basis can be facilitated, as it is a vital part of compliance. Therefore, it was deemed relevant to contact the Danish TSO, Energinet, responsible for issuing the current GOs on electricity and gas. Energinet has moreover carried out a pilot project on hourly RECs in Denmark called *ElOprindelser* (Energinet, n.d.-b). This was supplemented by an interview with an officer from the Danish Energy Agency, the legal authority in Denmark of the Renewable Energy Directive, hence, also RNFBOs. To provide an international perspective, EnergyTag was identified as a critical stakeholder, as it is a prominent, industry-led initiative promoting granular certificates (EnergyTag, n.d.). To summarise, six semi-structured interviews were conducted and are displayed in Table 1.

Table 1 Overview of the Informants – affiliation, position, and alias

Affiliation	Position	Alias
Developer of Power-to-X and renewable power generation assets	Head of Regulatory Affairs Denmark	Developer 1
Developer of Power-to-X and renewable power generation assets	Power-to-X Project Manager and Business Developer	Developer 2
Blue Power Partners	Consultant – Modelling and Data Analyst Power-to-X projects	Blue Power Partners
Energinet (Danish TSO)	Business Developer	Energinet
EnergyTag	Executive Director	EnergyTag
Danish Energy Agency (Legal authority)	Team Leader - Renewable Fuels	Danish Energy Agency

Notes The table provides an overview of the six informants, their affiliation, position, and how they are referred to in the present thesis (alias).

5.3.2 Designing the interview guides

Before the interview, an interview guide was produced and adjusted for the respective interviewee based on the stated purpose of the interview, hence, the interviewees were asked different questions. The complete interview guides can be found in *Appendix I Interview Guides*. To start the interview, the focus of the thesis was introduced to make sure the informant was aware of the context of the interview and the questions. First, the informants were asked to introduce themselves and their position within their respective organisations. Next, the informant was asked their initial thoughts on the delegated act on RNFBOs, followed up with questions on the three aspects of *additionality/origin, geographical, temporal*, and the included derogations in the delegated act. These two questions were used as introductory questions to learn about their initial position on the delegated act and bring potential new information forward. The reasoning was to start with a general and open question to allow the informant to shape the interview (Kvale & Brinkmann, 2009, p. 155).

The questions prepared for the interviews were mainly characterised as open and exploratory questions starting with *what* and *how.* The follow-up questions were mostly stated as specifying or interpretive questions to test the understanding or hypothesis (Kvale & Brinkmann, 2009, pp. 156–157). To wrap up the interview, the informant was asked whether they had anything to add, while it only happened once that the informant had additional information to add relevant to the interview.

5.3.3 Validity and Reliability

Developer 1 and 2 had different positions and expertise within the respective organisations which contributed with different perspectives. For example, the Developer 1 informant was Head of Regulatory Affairs, so the interview was mostly centred around the jurisdictional interpretation of the DA i.e., state aid and PPAs. The outcome of the interview with Developer 2 was different, as the informant was engaged with the development of specific projects and therefore had greater knowledge of the more technical aspects and considerations about RNFBO projects, mainly related to one particular and quite advanced RNFBO project. In addition, the interviewee from Blue Power Partners worked with designing and optimising the business case for Power-to-X facilities. Hence, the informant had detailed knowledge of the technical aspects related to Power-to-X and the supply chain. The BPP interview did not take a point of departure in a specific project but revolved around general considerations when designing RNFBO facilities and the business case in light of the DA. All in all, the three interviews supplemented each other very well, shedding light on the potential impact of the DA from different perspectives both in terms of position and organisation. The broad range of informants strengthens the empirical data's validity, enabling triangulating information and converging several sources of data and information (Creswell, 2009, p. 177). However, because only RNFBO developers from companies with a significant RES generation portfolio were interviewed, it should be noted that the DA may have a different impact on smaller RNFBO developers.

All three informants highlighted, that there is still substantial uncertainty related to assessing the impacts of the delegated act as there are still many unknowns in the jurisdictional interpretation, implementation of the act in national legislation, and due to the early phase in deploying RNFBO production facilities (Appendix II Developer 1; Appendix III Developer 2; Appendix IV BPP). After all, the empirical data gathered through the semi-structured interviews are considered valid and reliable.

5.4 Calculating the Levelized Cost of Producing Electrolytic Hydrogen using Linear Optimisation and Energy System Simulation

The qualitative semi-structured interviews will be followed by a quantitative assessment of the impact of the DA on the costs of producing RNFBOs, and, more specifically, electrolytic hydrogen. The focus in the quantitative evaluation is reduced to focus on electrolytic hydrogen instead of the broader term RNFBOs; this was done to narrow the potential pathways and eliminate the numerous ways of producing RNFBOs. Further, electrolytic hydrogen is a potential end-product and key feedstock for RNFBOs (European Commission, DG ENER, 2023, p. 14).

The quantitative assessment will build on the findings from the interviews, which will be used to shape the quantitative research design actively. This will take place in Section 7.1. The quantitative assessment will be conducted using OpenSolver, a linear optimisation in Microsoft Excel, to identify a cost-optimal and, therefore, likely combination of RES electricity supply to the RNFBO production. The output of this exercise will then be used as an exogenous input in the energy modelling software, EnergyPRO, to simulate the facility's operation under varying regulatory scenarios and RNFBO production setups. The output of EnergyPRO in terms of variable costs of production and production profile will then be processed in Microsoft Excel to identify the exact costs when including investment costs, cost of capital, etc. The following sub-chapter will unfold the exact methods applied, scope, formulas, and finally, the limitations.

Thus, the modelling is performed in two optimisation steps. 1) Identifying the cost-optimal combination of RES technologies to supply the RNFBO production under a set of constraints, and 2) Using the fixed input in EnergyPRO to optimise the production of electrolytic hydrogen, e.g., by optimising against the wholesale electricity market when applying monthly and hourly temporal matching etc., Following these two steps, the technical and economic reports from EnergyPRO is processed in Microsoft Excel. The structure of the sub-chapter will follow the order of application as described.

5.4.1 Linear Optimisation using OpenSolver in Microsoft Excel

The purpose of using linear optimisation is to identify a cost-optimal RES supply for the RNFBOs, increasing the likeliness of the analysed RNFBO setups to reflect the direction of the industry. This was done to substantiate the foundation of the input used in EnergyPRO. Linear optimisation was conducted using OpenSolver, an add-on to Excel, which can solve linear problems and handle a large number of variables (Mason, 2012). OpenSolver was chosen as the preferred software considering time and resources, though more complicated problems can be solved using more sophisticated software, e.g., Python and Gams.

A linear optimisation model comprises an objective function, decision variables, and constraints (Jain, 2022; Mason, 2012). The following will describe each component, and the exact assumptions applied are presented and elaborated later in Table 2 in Subsection 5.4.4

5.4.1.1 Decision Variables

The decision variables are the values being adjusted to identify the optimal combination reaching the desired goal, as determined by the objective function and the constraints. In this case the model has four decision variables, the generation capacities [MW] of onshore wind, offshore wind, and utility PV. They are denoted as $GC_{Onshore}$, $GC_{Offshore}$, and GC_{PV}, with the common denotation is GC_{RES} referring to the sum generation capacity for the three technologies. And lastly, the maximum electrical input of the electrolysis [MW_e] is denoted as $Elec_{cap}$. The resulting production from generation capacity is the sum of the annual production found by using the respective production profiles with hourly resolution that scales with the respective GC_x

This means that the decision variables determine the volume produced by RES, though the time of production is fixed.

5.4.1.2 Objective Function

The objective function refers to the overall objective with linear optimisation, either maximising or minimising a cell by changing the decision variables. In this case, the objective is to minimise the costs associated with producing X volume of RES over a year. Hence, the objective function is defined as:

$$\min(AnnGenCost_{RES} + AnnTransCost + AnnGenCost_{elec})$$

Where, *AnnGenCost* is the total annual costs associated with the generation of renewable electricity comprising the investment costs (CAPEX), fixed operational costs (Fixed OPEX), and variable operation costs (Variable OPEX). The *AnnTransCost* covers the annual costs associated with the transmission of electricity from the point of production to the point of consumption.

The annual costs of electricity generation, *AnnGenCost,* is calculated using the following formulas:

$$AnnGenCost_{RES} = \sum GenCAPEX_{RES} * GC_{RES} + GenFix_{RES} * GC_{RES} + AnnGen_{RES} * GenVar_{RES}$$

Where *GenFix* is the fixed operating costs annually, *AnnGen* is the annual electricity production from the RES technologies determined by the capacity factor (CF_{RES}) and GC_{RES}, and *GenVar* is the variable operating costs of generating one unit of renewable electricity.

$$AnnTranCost = \sum TransTariff_{cons} * AnnCons_{elec} + TransTariff_{prod} * AnnGen_{RES}$$

Where $TransTariff_{cons}$ are the costs of transmission one unit of electricity via the transmission grid and $AnnCons_{elec}$ is the annual power consumption of the electrolysis, meaning that transmissions tariffs are only paid for the electricity consumed. In contrast, the cost of for feeding electricity into the grid covers the entire annual electricity production from the RES units.

The last part of the objective function relates to the costs of converting electricity to hydrogen via electrolysis.

$$AnnGenCost_{elec} = \sum Elec_{cap} * ElecCAPEX + Elec_{Cap} * ElecFix + ElecVAR * AnnCons_{elec} * ElecConv$$

Where $ElecConv$ illustrates the efficiency of the conversion process [kgH_2/MWh electricity], by the hydrogen [kg] produced from one unit of power [MWh], which is deduced from the overall efficiency of the electrolysis. The annual generation costs of hydrogen cover the investment in the electrolysis and fixed and variable operation costs.

5.4.1.3 Supply and consumption constraints

The power generated from the RES generation technologies varies hourly and is determined by the installed generation capacities (GC_{RES}) and the capacity factor of the technologies (CF_{RES}), and need to be constrained in several ways. The constraints ensure that the renewable energy supply is at least 1 TWh/year and that the electricity consumption of the electrolysis process does not exceed the available renewable energy supply. The capacity variables are non-negative.

$AnnGen_{RES} = 1\ TWh$

For example, it is necessary to constrain the model to introduce negative values (<0), the same goes for the capacity of the electrolysis. Thus, the following constraints are added to the model:

$CF_{RES} \geq 0, Elec_{Cap} \geq 0$

Furthermore, it the electrolysis is not allowed to consume more electricity than generated from the RES units in the given period.

$AnnCons_{elec} \leq AnnGen_{RES}$

This is constrained on an annual basis, as the linear optimisation model had limitations and could not include the RES supply and consumption on a more granular basis, e.g., hourly. Therefore, it was impossible to fully identify the most cost-efficient RES capacities when including the electrolysis capacity. That is also why the objective function does not include the revenues from electricity sold at the wholesale market, as this coupling was identified as a non-linear relationship, hence, could not be solved by OpenSolver. The consequences of this limitation are elaborated in the following subsubsection, and further in Section 7.5.

However, it was possible to ensure that the electricity consumption was within the RES generation annually, which was then used as input in EnergyPRO, where it was subject to monthly and hourly matching requirements. Furthermore, a scenario was created simulating a fixed monthly offtake. This was done by constraining the model to produce a minimum of electricity monthly. A flat demand was assumed by dividing 1 TWh/12 = 83.3 GWh/month. Hence the following constraint was applied:

$MonthlyGen_{RES} \geq 83.3\ GWh$

The following sub-sub-chapter will cover the limitations of the designed model.

5.4.1.4 Limitations of the Linear Optimisation Model

First, it is essential to recall the purpose of optimising the RES supply for RNFBO production. The objective is not to identify the most cost-efficient pathway to produce hydrogen by optimising across the entire supply chain but rather to identify a likely RNFBO production setup to examine the impacts on cost from the DA. The created linear optimisation model does that despite its limitations. The most prominent limitation is the inability to fully optimise the RES capacities together with the electrolysis capacity, as the model could not manage to optimise the decision variables when including the actual volume of the produced hydrogen. This is due to the limitations of the applied tool and the non-linear relationship between RES supply and hydrogen production when the consumption is constrained to balance on a monthly and hourly basis. Without being able to make such constraints, the outcome will only show the most cost-efficient source of producing the desired volume of RES electricity. Hence this is determined by the inputs in respect of CAPEX, OPEX, and capacity factor that constitute the levelized electricity cost of the available RES technologies. This limitation is essential to have in mind, though it does not obviate the use of the model nor its output.

5.4.2 Modelling the Operation of the Electrolysis in EnergyPRO

The second optimisation step of the quantitative analysis entails the use of the techno-economical simulation software EnergyPRO.

The energy system modelling software EnergyPRO was used to simulate the functioning of a cost-cutting system. EnergyPRO is a deterministic techno-economic energy project modelling software that can be applied at plant level to optimise the operation of small energy systems (EMD, 2022, p. ix). Simulation of an energy system is defined as the representation of the behaviour of a system given certain conditions (Lund et al., 2017, p. 3). EnergyPRO falls within this category as it minimises cost but within defined conditions. EnergyPRO was chosen because it allows the user to create a customised energy project while also allowing to constrain the operation, hence, applying temporal matching requirements etc. and in addition, provides comprehensive prints of technical and economic data at hourly resolution. The prints are uploaded separately at submission as an Excel file with technical and economical prints with hourly resolution.

In EnergyPRO, the RES generation and electrolysis capacities are fixed exogenously by applying the capacities generated from the linear optimisation in OpenSolver. EnergyPRO then simulates the operation of the electrolysis and the interaction with the wholesale market using hourly resolution with the objective of minimising costs. The model created is displayed in Figure 4.

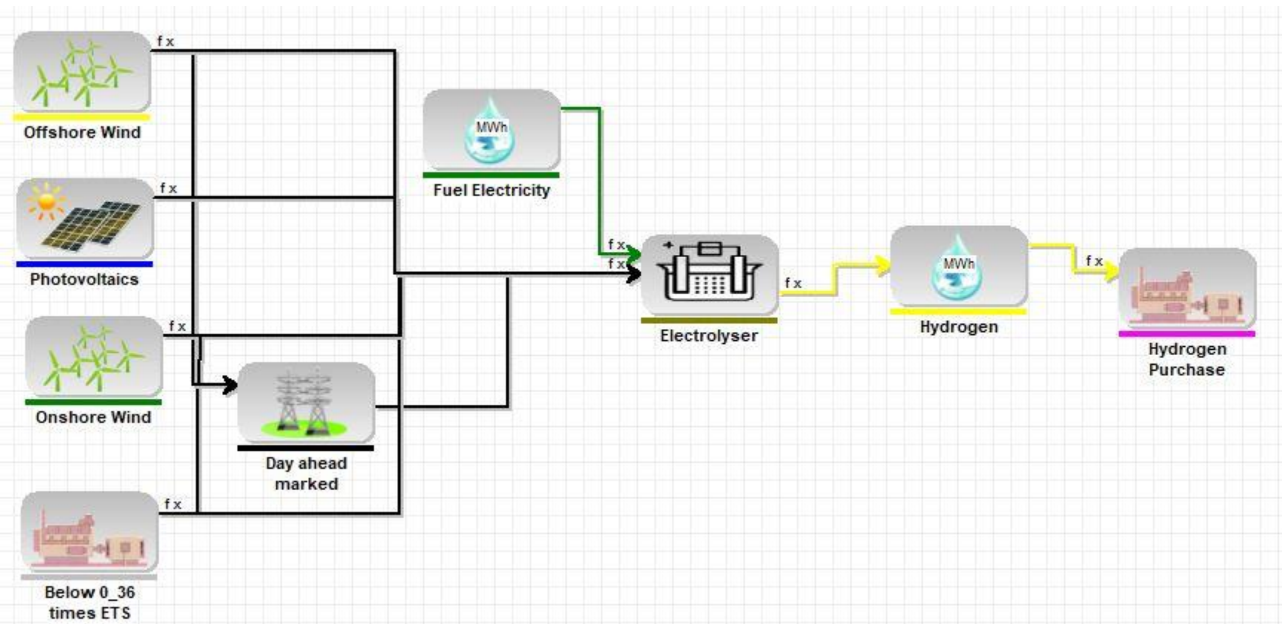

Figure 4 Overview of the EnergyPRO Model

Notes The figure shows the three available RES electricity sources, which can sell the electricity at the Day-Ahead Market or be used directly in the electrolyser. The derogations are added via the production unit Below 0.36xEUA by using a time series adjusted to the electrolyser capacity. The Fuel electricity limits the operation of the electrolyser to not exceed the available RES within defined periods.

Source Own illustration.

The EnergyPRO model was set to utilise the available RES resources within the defined periods of temporal matching; monthly and hourly, while optimising against the Day-ahead prices entered. The model was tweaked to fully utilise the hydrogen production potential, which led the model to produce more hydrogen, risking going beyond the optimal point of production. The consequences of this are discussed in context with the results in Section 7.5.

The EnergyPRO model in the present thesis represents a setup where the RNFBO production is operated in a profit-maximising manner, the model further assumes perfect predictability in prices and RES availability. The aim of simulating the hydrogen production in EnergyPRO is not to identify the one optimal way of producing hydrogen but instead to simulate various setups to explore the impact of the DA in different scenarios and, in this way, better reflect the heterogeneity of the real world's hydrogen projects. This approach is substantially different from energy system optimisation modelling, which is applied in the identified literature (Lund et al., 2017, p. 8).

5.4.2.1 Simulation vs. optimisation

Optimisation is often used synonymously with energy system modelling, where decision variables are computed to either minimise or maximise the defined objective function. However, several modelling approaches exist and Lund et al. (2017) argues that modelling approaches highly vary in method, and theoretical legacy, which need to be explicit as this influence the outcome of the model.

One key difference between optimisation and simulation is the conviction of whether the model itself can identify the single optimal solution. Optimisation models are expected to do so, while simulation models leave it to the user to make such decisions on the basis of various considerations (Lund et al., 2017, p. 5). The user of simulation models will then identify key elements and assess various combinations to substantiate decision-making (Lund et al., 2017, p. 5). Therefore, EnergyPRO is found suitable for the purpose of the present thesis. Energy system simulation fits well with the theoretical framework of Choice Awareness that aims to explore and include multiple scenarios in decision-making and the multiple constituents of technology to substantiate the basis of decision-making and regulation as described earlier in Chapter 3.

The following chapter will unfold how the outputs from the simulated setups are being processed in Microsoft Excel to identify the DA's impact on RNFBO production, followed by the assumptions made in the assessment.

5.4.3 Calculating the Levelized Cost of Hydrogen

To compare the performance across scenarios, it can be useful to identify a metric to do so. Here the tool Levelized Cost of Electricity (LCOE) was identified as a useful metric. LCOE yields a break-even value for investing in an electricity production system, hence, enabling comparing the costs of electricity generation across technologies, plant configurations, etc. (IEA et al., 2020, p. 33). In the case of hydrogen production, the metric is Levelized Cost of Hydrogen, denoted LCOH, expressing the economic costs of producing one unit of hydrogen [kgH_2] under various conditions. In this context, it is important to emphasise that LCOE/LCOH is not a complete metric, as it entails multiple limitations to note when applying the metric (IEA et al., 2020, pp. 33–34). The LCOH does neither reflect the true costs of energy production from a business nor socio-economical perspective, as it leaves out externalities and investment-specific conditions, though it can be adjusted to be included in decision-making. Though, this is not the original purpose of the tool (IEA et al., 2020, pp. 33–34).

The methodology of calculating the LCOH will first be illustrated, followed by each of the components of the equation. The approach follows the International Energy Agency et al. (2020, pp. 34–35)

The LCOH-equation express the equality between the present value of all discounted costs and revenues over the lifetime of the plant divided by the total electricity generated in the lifetime. The LCOH is expressed by the following equation:

$$LCOH = \frac{\sum(LCOE_{RES}*Gen_{RES}+GenCAPEX_{elec}+GenFix_{elec}+GenVar_{elec}+TransCost+MarExp-MarRev)*(1+r)^{-t}}{\sum Gen_{H2}*k}$$

Starting with the denominator, the produced volume of hydrogen is assumed to be stable throughout the investigation period, why this is calculated by the following equation.

$$Gen_{H2} = AnnCons_{Elec} * ElecConv$$

So, the annual volume of consumed electricity by the electrolysis times the conversion efficiency. Moving on to the more extensive numerator of the LCOH equation. Though it seems complicated, the numerator represents the sum of present value each year, denoted as *t,* taking into consideration the CAPEX of RES and electrolysis, fixed and variable OPEX, transmission costs, and the expenses and revenues from the electricity wholesale market. Let us start from the left. The LCOE term is also applied for the RES generation units to allow annualising the costs. Annualising costs divide the investment costs over the investigation period while considering the various technical lifetimes of the technologies, which returns the periodic payment for annuity (PMT formula in Excel). The annuity approach and formula follow the guidelines set out by the Danish Energy Agency (2021, p. 19). So first, the investment costs need to be annualised for the RES technologies.

$$PMT_{RES} = \frac{r}{1-(1+r)^{-L_{RES}}} GenCAPEX_{RES} + GenFix_{RES}$$

Where r is the discount rate or, in this case, the cost of capital (WACC). L_{RES} is the technical lifetime of the RES plant, where the latter of the equation represents the investments cost. Then finally, the fixed OPEX is added to the annuity.

This enables calculating the LCOE for the RES technologies.

$$LCOE_{RES} = \frac{PMT_{RES} + GenVar_{RES}}{(CF_{RES}) * 8760}$$

So, the variable operating costs are added to the annuity of the RES technology, then this is divided by the annual electricity production, calculated as a product of the capacity factor (CF_{RES}) of the technology and number of hours in a year.

Now the LCOE can be identified by each technology, making it easy to include in every year of the investigation period. Moving to the right on the numerator in the LCOH equation. Then the CAPEX and fixed and variable OPEX for the electrolysis is added, followed by the transmission tariffs for the consumed electricity and the feed-in tariffs for produced electricity covered under $TransCost$. The expenses associated with buying electricity at the wholesale market are added, and finally, the revenues from selling at the wholesale market are subtracted. Finally, the costs and revenues are discounted by adding the following to the equation to identify the present value of the expenses and revenues in the numerator:

$(1 + r)^{-t}$

Where r is the discount rate corresponding to the cost of capital in year *t*.

The following sub-chapter will unfold the assumptions that are used as input in the equations.

5.4.4 Assumptions

Table 2 displays the critical assumptions for the analyses conducted. The key assumptions will be elaborated below the table and additional context and information for the figures.

Table 2 Key Assumptions

Symbol	Type	Unit	Value	Source
k	Investigation period	Years	20	(Energistyrelsen, 2022a, p. 14)
r	Cost of Capital	% p.a.	5	Mean (IRENA, 2023)
	The price of emissions allowances (EUA) traded on the ETS	€/tonnes CO_2	118	(Energistyrelsen, 2023a)

Symbol	Technology	Type	Unit	Value	Source
$L_{Offshore}$	Offshore Wind	Technical Lifetime	Years	30	(Energistyrelsen, 2022b)
$GenCAPEX_{Offshore}$	Offshore Wind	CAPEX	€/kW	1,800	(Energistyrelsen, 2022b)
$GenFix_{Offshore}$	Offshore Wind	Fixed OPEX	€/kW/Year	39	(Energistyrelsen, 2022b)
$GenVar_{Offshore}$	Offshore Wind	Variable OPEX	€/kWh	0.00389	(Energistyrelsen, 2022b)
$CF_{Offshore}$	Offshore Wind	Capacity Factor		0.45	Calculated
$L_{Onshore}$	Photovoltaics	Technical Lifetime	Years	40	(Energistyrelsen, 2022b)
$GenCAPEX_{PV}$	Photovoltaics	CAPEX	€/kW	380	(Energistyrelsen, 2022b)
$GenFix_{PV}$	Photovoltaics	Fixed OPEX	€/kW/Year	9,5	(Energistyrelsen, 2022b)
$GenVar_{PV}$	Photovoltaics	Variable OPEX	€/kWh	0	(Energistyrelsen, 2022b)
CF_{PV}	Photovoltaics	Capacity Factor		0.13	Calculated
$L_{Onshore}$	Onshore Wind	Technical Lifetime	Years	30	(Energistyrelsen, 2022b)
$GenCAPEX_{Onshore}$	Onshore Wind	CAPEX	€/kW	1,040	(Energistyrelsen, 2022b)
$GenFix_{Onshore}$	Onshore Wind	Fixed OPEX	€/kW/Year	12.6	(Energistyrelsen, 2022b)
$GenVar_{Onshore}$	Onshore Wind	Variable OPEX	€/kWh	0.0014	(Energistyrelsen, 2022b)
$CF_{Onshore}$	Onshore Wind	Capacity Factor		0.40	Calculated
$ElecCAPEX$	Electrolyser	CAPEX	€/kWe	432	(Glenk et al., 2023, p. 43)
$ElecFix$	Electrolyser	Fixed OPEX	€/kW/year	8.19	(Glenk et al., 2023, p. 43)
$ElecVar$	Electrolyser	Variable OPEX	€/kgH_2	0.073*	(Christensen, 2020)
L_{elec}	Electrolyser	Technical lifetime	Years	20**	(IEA, 2019)
	Electrolyser	Efficiency (Lower heating value)	%	68	(Danish Energy Agency, 2021, p. 86; Glenk et al., 2023, p. 43; IEA, 2019)
	Electrolyser	Energy to compress hydrogen (30-150 bar)	kWh/kgH_2	0.399	(Christensen, 2020, p. 19)
$ElecConv$	Electrolyser	Hydrogen per unit electricity	kgH_2/MWh	19.85	Deduced using the efficiency (LHV) and compression

Included in $ElecVar$	Hydrogen compression	CAPEX	€/kgH_2	0.14	Mean from Christensen (2020, p. 19)
$TransTariff_{cons}$	Transmission	Tariffs	EUR/MWh	16.67	(Energistyrelsen, 2022a)
$TransTariff_{prod}$	Transmission	Feed-in tariffs	EUR/MWh	0.56	(Energinet, 2023)

Notes *Covers water consumption.
**The stack lifetime is set to 95,000 full load hours, translating to approx. 20 years with a capacity factor of around 0.55.

Source The sources appear in the last column.

The temporal scope of the analyses is 2030, so the CAPEX and OPEX are based on the expected learning curves of the respective technologies up until 2030, which gives rise to uncertainty. The year 2030 is chosen, as the temporal correlation shifts to hourly by 1st January 2030 is why it was considered relevant to use 2030 data in both cases (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 6). The investigation period is set to 20 years, aligning with the Danish Energy Agency guidelines. Still, the models do not include any indexation or learning curves, as the expenses and revenues from 2030 to 2050 are discounted to the present value of 2030. The Cost of Capital 2 (denoted CoC) defines the discount rate.

5.4.4.1 Cost of Capital

The CoC is set at five pct. p.a. deduced from IRENA's Cost of Capital for Renewable Energy Projects report. The five pct. p.a. is the mean identified for RES generation projects in Europe (IRENA, 2023, p. 4). The CoC is related to the commercialisation state of the technology and varies between RES technologies and geographical context (IRENA, 2023). The Cost of Capital can be a decisive factor in whether an energy project is feasible. In some cases, the cost of capital can constitute 20-50 pct. of the LCOE, as seen with some utility solar projects (IEA, 2021). The ICCT uses a CoC of 7 pct., arguing that it can reasonably be higher due to the commercialisation state of large-scale electrolyser systems (Christensen, 2020, p. 21). Hence, it could be argued that a higher CoC would better reflect the current state and further differentiate the CoC on the technologies by their technological readiness (IRENA, 2023). A higher CoC would increase the cost of RNFBOs across all setups assessed and could potentially favour setups with a higher share of investment costs relative to setups with a higher share of variable expenses/revenues.

5.4.4.2 Electrolyser System and RES Electricity Supply

The electrolyser system utilises the alkaline technology as the technology currently has the highest installed capacity and the lowest average system prices (Glenk et al., 2023, p. 3). The atmospheric alkaline version is applied with a system outlet pressure between 30-150 bar to allow injection in pipeline (Christensen, 2020, p. 18; IRENA, 2020, p. 38). The conversion efficiency from power to hydrogen is slightly lower for the alkaline technology compared to the Polymer Electrolyte Membrane (PEM) by 2030 (Glenk et al., 2023, pp. 7–8). The conversion efficiency is assumed to be 68 pct. by 2030, a mean from the range expected by the IEA (2019, p. 45). Similar efficiency is expected by Glenk et al. (2023, p. 7). Further, the efficiency is assumed to be constant, so disregarding the load, though this is not the case in reality (IRENA, 2020, p. 45). The electrolysis is constrained to a minimum load of 10 pct. (IEA, 2019, p. 43).

The electrolyser system is operated as a stand-alone system, disregarding the potential further processing of the electrolytic hydrogen to synthetic fuels. Furthermore, the electrolyser system is assumed to be connected to the transmission grid. Hence, transmission tariffs must be paid for the power consumed from the transmission grid and feed-in tariffs for electricity fed into the transmission grid.

The electricity prices in 2030 are obtained from the dataset provided by Danish Energy Agency's *Analyseforudsætninger til Energinet 2022,* which includes Day-ahead spot prices from the bidding-zones DK1 and DK2 with hourly resolution (Energistyrelsen, 2023a). The present thesis applies the Day-ahead spot prices from DK1. The electricity prices are simulated using the weather year 2014. Since the dataset does not include any hours with negative Day-ahead prices, the derogation included in the DA on reducing RES generation curtailment is not included in the model.

The capacity factors for the RES electricity generation technologies are calculated using EnergyPRO by simulating the production profiles with hourly resolution. The weather data from 2014 was chosen in EnergyPRO, and the power curves from a 5 MW onshore and 10 MW offshore turbine were added. The power curves were obtained via National Renewable Energy Laboratory (NREL, 2017, 2019). For photovoltaics, an example enclosed with EnergyPRO was used.
As no publicly available information is available on PPA tariffs, therefore the LCOE of the RES technologies was used as a PPA tariff, following a similar approach as Christensen (2020, p. 4) and Jain (2022, p. 6). The LCOE for each technology was calculated using the approach unfolded earlier in Subsection 5.4.3.

A fixed demand was set as a constraint to the model to identify the most cost-efficient supply using linear optimisation. The annual RES electricity supply was set a 1 TWh to reach RES generation and electrolysis capacities on the level of the ones announced by the year 2030 (Brintbranchen, 2023b). Optimising against a fixed offtake, annually or monthly, has some limitations compared to optimising the production using a market price. However, as there is no established market for RNFBOs nor renewable electrolytic hydrogen, a fixed demand is defined in the linear optimisation model, which is also used in the EnergyPRO models (Zeyen et al., 2022, p. 10). The approach is similar to the one of Zeyen et al. (2022, p. 3), and Brauer et al. (2022, p. 10).

6 From Tracing to Compliance: Understanding the Implications of the Delegated Act on Renewable Power Purchase Agreements for RNFBOs

To grasp the DA's impact on RNFBO production, it is instructive first to assess how the requirements can be met and then how the DA influences decisions regarding RES electricity supply for RNFBO facilities. To evaluate these perspectives, the first sub-question is worded as follows:

How can renewable electricity be traced and accounted for on a granular basis, and how will the delegated act impact the design of renewable PPAs for RNFBO production?

The subquestion consists of two parts, whereas the former enables the latter. First, it is essential to examine how granular accounting of renewable electricity can be enabled and done in practice by drawing on experiences from the Danish TSO, Energinet, and interviews with Energinet and EnergyTag on granular GOs. Second, the analysis will demonstrate how the GOs and PPAs can play a key role in RNFBO compliance and, further, how the two concepts are interlinked. This will be examined by first exploring the common structures and types of PPAs based on the literature and then using the empirical data gathered via interviews with developers and Blue Power Partners (BPP) to assess the impact of the DA on PPAs signed by RNFBO producers. Lastly, the key findings will be summarised.

It is important to note that the regulatory requirements differ in time and place. The present analysis will consider a situation where the requirements on temporality, origin, additionality, and geography are valid.

Two things need to be established before unfolding the potential role of GOs concerning RNFBOs. First, the legislative connection between RNFBOs, GOs and PPAs, and second recalling the concept of bundled and unbundled GOs as introduced in Section 2.1.

The DA impose RNFBO producers with grid-connected assets to conclude PPAs, that generate a volume equal to the volume consumed from the grid, balanced within the temporal correlation period: monthly before 2030, and hereafter hourly (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 4, 6). Further, the DA explicitly refer to GOs in recital 15, stating that REDII (Article 19) ensures that renewable electricity is not claimed twice, both by the renewable electricity producer and the producer of RNFBOs, because the renewable electricity producer is mandated to cancel the GOs when issued (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Recital 15). Thus, GOs combined with PPAs can play a role in accounting for and tracing renewable electricity used in RNFBO facilities. Therefore, it is evident to examine the state of the current GO framework, what role GOs can play and, further, identify possible shortcomings for complying with the provisions in the DA.

Second, when producing renewable electricity, two products are concurrently produced: The electricity and the GO, which can both be sold on the wholesale market either jointly (bundled) or separately (unbundled). The electron can be sold ex-ante, so before the time of production, on the forward market, on the Day-Ahead Market, or Intra-Day, while the renewable attribute (the GO) can be sold ex-post up to 12 months after the point of production. The buyer of the GO can claim the renewable attribute of the electricity.

The following subsection will examine the state of the current legislation in place and assess the fitness for DA compliance.

6.1 Granular Renewable Energy Certificates: Guarantees of Origin

REDII's Article 19(7a-d) specifies the information that must be disclosed when renewable electricity producers issue GOs (*Renewable Energy Directive 2018/2001*, 2018). Worth highlighting concerning the DA is five attributes (in bold), followed by a remark on their relevance:

1. **Time of production:** To meet the temporality requirements: monthly or hourly temporal correlation. Granular GOs will assist with this.
2. **Location of production:** Ensure the electricity is produced in the same or an interconnected bidding zone or interconnected offshore bidding zone. If sourced from an interconnected bidding-zone additional information must be disclosed showing that the spot price was higher in the zone of the RES generation asset; how to determine this is unclear.
3. **Generation technology (origin):** Ensure the electricity is generated from RES, as defined in REDII Article 2(1), except for biomass-based electricity cf. Article 2(3) (*Commission Delegated Regulation C(2023) 1087 Final*, 2023)
4. **Received investment support:** Ensure that the RES electricity generation asset has not received support in the form of operating or investment aid.
5. **The date on which the installation became operational:** If additionality is required, this information is relevant to ensure the RES plant came into operation within 36 months before the RNFBO production facility.

Accordingly, the current GO scheme can, to a great extent, provide the information needed to comply with the DA, though some adjustments are required. For example, the standard size of a GO is defined as 1 MWh, which complicates hourly matching, as it is necessary to allow issuing and claiming more granular GOs to enable hourly matching (*Renewable Energy Directive 2018/2001*, 2018, Article 19(2); Appendix V EnergyTag). Meaning that GOs smaller than 1 MWh can be issued, e.g., 1 kWh and in addition, increased temporal granularity to allow an hourly time interval, as a minimum, of consumption to be linked with the corresponding time interval of production (EnergyTag, 2021, p. 6). Further, it must be clear when the GO is issued (time of production) by the RES electricity producer and claimed by the RNFBO producer (cancelled). The issued and claimed GO volumes must match monthly or hourly to comply with the temporal correlation provisions.

EnergyTag expects the revised RED(III) to remove the regulatory barriers and open the door for granular GOs (Appendix V EnergyTag). However, reservations should be expressed because the REDIII has yet to be adopted before the submission deadline.

Regarding additionality, GOs do not ensure the installation is additional capacity as described earlier in Section 2.1. That is why PPAs are introduced in the DA *"as a suitable tool to incentivise the deployment of new renewable electricity generation capacity"* ((*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Recital 9). This is backed by Energinet, who states that PPAs incentivise additionality, but ultimately the additionality is ensured by compliance with the 36 months cut-off. The 36-month cut-off date has been introduced to ensure PPAs are concluded with relatively new RES generation assets, which can be demonstrated by the PPA and/or GO.

GOs serve as the accounting framework for the production and consumption of renewable electricity to comply with the requirements, why PPAs and GOs are needed in combination to comply with the RNFBO standards (Appendix VI Energinet). This means that the GOs claimed by the RNFBO producer must be bundled, otherwise, the RNFBO producer cannot meet the origin nor additionality requirements.

To summarise, the current GO scheme does already, to a great extent, provide the information needed to comply with the DA, which is also illustrated by the green boxes in Table 3. However, adjustments are required and are expected to come with the revised RED. This mainly concerns the granularity of the GOs, hence, the box on temporality is marked yellow. GOs account for and trace the renewable electricity concluded via PPAs to ensure the valid requirements on temporality, geography, origin, and to some extent, the aspect of additionality is met. Table 3 further illustrates that both PPAs and GOs are needed to provide the required information and that some questions still need to be answered regarding financial aid.

Table 3 Potential compliance roles for GOs and PPAs

	GO	PPA
Origin	Reveal information of generation technology	A PPA contract with specific renewable electricity generation assets
Temporality	Issuance and cancelling of GOs need to be matched. GOs can thus assist this.	
Geography	Reveal information on point of production	Reveal the location of the RES generation asset. Need to be consistent with the GO
Additionality	Date the asset came online	A PPA contract with specific renewable electricity generation assets
Financial aid	Reveal if the RES generation asset has received financial aid, however additional information is needed to show it has been repaid	Potentially provide information of repaid financial aid
Account grid-electricity fully renewable	Metering data is needed to reveal the time of consumption combined with data on the EUA price or spot price at time of consumption	

Notes Green indicates that GOs or PPAs can help provide the information needed to comply with the requirements listed in the first column. Yellow means that it can potentially provide the required information, and red indicates that it is not able to provide the needed information.

The following subsection will showcase a prototype of a granular certification scheme developed by the Danish TSO, Energinet.

6.1.1 Developing a scheme for granular energy certificates

The Danish TSO, Energinet, is the issuing body for GOs on gas and electricity and has developed a platform for granular certification called Energy Origins as part of Project Energy Origin (Energinet, n.d.-a; Appendix VI Energinet).

The prototype of Energy Origins is a web-based platform for producers and consumers of renewable electricity. The platform allows companies to participate by connecting specific meter points for electricity consumption (Appendix VI Energinet). The platform can provide the data needed to comply with temporal matching requirements by tracking the correlation between supply and consumption at hourly resolution and the issuance and cancelling of GOs. However, additional communication is needed between the RES producer and RNFBO producer to schedule production ahead (Appendix VI Energinet). Furthermore, it is pivotal that a future granular GO scheme must be integrated with the current GO scheme to avoid double counting and creating to separate systems (Appendix VI Energinet). The informant stated that the barriers identified are not related to the granularity but related to the safety and reliability of the platform, which aligns with the claims made by EnergyTag (Appendix VI Energinet; Appendix V EnergyTag). This suggests that if the regulatory framework allows issuing granular GOs, a scheme can be developed, enabling temporal matching.

As GOs can only serve as the accounting and tracking scheme for the electricity supplied by PPAs, PPAs play a key role in compliance. Therefore, the following section will examine the common types and structures of PPAs, and how the DA will impact the design of PPAs for RNFBO production.

6.2 Power Purchase Agreements

Industrial and corporate PPAs are not a new phenomenon, yet the requirements introduced in the DA do make PPAs for RNFBOs stand out from the current standard PPA. A PPA is a performance-based contract that serves to share risks between seller and buyer, and by mitigating investment and financing risks, it can help deploy more renewable generation capacity (Mendicino et al., 2019, p. 1). A PPA can be structured differently depending on the location of the RES generation asset and the offtaker of the electricity, as well as its financial structure. As stated in Section 2.1, standard corporate PPAs do not consider the temporal generation details of the assets as they are balanced on an annual basis, aligning with the corporate GHG scope 2 standards in the GHG Protocol. To reduce scope 2 GHG emissions the company can settle with unbundled GOs and still claim the renewable attributes in the GHG inventory. This is not the case for RNFBO producers, as the DA set out several standards for sourcing grid electricity to allow claiming the end-product as renewable.

The DA is explicit on grid-sourced electricity, which can be claimed renewable by concluding PPAs:

"Fuel producers have concluded directly, or via intermediaries, one or more renewables power purchase agreements with economic operators producing renewable electricity in one or more installations generating renewable electricity for an amount that is at least equivalent to the amount of electricity that is claimed as fully renewable and the electricity claimed is effectively produced in this or these installations"
- (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 4(2a))

In the context of PPAs, attention should be drawn to the underlined sentences stating that the amount of electricity claimed renewable and sourced from the grid electricity must not exceed the volume effectively generated by the contracted RES PPA assets. Article 6 on temporal correlation specifies the periods in which the volumes must be balanced: Monthly before 2030 and hereafter hourly.

The provisions in the DA defining the compliant renewable generation technologies, first of all, exclude biomass-based electricity and can further leave out other RES generation technologies relying on financial support. Therefore, onshore wind, offshore wind, and utility-scale PVs are regarded as the most relevant RES technologies to include in the present thesis.

At a general level, a PPA for industrial or corporate users is structured to satisfy the energy needs of one or more customers (i.e., offtaker or buyer) which is usually delivered using the grid. The contract is an agreement between an energy consumer (buyer) and producer (seller) (Mendicino et al., 2019). The terms of the PPA are often pre-established, defining e.g., contractual length, price, volume, and point and times of delivery (Mendicino et al., 2019, p. 2). The price structure can be either fixed or tied to e.g. the sport market price with a fixed floor, with many variations of both structures (Mendicino et al., 2019, p. 3). The contractual length is usually 10 years or more (Mendicino et al., 2019, p. 3). The volume is often matched at an annual level and aligned with the Corporate GHG Protocol Scope 2 guidance, though, some movement is identified towards increasing the correlation between time of production and consumption under the name '24/7 Carbon-Free Energy', which aims at balancing production and consumption every single hour during the year (Miller, 2020). Further, depending on the structure of the PPA the contract can specify volumes delivered at specific times or time ranges, e.g., set volume delivered monthly.

The following subsection will elaborate on the three main types of PPAs, and how they satisfy the standards set out by the DA by drawing on literature and the interviews conducted.

6.2.1 Three Main Types of Power Purchase Agreements

There are three main varieties of corporate PPAs; Behind-the-meter Physical and Virtual as illustrated in Figure 5. Figure 5 further illustrates how they differ in terms of financial structure and the relative location of the point of production and consumption. The following paragraphs will unfold the differences.

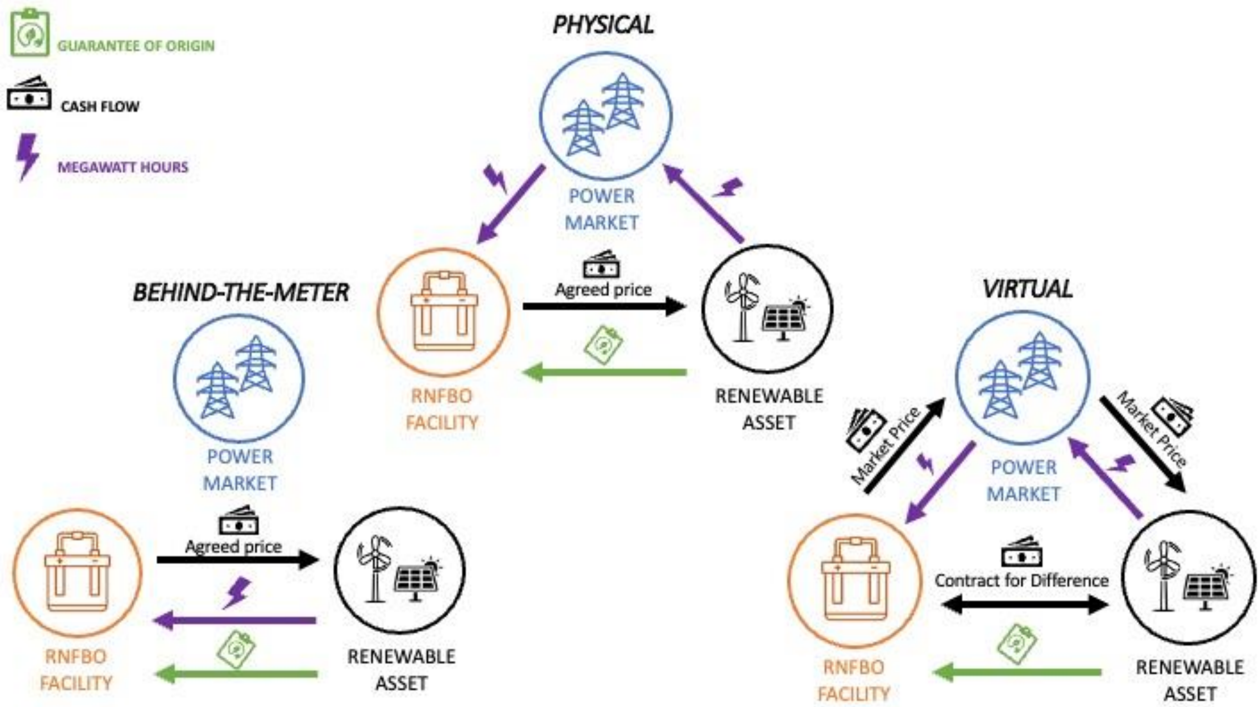

Figure 5 Three Main Types of Power Purchase Agreements

Notes It is important to note, that although the virtual and physical PPA looks similar in terms of transferring the RES electricity, the RES asset and RNFBO facility are not connected to the same grid.

Source Own illustration

6.2.1.1 *Behind-the-Meter*

The renewable generation plant is physically connected to the RNFBO production facility, hence, the name Behind-the-meter (hereafter BTM), see Figure 5. Examples of this can be an RNFBO production facility located on-site with a utility-scale PV plant or onshore wind turbine(s), or even offshore wind turbine(s). With a BTM PPA, the renewable attribute of the electricity is transferred to the offtaker (bundled), who can then disclose them in their GHG inventory. However, the GO can potentially be sold on the European GO market (unbundled). A BTM setup requires that the additionality and temporality requirements are met (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 3). Using a BTM setup, the producer and offtaker avoid paying tariffs related to the transportation of the power from the point of generation to the point of consumption. However, the offtaker's load profile is unlikely to be matched exactly by the seller's production profile, as the buyer has to buy the remaining electricity on the wholesale market. The seller cannot sell the excess electricity on the spot market if no grid connection is deployed (Mendicino et al., 2019, p. 4).

This fact does not make BTM setups irrelevant, as multiple RNFBO projects are being announced with direct-connection to a RES generation plant (European Energy, 2023; Ørsted, 2021; Appendix V EnergyTag; Appendix III Developer 2). Developer 1 backed this tendency and argued that a BTM setup supplemented by grid-sourced electricity is desirable from a developer perspective, as this gives a high level of control of the electricity sourced (Appendix II Developer 1).

6.2.1.2 Physical

A physical PPA (see mid-figure 5) involves a grid connection contrary to the BTM PPA, as the RES generation facility and RNFBO facility is located off-site but are connected to the same grid. A physical PPA can vary in setup regarding how the electricity is supplied to the buyer. It can further involve an intermediary balancing party, usually a utility company functioning as the supplier of the actual electricity (Mendicino et al., 2019, p. 4). The utility delivers the electricity to the buyer and manages bills, the potential mismatches between supply and demand caused by the intermittent nature of variable RES. The utility then receives a sleeving fee for providing these services, which is why a physical PPA is also referred to as a 'sleeved PPA' in the literature (LDES Council & McKinsey, 2022, p. viii; Mendicino et al., 2019, p. 4). Whether an intermediary is needed also depends on the structure of the PPA.

The electricity is sold at a fixed price, which can be indexed or includes a fixed floor. The GO is transferred to the buyer with the electricity, making it a bundled GO.

6.2.1.3 Virtual

Finally, the 'virtual PPA' is structured similarly to the physical PPA, though it is a pure financial structure as the buyer doesn't take possession of the electricity (LDES Council & McKinsey, 2022; Mendicino et al., 2019, p. 5). Hence, the generator and buyer do not need to be connected to the same grid. The electricity generated is sold directly on the wholesale market, and the buyer buys electricity from the wholesale market immediately or when needed (Tang & Zhang, 2019, pp. 2–3). A virtual PPA is a financial contract. The GOs are transferred to the buyer, though it is an unbundled GO because it is separated from the electron consumed by the buyer.

Virtual PPAs are generally structured using a Contract for Difference (denoted CfD) (Tang & Zhang, 2019, p. 2). A CfD is a financial derivate settled between two commercial entities and is well known in commodity markets, helping to hedge against volatile prices to create price stability and predictability (Schlecht et al., 2023, p. 2). The payment between the two entities is calculated as the difference between the pre-agreed level (strike price) and the spot price multiplied by electricity produced by a specific RES asset (see Figure 6). If the spot price exceeds the strike price, the RES supplier pays the difference, and contrary, if the spot price is lower than the strike price, the offtaker pays the strike price. This can be settled on, e.g., hourly or monthly (Schlecht et al., 2023, p. 2). The physical PPA can structure the pricing using a CfD if desired.

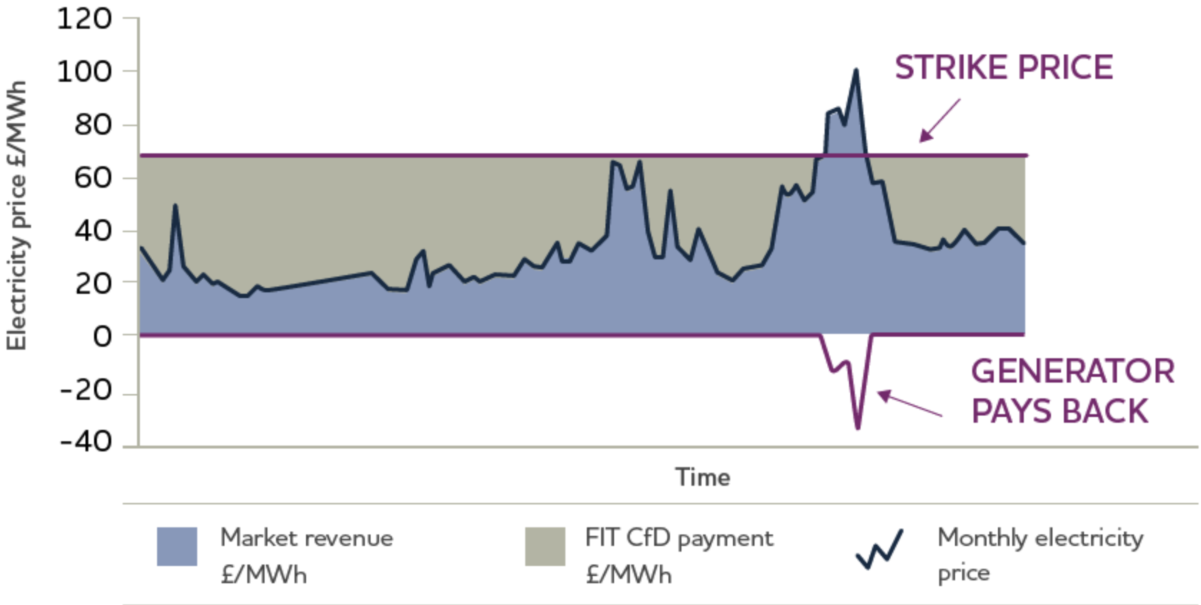

Figure 6 Visualization of a CfD with an intermittent Feed-in-Tariff

Notes The figure shows an illustrative example of a Contract for Difference (CfD). The strike price is the agreed price between the RES supplier and RNFBO producer. The blue line illustrates the Day-ahead price. If the Day-ahead price the RES supplier pays the difference between the strike price and Day-ahead price.

Source Copied from Fernández (2021).

From an energy system perspective, there can be some undesirable consequences related to electricity CfDs, as the buyer is not exposed to the market signals in the form of the volatile spot price and potential distortion on intraday and balancing markets (Schlecht et al., 2023, p. 7).

At this point, the typical PPA types have been introduced in relation to RNFBO production. Given the potential impact of the DA on PPAs, it is crucial to assess the legal feasibility of various PPA types.

6.2.2 DA Compliant PPAs

Because the DA does not provide detailed information on how a PPA is defined and thus compliant, the following section will evaluate two things: 1) unfold the information provided in the DA, and 2) provide an assessment of to what extent the three PPA types can or cannot be compliant.

Regarding complying with the DA, the responsibility of complying and disclosing adequate information as proof is the RNFBO producers' (Appendix VII Danish Energy Agency). The Danish Energy Agency expects a solution like the voluntary biofuel schemes, where a third party can be certified by the European Commission to audit and examine the RNFBO producers (Appendix VII Danish Energy Agency). Article 8 includes the information RNFBO producers must provide to comply with the DA, this regards information to prove the amount of electricity sourced from the grid can be claimed renewable in accordance with the various provisions allowing so.

A PPA is required if the RNFBO facility is connected to an electricity grid that does not meet the <90 pct. RES-share threshold and will claim electricity from the grid as renewable. If the <18 gCO_2/MJ threshold is met, a RES PPA is needed, though no additionality is required why the provision of financial aid is eliminated (*Commission Delegated Regulation C(2023) 1087 Final*, 2023, Article 4(2)). Therefore, the RES PPA shall be concluded with a plant meeting the renewable definition in REDII excl. biomass. Geographical and temporal correlation is still valid. In the general case, a RES PPA that meets the additionality provision is required to claim the electricity sourced via the grid renewable.

The delegated act does not include a definition of a PPA, but several provisions in the DA can be examined to assess the terms under which a PPA can be compliant (*Commission Delegated Regulation C(2023) 1087 Final*, 2023). The following bullets will highlight the provisions of PPAs:

1) Article 5: RNFBO producers must directly or via intermediaries conclude one or more renewable PPAs with installations effectively producing electricity equal to the amount claimed fully renewable.
2) Recital 9: The fuel producer can own the renewable electricity generation capacity, allowing companies to conclude so-called *internal* PPAs.

In the case of RES PPA requires additionality, then the following must additionally be met:

3) Article 5(a): The RES generation asset came into operation 36 months before the RNFBO production facility.
4) Article 5(b): The renewable electricity generation capacity cannot receive financial support in terms of investment or operational aid except if the financial support is repaid or following a repowering[2]. In addition, financial aid for land or grid connections is not considered financial support.

All three types of PPAs can support claims of additionality, however, it cannot be ruled out that PPAs are concluded with existing renewable generation capacity (Appendix II Developer 1). Additionality is proved by disclosing information showing that the PPAs a concluded with assets respecting the 36 months threshold, hence, additionality compliance can be disclosed via the PPA contract and/or related GO.

As the virtual PPA does not transfer the actual electricity sourced by the buyer, it is unclear whether a virtual PPA complies with the DA. A virtual PPA is considered a derivative and not a power contract, and it is questionable if a virtual PPA can be considered compliant (Tang & Zhang, 2019, pp. 2–3). However, since the DA also impose geographical constraints, all PPAs will essentially be physical PPAs, and not virtual, as they are connected to the same grid, disregarding the financial structure of the PPA (Appendix V EnergyTag).

This suggests that given the DA standards are met, incl. the geographical requirements, a grid-connected RNFBO production facility will be connected to the same grid as the RES generation plant, making it a physical PPA. In addition, this further prerequisite that the GOs are transferred to the buyer (bundled) to claim the renewable attributes of the electricity needed for compliance.

The three PPA varieties are not mutually exclusive as RNFBO production facilities can have a BTM setup and a grid connection enabling physical PPAs with other generation assets to increase the capacity factor of the production facility, in fact, this is likely a setup. This approach is taken on one of the advanced projects in Developer 2's portfolio (Appendix III Developer 2). Besides concluding several PPAs, battery storage and

[2] It is considered repowering if the investments exceed 30% of the investment that would be needed to build a similar new installation and comply with REDII Article 2(10) on repowering (Commission Delegated Regulation C(2023) 1087 Final, 2023 Article 2(5))

oversizing the RES generation capacity can help increase the electrolyser's capacity factor (Appendix V EnergyTag).

The three PPA setups and their compatibility with the DA have been illustrated in Table 4. There is still a degree of uncertainty surrounding when PPAs comply with the DA, however, all three types can claim additionality under given circumstances. The interviews and interpretation of the DA suggest that the GOs must be bundled with the electricity sourced via the PPA. Furthermore, if grid-connected, it seems evident that physical PPAs are the obvious choice in terms of risks, however, the financial structure can vary.

Table 4 PPAs Compliance with the DA

	Behind-the-Meter	Physical	Virtual
Origin		PPA needed	PPA needed
Geography		If located in the same or interconnected bidding-zone	
Temporality	Via a smart meter show that no grid electricity is sourced	Additional information needed	Additional information needed
Additionality	36 months cut-off date	36 months cut-off date	36 months cut-off date

Notes The columns represent the three main types of PPAs, and the rows the four key regulatory provision from the DA. The colours represent the PPAs compliance. Green indicates the PPA does comply. Yellow indicates that the PPA can comply if X information or y provision are respected. Red indicates that the PPA cannot comply with the DA on this aspect.

Source Own table based on (Commission Delegated Regulation C(2023) 1087 Final, 2023)

Table 4 further shows that a BTM PPA easily complies with the DA, as the electricity sourced from the direct-connected RES generation unit is not subject to additional requirements besides the additionality requirement. Contrary, RNFBO units sourcing grid electricity must contract a physical or virtual PPA to comply with origin, geography, temporality, and additionality requirements from the DA. As demonstrated in the present analysis, this can, to a great extent, be done using GOs combined with a PPA contract. In addition, Table 4 shows that a virtual PPA does not meet the geography requirements, as the RES generation unit and RNFBO production unit are not connected to the same grid.

To summarise, a BTM is the case that requires the least amount of documentation to comply with the DA. At the same time, it is still necessary to provide information to prove compliance with temporal correlation, e.g., via a smart-meter and additionality. A physical PPA requires several pieces of information where some can be provided by granular GOs, e.g., origin and geography, whereas additional information is needed to comply with temporality regarding issuing and claiming GOs. Contrary, a virtual PPA would likely not be compliant since it does not respect geographical correlation, however, the financial structure of a virtual PPA can be copied to a physical.

6.2.2.1 Trading DA-Compliant Electricity on the Short-Term Markets

Now that both granular GOs and PPAs have been introduced, and it is evident that both are instrumental in complying with the standards set out by the DA, it can now be assessed if and how electricity can be traded by RNFBO producers and their RES suppliers on the short-term ex-ante markets, like the Day-ahead and intraday markets. But first, it is necessary to identify the situations where short-term trading is compliant and second, situations where it might be needed and whether this aligns with the DA.

In the context of electricity trading, attention should be drawn to Article 4(2a), as mentioned earlier in Section 6.2, stating that the amount of electricity claimed renewable and sourced from the grid electricity must not exceed the volume contracted by RES PPAs. Article 4(2a) does not specify that the electricity sourced from the grid must be the electricity supplied by the RES supplier, the only requirement is that the volumes are balanced within the given periods of temporal correlation. Then Article 6 on Temporal Correlation specifies the periods in which the volumes must be balanced. It is important to note that Article 4(2a) refers to the electricity generated and not contracted, this is a critical distinguishment to make, as the predicted/contracted volume can differ from the actual production due to conflicting interests when concluding a PPA as covered by Ghiassi-Farrokhfal et al. (2021). The RNFBO producers can freely exchange with the market as long as the volumes are balanced within the given periods. This implies that the RNFBO producer can only buy a volume on the short-term market that does not exceed the volume sold at the market by the PPA contracted asset(s) in the given month or hour.

So, in a case where the actual generated electricity volume falls short of the predicted volume is most likely only an issue at hourly matching, as monthly matching leaves room for settling this gap by producing more RES or constraining the RNFBO production later, this is not possible to the same extent at hourly matching. At hourly matching, the RNFBO producer is forced to curtail production or maintain the production but then produce a non-renewable fuel. The decisive factor here is whether producing a non-renewable fuel would be economically feasible. An electrolysis can respond quickly to power signals, within seconds, according to the Danish Energy Agency (2021, p. 86), hence, an electrolysis can constrain production if the actual RES generation is lower than expected. Though, the RNFBO production facility flexibility can be hindered by, e.g., a methanol synthesis used to produce methanol (IEA, 2019, p. 198).

The absence of a PPA definition fosters another interesting aspect of short-term trading by RNFBO producers. This was a question raised by Developer 1 and is interesting to dwell with. Or framed differently: how short a period or small volume of electricity can legally be defined as a PPA? If the current definition and interpretation of a PPA are challenged and stretched, this might create the opportunity for a market to emerge.

EnergyTag mentioned, that an organisation was already thinking about how to develop such sub-national ex-ante markets for RNFBO producers and their electricity suppliers. If allowed, the market would enable RNFBO producers that have concluded PPAs to sell excess electricity and its attributes to other RNFBO producers who need a top-up to boost their capacity factor (Appendix V EnergyTag). As stated, it is likely that hourly matching forces RNFBO producers to hedge against volume risks by concluding several PPAs, hence, risking one-hour periods where they are not able to off-take all the generated electricity. In such a situation, selling the excess electricity to other RNFBO producers is obvious. EnergyTag appraised such a market as it would create flexibility and, therefore, desirable given that the requirements in the DA are met (Appendix V EnergyTag). The likeliness comes down to the legal interpretation of a PPA.

In a similar situation, developer 1 had some concerns regarding the liquidity of such a market. Developer 1 expressed concerns about the prospect of a very limited market for renewable electricity produced from RES assets in the same hour, in the same or neighbouring bidding zone, and at the same time can be considered additional. Developer 1 further argued that it is likely that wind and solar generation is equally high or low at the same time in the relatively small bidding zones in Denmark (DK1 and DK2) in terms of size (Appendix II Developer 1).

To recap, the current DA does not allow RNFBO producers to buy electricity on the short-term ex-ante markets that exceed the volume generated from the RES contracted assets in the given balancing period. Therefore, when hourly matching applies, the operation would likely be constrained. The RNFBO producer can, however, continue the operation if it is considered feasible to produce a non-renewable product.

The following subsection will assess the typical structures of PPAs in terms of contracted volume and time of delivery for later to be able to identify structures suitable for RNFBO production.

6.2.3 Common Structures of PPAs

Besides the three PPA types introduced, a PPA contract can also differ in structure in terms of volume and when the electricity is delivered, which places the risks differently on the two contracting parties: seller and buyer. The three types cannot be combined with each of the four main structures displayed in Figure 7, and this is especially the case for the BTM setup.

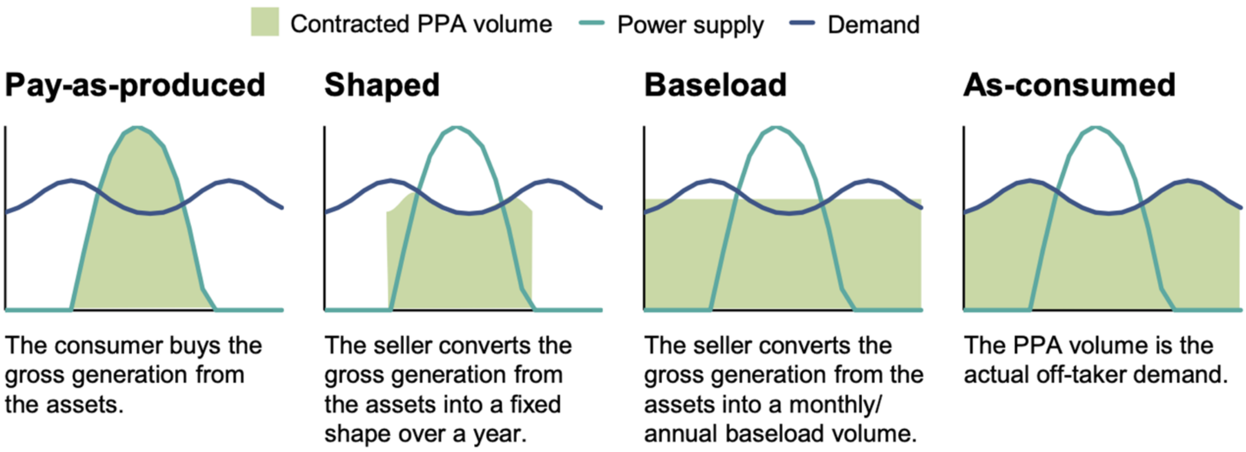

Figure 7 Four Common PPA Structures

Notes The figure illustrates four common structures of PPAs. The structures regard the volume contracted and when it is delivered. Moving right on the figure the PPA is shaped until it perfectly matches the consumption profile of the offtaker. The profiles should be interpreted illustratively as the production profile differs from a RNFBO production facility.

Source Copied from (LDES Council & McKinsey, 2022)

Figure 7 illustrates four main structures and are described by LDES Council & McKinsey (2022, p. viii). The four structures can be achieved with one or several PPAs simultaneously, however, the shaped PPA products require a larger RES generation portfolio for the supplier, contrary to a Pay-as-produced. The visualisations in Figure 7 are intended to be illustrative, and the most critical distinction in the case of RNFBOs is between the Pay-as-produced PPA and the three shaped PPA structures: Shaped, Baseload, and As-consumed. The following paragraphs will unfold the structures of PPAs and their relevance for RNFBO production.

Pay-as-produced is the most common and relevant in the case of RNFBOs (Appendix IV BPP). A pay-as-produced structure means that the consumer buys the electricity immediately when generated. The pay-as-produced structure is associated with the physical PPAs, as the seller and offtaker need to be connected to the same grid to transfer the electricity. It is essential to note that the contract is typically based on expected generated electricity volumes (Ghiassi-Farrokhfal et al., 2021, p. 2).

Shaped PPA structures do, in contrast to Pay-as-produced, actively form the supplied volume. As aforementioned, the more the product is shaped, the greater the project portfolio is needed for the supplier and is often contracted via a third party (LDES Council & McKinsey, 2022, p. viii). The shaped PPA, as illustrated in Figure 7, can be supplied by a supplier with several RES generation assets, as the supplier can provide the agreed volume by sourcing from different RES generation assets, e.g., onshore and offshore wind, PVs, and thereby taking advantage of the diverse production profiles. However, the more shaped PPA structures, like Baseload or As-consumed, might require firm generation capacity, storage facilities, and/or a vast RES generation portfolio.

6.2.4 Structuring PPAs for RNFBO production

This subsection delves into the intricacies of structuring RES PPAs tailored for RFNBO production, highlighting the key factors and challenges. But first, it is important to emphasize that the design of a PPA for the RNFBO production facility is highly case-specific and cannot be assessed in isolation, making it difficult to generalize (Appendix IV BPP).

Developer 1 argued, from a fuel producer perspective, it is desirable to structure the PPA as a baseload or shaped PPAs to provide certainty and hedge against price and volume, but shaped products include a higher price risk for suppliers (Appendix II Developer 1). Ensuring stable and predictable sourcing of renewable electricity at a fixed price while placing the price risk on the seller (Appendix II Developer 1). However, the risk is reflected in the price resulting in a higher price compared to a Pay-as-produced structure (Appendix II Developer 1). Developer 1 argues that in order to create a Baseload-like sourcing of electricity, several PPAs need to be concluded from different generation technologies, preferably also differentiating in location, which entails increased transaction costs (Appendix II Developer 1). Developer 1 adds that shaped PPAs are not that great a risk until 2030, while monthly matching is valid because if the RES generation asset produces less than expected in a given period. This can be settled by producing more at another point of the month, and in that way balance the contracted and supplied volume on monthly basis (Appendix II Developer 1). This is inherently more challenging on an hourly basis.

A pay-as-produced contract is desirable from a seller's perspective, as it creates investment certainty, conversely, the buyer carries the risk related to the variability of production in terms of volume and time (Ghiassi-Farrokhfal et al., 2021; LDES Council & McKinsey, 2022; Appendix II Developer 1). The buyer risks low level of full load hours or failing to meet potential off-take agreements, which will be increasingly pertinent when hourly matching is applied by 2030. Blue Power Partners is convinced that PPAs for RNFBO production will be structured as pay-as-produced instead of shaped PPAs because the costs associated with shaped and especially baseload PPAs are too high and will be too difficult to source (Appendix IV BPP). And further added that Pay-as-produced PPAs are desirable in socio-economic terms and from the operator's point of view to run the electrolyser when electricity prices are low and vice versa (Appendix IV BPP). Concerning Pay-as-produced PPAs, which Developer 1 also acknowledged as a feasible structure from the supplier perspective, though, RNFBO producers would likely need to conclude several PPAs (Appendix II Developer 1). Hence, risking over-procurement in terms of volume, the excess electricity will be sold at the Day-ahead market resulting in either a loss or revenue. Both Developer 1 and Developer 2 declared they expect to conclude so-called *internal* PPAs, so sourcing the renewable electricity from their own portfolio (Appendix II Developer 1; Appendix III Developer 2). Again, this raises questions in relation to the interpretation of a PPA and their flexibility. The developers had not arranged a procedure for this at the time of the interviews.

BPP had similar considerations and argued on this basis that PPAs for RNFBO production would likely be structured as Pay-as-produced with a fixed price structure, thereby also taking advantage of the electrolyser's flexibility (Appendix IV BPP; Appendix V EnergyTag; Appendix III Developer 2). This does not eliminate the possibility of signing several Pay-as-produced structured physical PPAs to approach a Shaped or Baseload-like sourcing, hence, providing the full load hours needed to create a viable business case for the RNFBO production facility (Appendix IV BPP; Appendix V EnergyTag). This can, e.g., be a BTM setup supplemented by Physical PPA(s).

A vital element of the contract is the duration of the contract. The duration of the contract might also be subject to conflicting interests by the supplier and RNFBO producer as the RES supplier prefers long contracts for the assets to create financial stability and predictability. On the other hand, an RNFBO producer might prefer to avoid committing for extended periods (Appendix II Developer 1). Developer 1 pointed out that most of the costs of producing electrolytic hydrogen relate to electricity consumption. Developer 1 continued even though long-term contracts create stability for the RNFBO producer and can be favourable if Day-ahead prices increase. However, if the opposite happens, there is a risk of being outmatched by the producers with short-term contracts (Appendix II Developer 1).

To summarise, PPAs concluded by RNFBO producers can be combined in various ways in terms of type and structure. However, the analysis suggests that PPAs are likely to be structured as Pay-as-produced and potentially entail several PPAs with different generation technologies. This does, thus, entail the price risks of over-procuring volumes. BPP further emphasised that the given sourcing cannot be assessed in isolation but highly depends on choices made in production setup, the off-take obligations, and the flexibility or inflexibility provided in the later steps (Appendix IV BPP). This will be returned to in the following chapter. It is essential to highlight that due to the recent publication of the DA, developers are still figuring out how to create an efficient supply chain and are still left with questions and need for clarification regarding DA-compliant PPAs (Appendix II Developer 1; Appendix III Developer 2).

6.3 Preliminary Conclusion

The purpose of the present analysis was to answer the following sub-question: *How can renewable electricity be traced and accounted for on a granular basis, and how will the delegated act impact the design of renewable PPAs concluded for RNFBO production?* This was examined by conducting interviews with professionals within the field and drawing on literature.

Regarding the first part of the question, it is evident that the GO scheme can play a key role in tracing and accounting for renewable electricity, making sure it is not claimed twice, and while being able to provide the information needed for RNFBO producers to claim compliance. The current GO scheme already imposes on issuers to disclose information that can help show compliance with temporality, additionality, geography, and origin. Though, it must be emphasised that it is important that the revised RED enables granular GOs as they are essential for compliance when hourly correlation applies. Accounting electricity on an hourly or sub-hourly basis can be enabled by using metering data, and the potential issues when developing a scheme are not related to the granularity but to the safety and reliability of the platform. Such a platform can further track the issued and claimed GOs balanced with the given temporal matching period. Hence, it can be concluded that granular GOs can track and account for the grid-sourced electricity contracted from RES PPAs for RNFBOs, and no insoluble barriers remain for granular tracking and accounting of electricity. In addition to the information provided by the GOs, there is a need to prove that the claimed RES electricity and its attributes are contracted by a PPA.

Regarding the second part of the question, clear directions were identified on how the DA impacts the design of PPAs for RNFBO production. It is clear that several developers employ a BTM setup, hence proof of additionality needs to be disclosed and temporal matching. For PPAs concluded with assets off-site, the RES PPA will likely be structured as Pay-as-produced due to the requirement of hourly matching by 2030, as it is the option entailing the lowest risks for the supplier, hence, lowering the price for the RNFBO producer. Such PPAs will be considered physical as the geographical requirements in the DA mean that the RES generation asset and RNFBO production facility are connected to the same grid, though the financial structure can vary. Shaped PPA structures will be complex to design and require a significant RES portfolio, where the geographical requirements will constrain this to one or a few bidding zones. This is especially prominent at hourly matching by 2030. Therefore, a shaped-like structure will likely be obtained by concluding several Pay-as-produced PPAs with various generation technologies to increase the number of full-load hours. Nonetheless, this entails a risk of over-procurement. The excess electricity is then sold at the, e.g., the Day-ahead market resulting in revenue or loss.

7 The Delegated Act's Impact on RNFBO Production: The Effects on Production Costs and Facility Design

This analysis aims to assess the DA's impact on the cost of producing RNFBOs and the setup of the RNFBO production facility. As RNFBOs are not a homogenous concept and can be produced in multiple ways using various processes, the focus of this analysis will be on electrolytic hydrogen as it is the primary feedstock used for RNFBOs (European Commission, DG ENER, 2023, p. 14). The following sub-question will be examined:

How will the delegated act on RNFBOs impact the production costs and production facility setup?

The sub-question will be answered using linear optimisation and then simulating the operation of a stand-alone electrolyser system in EnergyPRO. As EnergyPRO is a simulation tool, the RES supply is optimised in Microsoft Excel based on cost-optimising the RES electricity supply of 1 TWh/year. The approach and assumptions are described in detail in the Section 5.4. The analysis builds on Chapter 6 by using the findings to create relevant RNFBO setups for assessing the impact of the DA with a focus on the temporal requirements and the derogations for accounting grid-electricity as renewable The influence of the derogations when <0.36xEUA or <20€/MWh will be assessed in combination with monthly and hourly matching requirements, as this was identified as a gap in the literature as covered in Section 2.3. The production setups are shaped by the findings from the previous analysis, where it was evident that the tendency points to either a BTM setup or Physical PPAs structured as a Pay-as-produced. The quantitative assessments will be followed by a more qualitative assessment of the impact on the designs of RNFBO production facilities by drawing on the interviews.

This approach leads to the following six-step structure of the chapter:

1) Linear optimisation to identify RES and electrolysis capacities.
2) LCOH at monthly and hourly matching requirements in a setup with fixed yearly demand and monthly demand.
3) LCOH at Behind-the-meter Setups is assessed when applying monthly and hourly matching.
4) Sensitivity exercise on the individual components of the LCOH and further the capacity factors to evaluate the robustness of the findings and identify potential risk components.
5) Qualitatively examination of the DA's impact on the design of the RNFBO production facility moving beyond the focus on the electrolyser to consider the entire production facility.
6) Preliminary conclusion.

Before starting the analysis, it is essential to note that the present thesis aims to assess the impacts of the DA in a general case, not a specific RNFBO production facility. Therefore, it is considered useful to use linear optimisation to identify a cost-optimal supply of RES instead of applying a configuration from one particular RNFBO project. This approach entails both pros and cons regarding the findings' generalizability which will be elaborated on in Section 7.5 and the discussion in Chapter 8.

7.1 Optimising PPAs for RNFBO production

The supply of renewable electricity needs to be identified to analyse the regulatory impact on the production cost. As the DA prescribes, the volume of grid electricity sourced by RNFBO producers must not exceed the volume generated by the contracted PPA RES generation assets in the given temporal matching period.

The linear optimisation's objective is to minimise the costs of producing a fixed amount of power in a year. As the power needs to be contracted via PPAs, the model needs to reflect this. Therefore, the model is structured as pay-as-produced PPA making the capacity of RES plants and electrolysis the decision variables, meaning that model finds the most cost-optimal way of producing 1 TWh/year.

7.1.1 Linear optimisation of RES supply

Optimising the costs of producing 1 TWh over the year resulted in erecting onshore wind, as this is the most cost-efficient RES technology in terms of LCOE identified. The LCOEs for onshore wind, offshore wind, and solar are 23, 37, and 28 €/MW, respectively, on top of this comes a consumption transmission tariff of 16.7 €/MWh. The model identified 286 MW onshore wind and a 211 MWe electrolyser as the most cost-optimal capacity combination. It is important to flag that the emphasis should be put on the ratio between the capacities and the general trends, not the exact values. Since the model has some limitations, the model was tweaked to include solar to increase the capacity factor of the electrolysis. This was also done to align with the literature and the expectations of developers (Appendix III Developer 2; Appendix IV BPP).

This resulted in a new outcome: 210 MW onshore wind turbine, 237 MW PVs, and 188 MWe electrolysis. This combination is applied at both monthly and hourly matching. The main characteristics of the two setups are presented in Table 5, named *Monthly* and *Hourly,* together with two additional setups when applying a fixed monthly offtake, called *Monthly (fixed offtake)* and *Hourly (fixed offtake).* These setups will broadly be referred to as wind-solar setups hereafter. Table 5 contains a significant amount of information, of which the key figures will be presented in the following.

Table 5 Key Characteristics of the Four Setups

		Unit	Monthly	Monthly (Fixed offtake)	Hourly	Hourly (Fixed offtake)
Onshore Wind	**Capacity**	MW	210	200	210	200
Offshore Wind	**Capacity**	MW	-	-	-	40
Photovoltaics	**Capacity**	MW	237	464	237	464
Electrolyser	**Capacity**	MWe	188	156	188	228
Electrolyser	**Capacity factor**		0.64	0.87	0.59	0.66
Hydrogen production		Tonnes H_2	20,900	23,493	19,168	26,039
Received Day-ahead	**Volume**	GWh	176	349	87	273
Delivered Day-ahead	**Volume**	GWh	228	312	32	34
Day-ahead	**Expenses**	M€	10.8	20.5	1.3	0.9
Day-ahead	**Revenues**	M€	11.5	13.9	3.2	9.5
Day-ahead	**Net-Result**	M€	0.7	- 6.5	1.9	8.6

Notes The four columns represent the four setups examined. Two with monthly matching, and two with hourly matching. The table display the key indicators and characteristics of the setups. Day-ahead expenses include transmission tariffs, and the feed-in tariffs are subtracted from the Day-ahead revenues.

Source Own calculations from Excel and EnergyPRO

First, let us dwell on the two setups *Monthly* and *Hourly* without a fixed offtake. Worth noting in the two setups is that the capacity factor of the electrolysis is reduced from 0.64 to 0.59 when applying hourly matching, which reduces the hydrogen production with 8 pct. Furthermore, as expected the Day-ahead trading activity is heavily reduced both in volume and amount spent. It is thus interesting to note, that both setups have a net revenue, though, it is higher at hourly matching despite the significantly smaller volume sold at the wholesale market. This indicates that *Monthly* matching does not benefit significantly from trading Day-ahead.

Figure 8 illustrates the electricity produced from the onshore wind turbine and PVs and the volume consumed by the electrolyser (in GWh) when applying monthly (left column) and hourly (right column) matching.

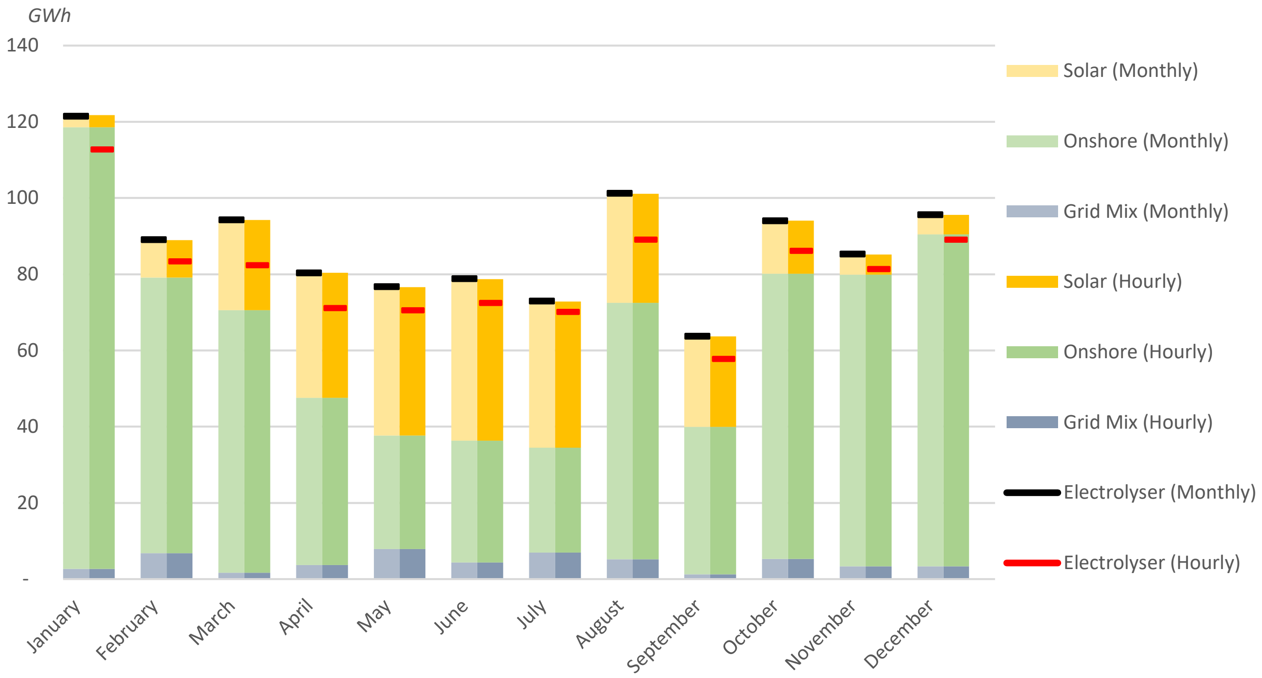

Figure 8 RES Production and RES consumption at Monthly and Hourly Matching

Notes The figure shows the RES electricity production aggregated monthly and the monthly electricity consumption (input) by the electrolysis at monthly and hourly matching requirements. Further, the DA allows to claim grid electricity mix as renewable when the Day-ahead price is below 0.36 times EUA and >20€/MWh, which is illustrated by Grid Mix. The share of grid mix is nonetheless rather small. From the figure it is evident that the electrolysis is not able to utilise all the RES available (red bar).

Source Own calculation. Data from EnergyPRO and Excel

From Figure 8 it is evident that the RES production highly varies throughout the year with most wind resources during the winter months and solar during the summer months. Onshore wind is the primary source making up 70 pct. of the electricity production, and solar 25 pct. The last 5 pct. is from the grid electricity mix accounted renewable when the Day-ahead price is below 0.36 times EUA price and >20€/MWh. In both cases the electrolysis source is just above 50 GWh from the grid, though this volume should be put in perspective to theoretical potential, which can be identified by multiplying the number of hours grid electricity mix can be claimed renewable by the capacity of the electrolysis. The theoretical potential is around 327 GWh in this case. This illustrates that there is a significant overlap between RES production and low Day-ahead spot prices.

Figure 8 further displays that at hourly matching, the electrolysis is not able to fully utilise the available RES electricity. The constraints imposed at hourly matching reduce the full load hours by 600 hours when compared to monthly matching, hence reducing the produced hydrogen volumes. This is well illustrated by Figure 9 displaying the RES electricity production profiles and electrolysers' consumption profile on three representative days.

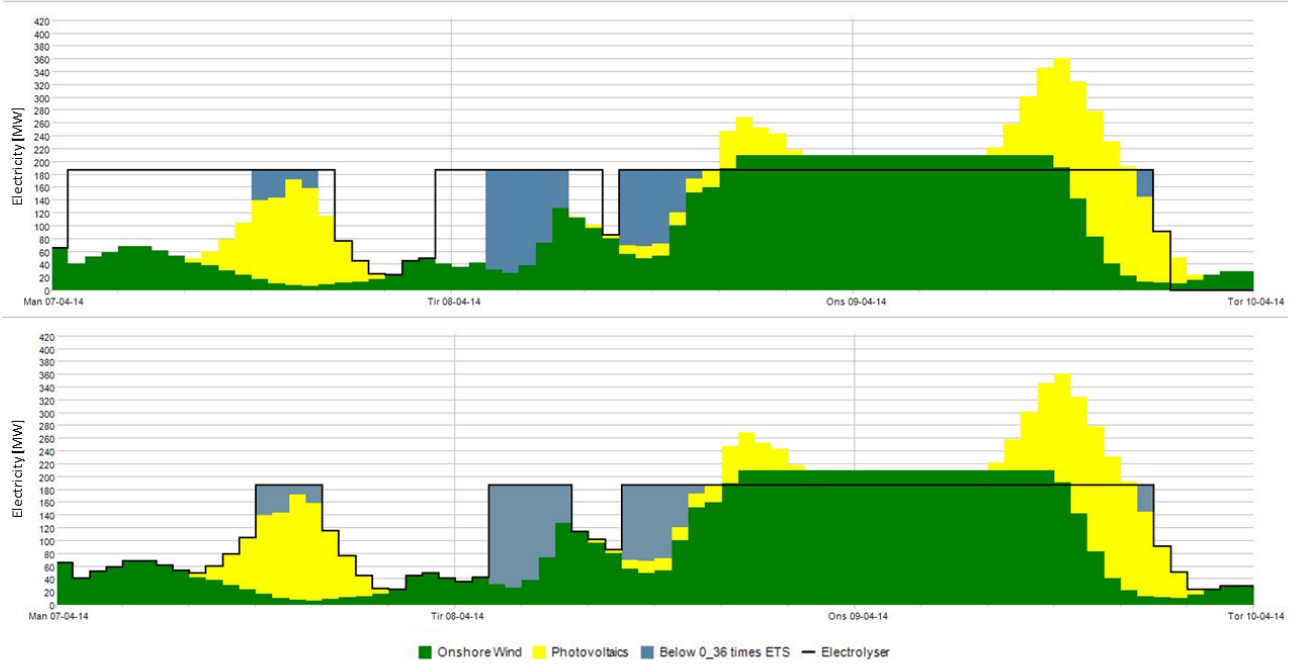

Figure 9 Snapshot of Production and Consumption at Monthly and Hourly Matching

Notes The two figures show the electrolysers' electricity consumption and RES production from 07.04 to 10.04 when applying monthly (top) and hourly (bottom) matching requirements. The two consumption illustrates that at hourly matching the electrolysis is dispatched and follows the available RES production. At monthly matching, the electrolysis can operate in periods with low renewable resource availability (see early April 7th) to balance the excess production taking place (see midday April 9th). At monthly matching, the electrolysis dispatches the operation even when RES is available (see top figure late April 9th), as the electricity price is high in these hours, so it is economical to sell at high electricity prices and the buy in periods with low prices. Further, the grey areas illustrate the periods when grid electricity can be accounted as renewable, and the electrolysis tops up production by sourcing from the grid.

Source Snapshots from EnergyPRO

Figure 9 illustrates the production constraints at hourly matching, as the operation of the electrolyser strictly follows the available RES production (see bottom Figure 9). Contrary, at monthly matching the electrolyser can balance production and consumption out by running full load in periods with low RES available (see top left Figure 9), and further fully dispatch production when electricity prices are high (see top right Figure 9). The grey areas represent the periods when grid electricity mix can be claimed renewable, and Figure 9 illustrates the claim of the correlation between low electricity prices and high-RES resources.

The informant from BPP emphasized the necessity to optimise the combination of RES for each RNFBO project, as it is highly project specific and must consider the offtake needs, whether it is flexible or fixed on a yearly, monthly, or daily basis. The informant further stated that it is ultimately the offtake that determines the flexibility of the operation, hence, also the RES supply (Appendix IV BPP). It can thus be argued that it is relevant to assess a situation with a fixed offtake.

7.1.1.1 Introducing a fixed monthly offtake

Now moving on to the monthly and hourly matching setup where a fixed monthly offtake was introduced. It was assumed to be a fixed offtake equally divided over the year, in this case, 1 TWh was divided by 12 so at least 83.3 GWh of electricity to be supplied and consumed every calendar month. Since the model does not include storage, the model was forced to supply a minimum of RES electricity every month. It is worth noting that the installed capacities differ from the setups without a fixed monthly offtake but also between them (see Table 5), the reason for this will be unfolded in the following paragraphs.

Introducing a fixed monthly offtake changes the output as a new constraint is introduced. First focusing on monthly matching, the electrolyser capacity is reduced from 188 MWe to 165 MWe, while onshore wind is slightly reduced from 210 MW to 200 MW, whereas the solar capacity is doubled from 237 MW to 464 MW. This indicates that the RES electricity supply had to be increased during the summer months in comparison to the supply with no fixed monthly offtake, which is also illustrated in Figure 10.

Furthermore, the capacities at *Hourly* (*fixed offtake*) are different than *Monthly (fixed offtake)*. This is due to the linear optimization model only able to introduce constraint at the supply and not the consumption, meaning that the capacities are optimised to produce 83.3 GWh/month and not concerning the electrolysis' consumption. This is presumably not an issue at monthly matching since the electrolysis can consume more at other periods, whereas this is not possible at hourly matching why hourly matching will fall short of consuming 83.3 GWh/month. This is also reflected in the high capacity factor at *Monthly (fixed offtake)* of 0.87. The model was then tweaked to meet the monthly consumption offtake. The outcome of this was significant increase of the electrolysis capacity from 156 MWe to 228 MWe, while also introducing offshore wind as the production profile is slightly different from onshore wind, though also more costly. This showcase that meeting a fixed offtake at hourly matching potentially can require a different setup than at monthly matching. The capacity ratio between the RES generation plants and electrolysis is smaller at hourly matching, hence, reducing the capacity factor relative to monthly matching.

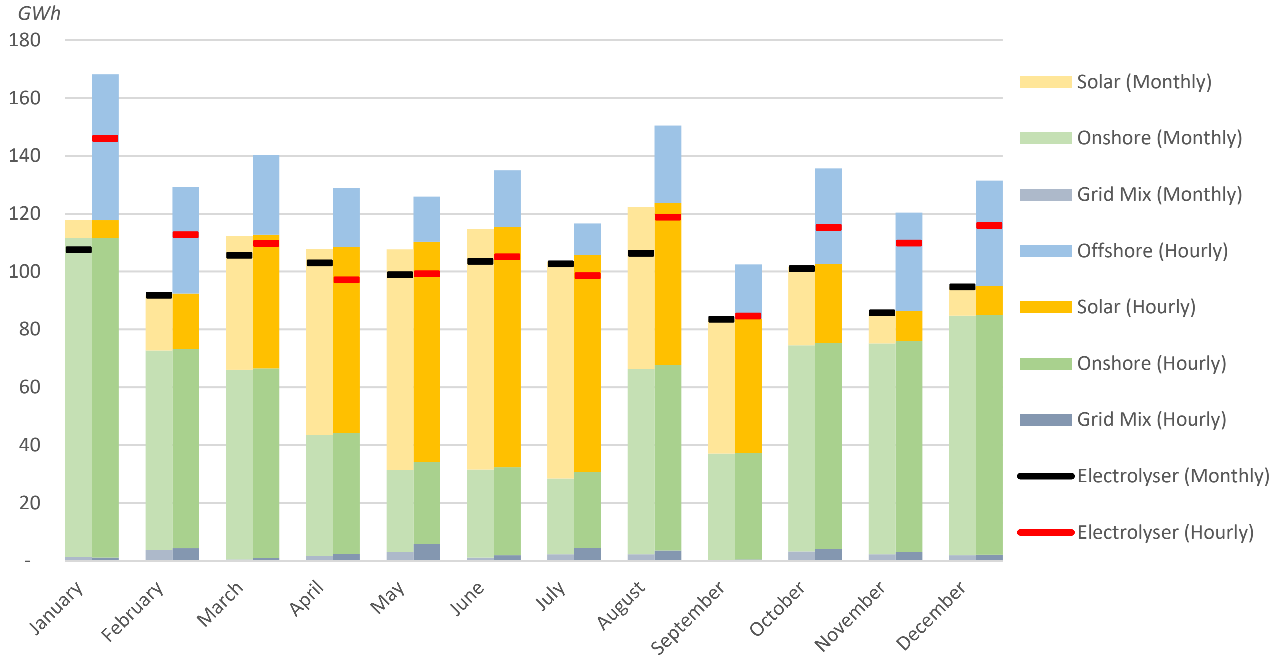

Figure 10 RES Production and Consumption with a Fixed Monthly Offtake at Monthly and Hourly Matching

Notes Figure 10 display the RES electricity production and the electrolysis' electricity consumption at monthly (left column) and hourly (right column) matching when introducing a fixed monthly demand, aggregated monthly. At hourly matching offshore wind is introduced to be able to respect the fixed monthly demand of 83.3 GWh. The electrolysis' monthly electricity consumption is displayed by the black and red bars and is the input in GWh.

Source Own calculation. Data from EnergyPRO and Excel.

Figure 10 shows that September was challenging as both the solar and wind resources were low, and the fixed monthly demand was just satisfied. Solar power peak production takes place during the summer, and wind power peak in the winter, which provides a complementary supply when aggregated monthly. However, applying a rigid fixed demand leads to a significant overproduction of RES at hourly matching (relative to the minimum of 83.3 GWh/month), this further pronounced when comparing to a setup with no fixed demand as illustrated by Figure 9. Such over-investments can be mitigated by investing hydrogen storage, such as Liquid Organic Hydrogen Carriers[3] stored underground or in tanks or alternatively by integrating offtake flexibility in the contract as Developer 2 (Reuß et al., 2017; Appendix III Developer 2).

The RES volumes supplied and consumed in various setups are only helpful to a certain extent in isolation. Thus, they need to be put in relation to the costs of buying the renewable electricity and deploying the RNFBO facility, in other words, assess the costs of producing electrolytic hydrogen at monthly and hourly matching to grasp the impacts of DA. The following section will do precisely that.

3 LOHC: Liquid organic compounds that store hydrogen by means of repeated, catalytic hydrogenation and dehydrogenation cycles An economical and promising way of storing hydrogen (Reuß et al., 2017)

7.2 Assessing the cost of producing electrolytic hydrogen

To examine the cost-effects of the DA further, the cost of producing electrolytic hydrogen at the setups identified in the previous Section 7.1 is examined in EnergyPRO, applying monthly and hourly matching, and the derogations allowing grid electricity mix to be claimed renewable.

Before imposing regulation, it is instructive to create a reference where no regulation is applied, in this case, the electrolyser is assumed to source grid-electricity mix purchased at the Day-ahead market. Instead of calculating the LCOH at a set capacity factor, it is assessed more beneficial to create Figure 11 illustrating the costs of producing hydrogen as a function of the utilisation rate of the electrolysis (full load hours a year). From Figure 11 it is clear, that the impact of CAPEX is reduced at higher utilization rates (orange area), though, this does also mean higher electricity prices which is illustrated by the black line (second y-axis) and the expenses for electricity purchase (blue area).

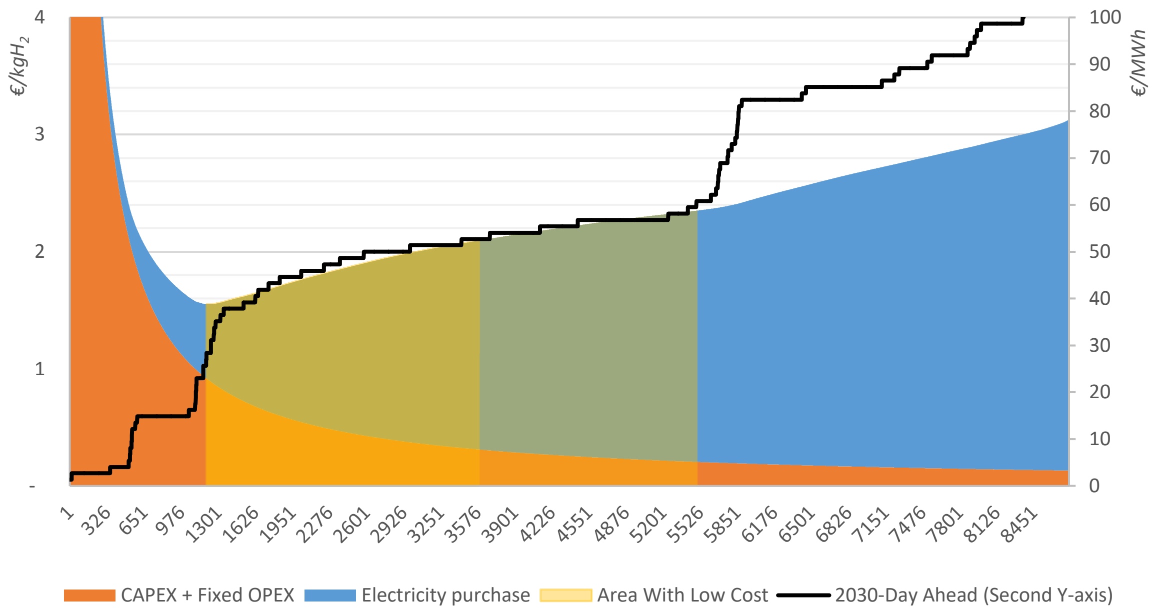

Figure 11 Hydrogen Costs from Electrolysis using Grid-Electricity

Notes The costs of producing electrolytic hydrogen using grid electricity (first y-axis) increase as the utilization rate increases (hours on the x-axis), the variable costs make up an increasing share of the LCOH. CAPEX includes investment costs of the electrolysis, fixed operating costs of the electrolysis, and compression of the hydrogen. Electricity purchase includes transmission tariffs. Cost of capital (WACC) is assumed to 5 pct. The assumptions and method are described in Section 5.4. The Day-ahead spot prices are from the year 2030, hourly resolution, from Analyseforudsætninger 2022 (Energistyrelsen, 2023a)

Source Own calculations inspired by International Energy Agency (2019, p. 48).

The LCOH is lowest at a relatively low utilization rate of approximately 1,000 full load hours, with of cost of 1.6 €/kgH_2, which steadily increase until around 5,700 full load hours a year after which the curve takes an upward bend as the electricity prices jump from 60 €/MWh to 80 €/MWh in only ten days. The yellow area marks the utilization rate in which a preferable LCOH is achieved, though the LCOH increased from 1.6 to 2.2 €/kgH_2 in the area, thus, at the same time the utilization increased with a factor of 5.
At full utilisation a LCOH just above 3 €/kgH_2 is found, almost doubled when compared to lowest LCOH. This tells, that the LCOH is especially sensitive to electricity prices. This finding is further underlined when

comparing to similar figures, such as the one published by the IEA using electricity prices from Japan (see page 48 in IEA (2019)) and the identical figure in Appendix VIII using 2018 wholesale electricity prices from DK1. This substantiates the sensitivity towards the variable costs, which represent 70-90 pct. of the overall costs of electrolytic hydrogen across electrolysis technologies and temporal matching requirements with the electrolyser system remaining stable at around 20-30 pct. of the overall costs (Brauer et al., 2022, p. 10; Glenk et al., 2023, p. 17).

7.2.1 Fixed Monthly Offtake at Monthly and Hourly Matching

The optimised RES electricity generation and electrolysis capacities with no fixed offtake and fixed monthly offtake from Table 5 are used as input in EnergyPRO to simulate the operation at lowest costs. LCOH is used as a metric to compare hydrogen production costs across setups.

Figure 12 displays the cost components of the four setups including the net-LCOH, which consider the revenues from electricity sold at the Day-ahead market. Variable OPEX represent most of the overall costs, between 82-88 pct, in all four setups, while the electrolyser system represents the residual 12-17 pct.

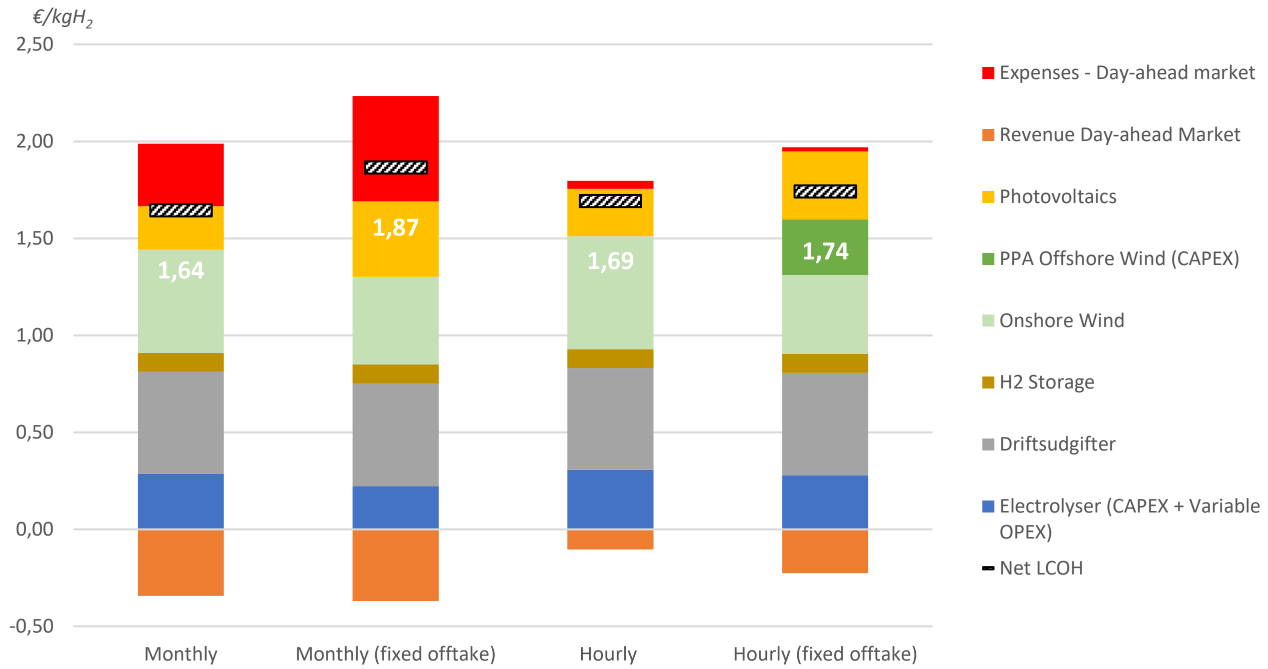

Figure 12 LCOH in a Wind-Solar Setup at Monthly and Hourly Temporal Matching

Notes The figure displays the individual cost components share of the total production costs at two setups applying no fixed offtake and when introducing a fixed monthly offtake *(fixed offtake)*. The net-LCOH is lowest in the setup with monthly matching and with no fixed offtake. The LCOH increases when introduced a fixed monthly offtake at both monthly and hourly matching.

Source Own calculations.

The net-LCOH reveals that the production cost increase when introducing a fixed monthly offtake and when applying hourly matching, see the net-LCOH at *Monthly (fixed offtake), Hourly,* and *Hourly (fixed offtake)* compared to *Monthly*. The biggest cost-premium is identified when introducing a fixed offtake at monthly matching as the LCOH is increased from 1.64 to 1.87 €/kgH_2, corresponding to 13-pct. which is substantial. In comparison, when going from *Monthly* to *Hourly* the LCOH increases from 1.64 to 1.69 €/kgH_2, a 3-pct.

increase, which is considered rather insignificant. In addition, the introduction of fixed offtake at hourly matching (from 1.69 to 1.74 €/kgH_2), is similarly considered rather small. The increased investments in the electrolyser and offshore wind is partly offset by significantly higher hydrogen production and revenues from selling excess electricity (see orange area).
To recap, cost premiums are identified in all three setups, when compared to *Monthly,* however, the identified cost premium at *Hourly* matching is negligible. The following paragraph will unfold, why a bigger cost premium is identified at *Monthly (fixed offtake)* than *Hourly (fixed offtake),* as it stands out.

The 13-pct. increase in LCOH identified at *Monthly (fixed offtake)* is due to increased expenses from trading on the Day-ahead market, which is doubled (see red area, Figure 12), while the volume purchased is only increased with 50 pct. (see Table 5). Hence the average Day-ahead price is higher at *Monthly (fixed offtake)* than at *Monthly*. This is further due to the higher capacity factor (0.87), hence trading at higher electricity prices. In addition, the revenues remain stable.

When going from *Monthly* to *Hourly* matching the cost premium is rather small. This is because at hourly matching the electrolysis is still able to source from the grid in periods with low electricity prices due to the derogations in the DA. In this way, one of the advantages of more lenient matching, namely the flexibility, is diminished, as hourly matching likewise can take advantage of the low electricity prices. Before drawing any conclusions, it is necessary to test the alleged impact of the derogations.

Figure 13 displays the net-LCOH when scrapping the option of claiming grid-electricity mix renewable when <20 €/MWh or <0.36xEUA. When comparing the net-LCOH in Figure 13 with the ones in Figure 12 it is evident that it increases slightly except from *Monthly (fixed offtake)* that experience a decrease. The highest increase is identified at *Monthly* matching from 1.64 to 1.68 €/kgH_2, however, this only corresponds to a 2-pct. increase, why it is considered negligible. Hence, the two derogations have a minor impact on the production cost in the setups assessed.

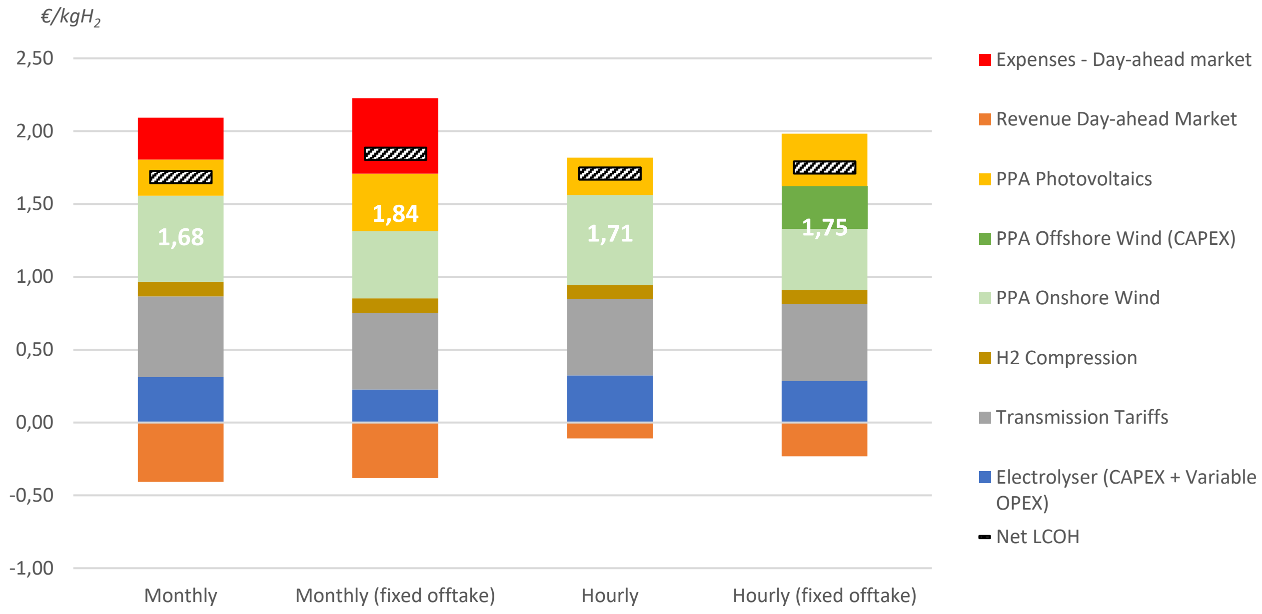

Figure 13 LCOH in a Wind-Solar Setup at Monthly and Hourly Temporal Matching - Excl. Grid Mix Derogations

Notes This figure shows the LCOH at a Wind-Solar setup when applying temporal matching requirements and a fixed monthly offtake. This differs from Figure 12, as the two derogations allowing claiming grid electricity mix renewable when <20 €/MWh or <0.36xEUA are scrapped. The figure illustrates that the lowest production cost is identified in the setups where not fixed monthly offtake is applied.

Source Own calculations.

However, the changes identified when removing the grid mix derogations still entail two interesting findings. 1) The costs are sensitive to the utilization rate as this impacts the variable costs of producing electrolytic hydrogen; lets recall that variable cost components constitute the vast share of the LCOH. Therefore, higher Day-ahead prices are reflected in the LCOH. This is also why the net-LCOH decreases at *Monthly (fixed offtake)* when lowering the capacity factor in Figure 13. And 2) the three setups *Monthly, Hourly, and Hourly (fixed offtake)* do benefit from the option to source grid electricity, though, the impact is negligible. This is due to the fact, that the four setups only source 2-5 pct. of the total electricity from the grid electricity mix via the two derogations indicating a high correlation between the availability of RES electricity and low electricity prices. The sensitivity towards the capacity factor will be scrutinized in Subsection 7.2.3.

The reason why a drop is identified at *Monthly (fixed offtake)* when scrapping the two derogations needs a bit more explanation, as it is a bit counterintuitive. It is because of the reduced volume of sourced grid electricity, while still being able to take advantage of the periods with low electricity prices but without balancing out surplus RES production in times with relatively high electricity prices (above 43 €/MWh). In periods with electricity prices below 43 €/MWh the electrolysis tops up with grid electricity, this means that the surplus RES volumes generated in periods where the electrolysis is not able to utilize it immediately, this volume needs to be balanced at other times, hence in periods when the electricity price is above 43 €/MWh. This is because the model is set to optimize hydrogen production within the regulatory framework imposed. In reality, the RNFBO producer might not choose to utilize all the available RES within a given month if it would lead to an increased LCOH, even though the DA allows so.

Additionally, the PPA is structured as pay-as-produced, the RNFBO producer buys all generated RES immediately at the agreed price, in this case the LCOE for the RES technology plus transmission tariff. If the RNFBO cannot utilize the electricity immediately it is sold at the wholesale market resulting in a revenue or loss. Based on the financial figures from the operation, it can be deduced that this mechanism is unfavorable for the RNFBO producer as there is a net loss related to the trading at *Monthly (fixed offtake),* while *Monthly* experiences a small revenue, see Table 5 in subsection 7.1.2. *Monthly (fixed offtake)* is the only setup experiencing a net loss from exchanging with the grid, which again highlights the correlation between RES availability and electricity price.

The LCOH at monthly and hourly matching must also be put in relation to the costs of producing hydrogen in a setup sourcing only grid-electricity mix and buying at the Day-ahead market, as illustrated by Figure 11 page 49. Such a setup is also relevant when member states reach a RES-share >90 pct. over a year, as this allows fuel producers to produce RNFBOs at such setup, as long as the number of full load hours do not exceed the RES-share times number of hours a year. The identified LCOH at monthly at 1.64-1.87 and hourly at 1.69-1.75 €/kgH_2 can be considered low when comparing to Figure 11. The LCOH identified in the four setup ranges from 1.64 to 1.87 €/kgH_2 which are comparable with electrolysis using grid electricity with 1,000 to 2,500 full load hours a year, corresponding to a capacity factor between 0.10-0.30 as displayed by Figure H. This is significantly lower than the capacity factors of the four setups (0.59-0.87), demonstrating that it is still viable to produce electrolytic hydrogen under the DA when compared to only grid-electricity setup. However, it cannot be ruled out that a more cost-efficient setups, than a 100-pct. grid-setup could be identified, thus, making the wind-solar setups less economically viable.

To summarise the findings at this point, the impact of the DA when going from monthly to hourly matching is considered trivial both in case of a fixed monthly offtake and in absence. Further, the production costs in all four setups are economically viable when comparing to a 100-pct. grid-electricity setup regardless of offtake and matching requirements. Furthermore, a pay-as-produced PPAs in combination with the two derogations do to a great extent eliminate the advantage of flexibility at monthly matching compared to hourly, which furthermore diminishes the economical differences between the monthly and hourly matching. Furthermore, the relatively high LCOH identified at *Monthly (fixed offtake)* is due to the high utilization rate, underlining the exposure to Day-ahead prices.

All four setups have a diversified RES supply, hence, it is reasonable to examine setups only sourcing from one RES technology. The following chapter will examine such using a BTM setup.

7.2.2 Behind-the-Meter Setup: Monthly and Hourly Matching

The two developers interviewed were both explicit about the tendency of PPA setups, namely the feasibility of BTM, having a direct line between a RES generation unit and the RNFBO production facility (Appendix II Developer 1; Appendix III Developer 2). This is also reflected in the publicly announced Power-to-X projects in Denmark with projects directly connected to utility solar or offshore wind turbines (Brintbranchen, 2023a; Energistyrelsen, 2022c; Erhvervsstyrelsen, 2021). Developer 2 emphasized, that using a BTM setup does not mean the RNFBO production facility will run on electricity exclusively from one RES asset but will likely be supplemented grid electricity contracted via RES PPAs, though the majority is expected to come from the direct connected asset (Appendix III Developer 2). Thus, it is pertinent to assess how the DA will impact the costs of electrolytic hydrogen produced from a BTM setup. To make setups that are clearly distinct from the earlier assessed wind-solar setups. Three setups are created basing the RNFBO production solely on either onshore wind, offshore wind, and solar, disregarding the possibility of supplementing the supply from other RES sources. The BTM the setups are not islanded to enable exporting excess electricity and importing grid-electricity to the extent possible.

The characteristics of the three BTM setups are presented in Table 6, which are referred to as *BTM Solar, BTM Onshore,* and *BTM Offshore.* The capacities are identified using linear optimization, following the same approach as applied earlier, and then applied at monthly and hourly matching in EnergyPRO. Subsection 7.2.3 includes sensitivity analysis of the electrolysis' capacity factor at monthly matching to examine, whether it is feasible to reduce the capacity to obtain a higher capacity factor.

Table 6 Specifications and Results of the BTM Setups

		Unit	BTM Solar		BTM Onshore		BTM Offshore	
			Monthly	**Hourly**	**Monthly**	**Hourly**	**Monthly**	**Hourly**
Onshore Wind	**Capacity**	MW	-	-	286	286	-	-
Offshore Wind	**Capacity**	MW	-	-	-	-	240	240
Photovoltaics	**Capacity**	MW	892	892	-	-	-	-
Electrolyser	**Capacity**	MWe	126	126	211	211	209	209
Electrolyser	**Capacity factor**		0.76	0.45	0.59	0.53	0.59	0.55
Hydrogen production		Tonnes H_2	16,657	9.877	21,811	19,460	21 525	20,116
Received Day-ahead	**Volume**	GWh	454	99	330	114	262	92
Delivered Day-ahead	**Volume**	GWh	616	602	232	135	178	80
Day-ahead	**Expenses**	M€	-34.0	-3.8	-19.6	-4.3	-15.3	-3.5
Day-ahead	**Revenues**	M€	23.8	22.4	15.2	6.1	13.1	3.9
Day-ahead	**Net-Result**	M€	-10.2	18.6	-4.5	1.8	-2.2	0.4

Notes The table displays the key results and characteristics of the three BTM setups modelled at monthly and hourly matching. The results include the option of account grid-electricity as renewable when <20 €/MWh or <0.36xEUA. Day-ahead expenses include transmission tariffs, and the feed-in tariffs are subtracted from the Day-ahead revenues.

Source Own calculations based on EnergyPRO and Excel.

Table 6 shows that the RES generation and electrolysis capacity are highest in the *BTM Solar* setup with a RES plant 7 times higher max capacity than the electrolysis, whereas the ratio is only 1.15 in the *BTM offshore* setup. This is also reflected in the total hydrogen production annually, which is significantly lower with at *BTM Solar* setup than the two wind setups. Furthermore, it is evident that applying hourly matching reduces the capacity factor in all setups, with the lowest identified at *BTM Solar.* This pattern is also reflected in the electricity sold at the wholesale market, where over 600 GWh is sold directly, this more than half of the total annual production of 1 TWh. Likewise, in the *BTM Solar* setup a great amount is also purchased at the wholesale market, around 454 GWh whereas as 100 GWh is grid-electricity claimed renewable when <20 €/MWh or <0.36xEUA. These results indicate that a *BTM Solar* setup with hourly matching results in poor direct utilization of the electricity produced from the photovoltaics. This is also reflected by the -10 M€ net result from trading Day-ahead at monthly matching, while a substantial net revenue is achieved at hourly matching, 18.6 M€.

These figures are also reflected when translating the results into LCOH. Figure 14 shows that *BTM Solar* benefit significantly from selling electricity at the wholesale market, illustrated by the orange area. The substantial revenue at *BTM Solar Hourly* brings down the LCOH to 1.09, making it the most cost-efficient of the three setups, however, relying on the revenue stream from excess electricity to such a degree can be risky to build a business-case on. BPP emphasized that each RNFBO developer is to decide on their willingness to rely on supplementary revenue streams from e.g., the Day—ahead market, and ancillary services (Appendix IV BPP). *BTM Solar Hourly* seems impracticable in this sense, further, the setup only produces half the electrolytic hydrogen as the BTM wind setups (see Table 6). In contrast, the two BTM wind setups rely to a lesser extent on a revenue stream from selling electricity, reflecting a better balance between the capacities. *BTM Onshore* provides the lowest LCOH, and again a drop is identified when going from monthly to hourly matching, from 1.22 to 1.16 €/kgH_2, corresponding to a 5-pct. drop. This again is not a substantial drop and is likewise due to the pay-as-produced structure together with transmission tariffs making it less favourable to trade electricity Day-ahead.

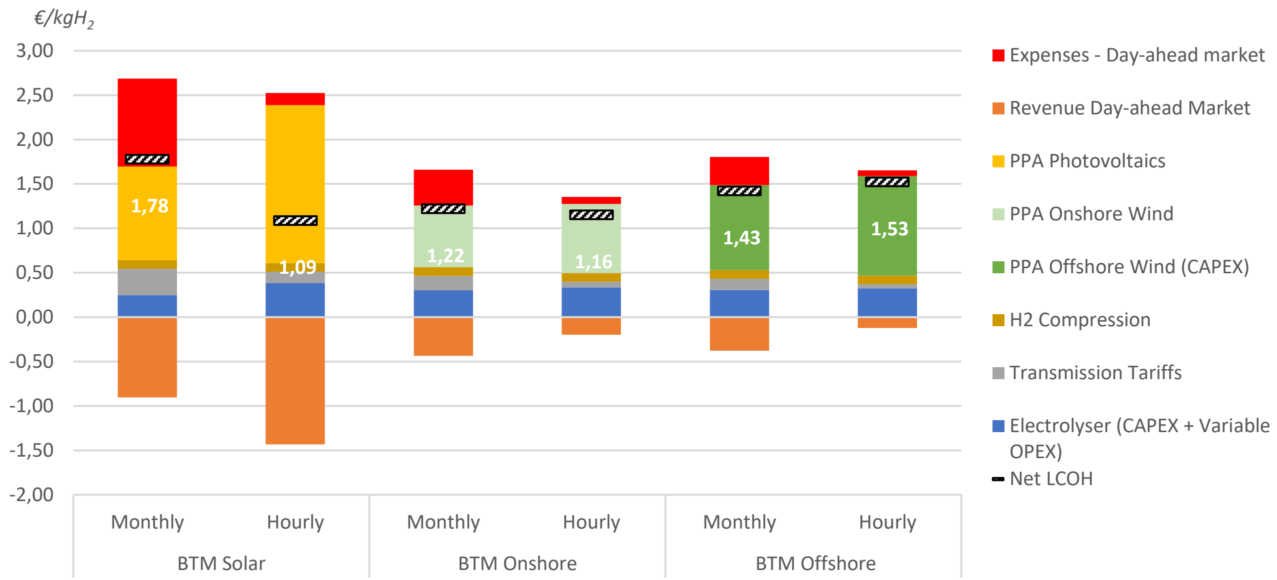

Figure 14 LCOH at Behind-the-Meter Setups with Monthly and Hourly Matching

Notes The figure shows the cost components at the three BTM setups at monthly and hourly matching. The impact of applying hourly matching at a BTM Solar setup is substantial, whereas the impact is less pronounced in the BTM setups with wind. Nevertheless, BTM Solar has a substantially higher revenue from excess electricity (orange area). The lowest production costs are identified at the BTM Onshore setup.

Source Own calculations based on EnergyPRO and Excel.

The two main takeaways from the three BTM setups are 1) A BTM can reduce costs as transmission tariffs are saved. 2) The feasibility of a BTM Solar setup heavily relies on the revenues from selling electricity, which is different for both a BTM onshore wind and offshore wind setup.

It must be emphasised that the three setups do not consider the realism of erecting 900 GW of solar, 284 GW of onshore wind, and 240 GW of offshore wind at a BTM setup especially not if additionality applies. The RES generation capacities fit an electrolyser with a 100-200 MWe capacity.

Suppose the three setups are run without the option to claim grid electricity mix renewable. In that case, the net-LCOH only changes slightly, as displayed in Figure 15. No consistent pattern can be identified between the six setups. The trivial impact is due to the different sourcing costs for the three RES technologies, hence, the LCOE, which is highest for offshore and lowest for solar, which affects the order of the advantage to source grid electricity mix when allowed.

Starting from the right with offshore, the net LCOH increases slightly, whereas *BTM Solar Hourly* and *BTM Onshore Monthly* decrease in price. So *BTM Offshore* benefit from the two derogations, this is because the <0.36xEUA translates to a <43 €/MWh[4] price threshold, meaning that whenever the Day-ahead price is lower than 43 €/MWh it can be claimed renewable. The sourcing cost from offshore wind is 37 €/MWh; why the sourcing costs are not increased substantially as the vast share of the electricity purchased in the periods <43 €/MWh is cheaper than the electricity from offshore wind. Hence, the average sourcing costs are lowered.

Contrary, onshore wind and solar are mainly disadvantaged from the derogation as the sourcing costs, 23 and 28 €/MWh, respectively, are mostly lower than the Day-ahead price paid when sourcing grid electricity mix (<43 €/MWh). Hence, the decrease identified in the case of *BTM Solar Monthly* and *BTM Onshore Monthly* is due to the same causes identified at the wind-solar setup assessed earlier; at monthly matching, the RNFBO producer already benefits from the flexibility of operating when electricity prices are low, hence, scrapping the two derogations would allow the RNFBO producer to place a higher share of the electricity consumption in these hours.

In general, the LCOHs are not changed substantially when scrapping the derogations, indicating they have little impact on the production costs of electrolytic hydrogen.

[4] Assuming a EUA price at 118 €/tCO_2 in 2030. See chapter X assumptions.

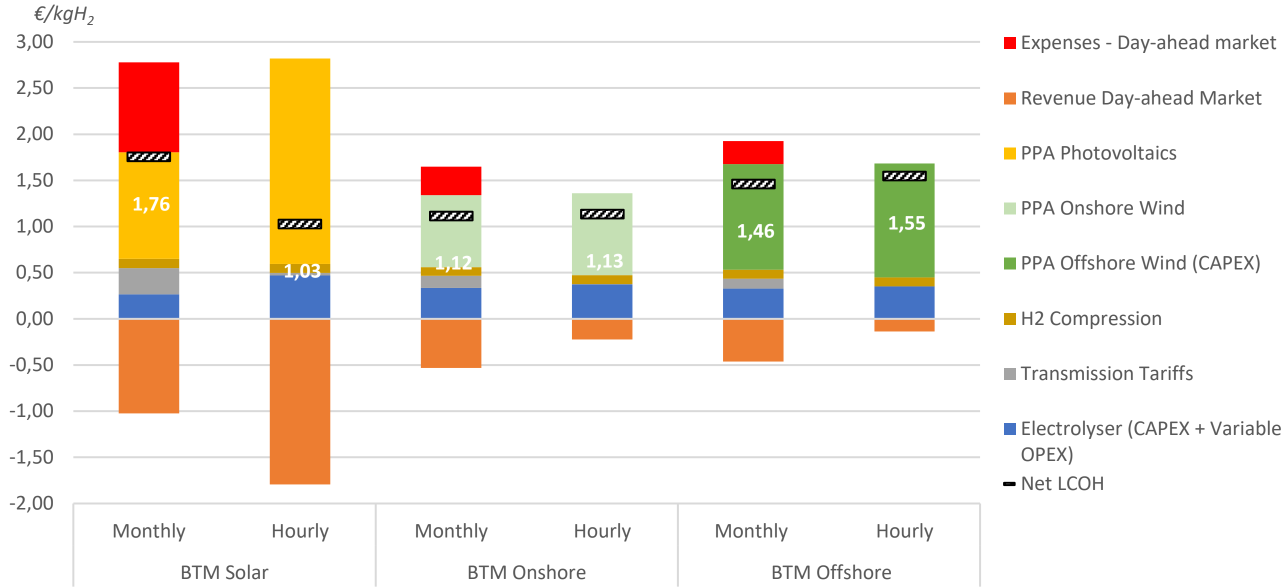

Figure 15 LCOH at Behind-the-Meter Setups with Monthly and Hourly Matching - Excl. Grid Mix Derogations

Notes The figure shows the cost components at the three BTM setups at monthly and hourly matching. This is similar to Figure 14 but without the option to claim grid electricity mix renewable when <20 €/MWh or <0.36xEUA. The impact of applying hourly matching at a BTM Solar setup is substantial, whereas the impact is less pronounced in the BTM setups with wind. Nevertheless, BTM Solar has a substantially higher revenue from excess electricity (orange area). The lowest production costs are identified at the BTM Onshore setup.

Source Own calculations based on EnergyPRO and Excel.

Figure 14 and Figure 15 do also display that there is little difference in LCOH when going from monthly to hourly matching for *BTM Onshore* and *BTM Offshore* setups. This can be explained by the rather small reduction in capacity factor, going from 0.59 at monthly matching to 0.53 and 0.55 at hourly matching, respectively. A significant drop in LCOH is identified in the *BTM Solar* setup when moving to hourly matching, which is due to the significant revenue stream from excess electricity while also reducing the hydrogen production, making it an unfavourable setup. It is important to note that this is not considering the option to conclude PPAs with other RES technologies, as the case was in the earlier in wind-solar setup.

To summarise the findings so far on the DA's impact on production costs at BTM setups: First, a *BTM Solar* setup relies heavily on revenues from the electricity wholesale market due to the high-capacity ratio between RES assets and electrolysis, which is especially pronounced when applying hourly matching. Second, no clear tendency is identified when going from monthly to hourly matching, as this can both increase and decrease the LCOH. The ambiguous findings are because at monthly matching, Onshore and Solar do not benefit from sourcing electricity, as this is most of the time more expensive than sourcing the respective RES generation asset with a lower cost (the respective LCOE). Additionally, the Pay-as-produced structure does also lead to unfavourable conditions for trading electricity at the Day-ahead market, as this often leads to a net loss. The differences in LCOH identified at the two BTM wind setups when moving to hourly matching are, however, considered rather small. Similar are the results identified when removing the option to source grid electricity mix, where only negligible changes are observed.

7.2.3 LCOH Sensitivities

This sub-chapter will examine the robustness of the results. First, a simple sensitivity analysis of each cost component in the setups is conducted in Excel, which will be followed an in-depth sensitivity exercise of the BTM setups' robustness to changes in the capacity factor simulated in EnergyPRO.

Each cost component in all assessed setups is subject to modification to determine how sensitive net-LCOH is to change in the given setup. The values are altered by 50 pct. Table 7 illustrates the percentage change in the net-LCOH when each cost component is altered by -/+ 50 pct. High numerical values mean high sensitivity.

Table 7 Percentage Change in Total LCOH with 50 pct. Sensitivity

	PPA Onshore	PPA Offshore	PPA Solar	Electro-lyser	Revenue Day-ahead	Expenses Day-ahead	Trans. Tariffs	H_2 Comp.
Monthly	16%	0%	7%	9%	-10%	10%	16%	3%
Monthly (fixed offtake)	12%	0%	10%	6%	-10%	15%	14%	3%
Hourly	17%	0%	7%	9%	-3%	1%	16%	3%
Hourly (fixed offtake)	18%	0%	16%	9%	-13%	1%	16%	3%
BTM Solar Monthly	0%	0%	27%	7%	-22%	26%	9%	3%
BTM Solar Hourly	0%	0%	82%	18%	-66%	6%	6%	4%
BTM Onshore Monthly	28%	0%	0%	12%	-18%	16%	7%	4%
BTM Onshore Hourly	34%	0%	0%	14%	-9%	3%	3%	4%
BTM Offshore Monthly	0%	34%	0%	11%	-13%	11%	5%	3%
BTM Offshore Hourly	0%	37%	0%	11%	-4%	2%	2%	3%

Notes The operational signs are reversible, so if the costs would decrease with 50 pct. the operational sign would reverse. Note that revenues from Day-ahead have a negative operational sign as it is a revenue and not expense.

Source Own calculations based on EnergyPRO and Excel.

Table 7 shows that the sensitivity towards the individual components vary substantially between the setups. In general, the sensitivity towards the electrolyser system is generally low, though, it increases in some of the BTM setups. Additionally, it is evident all setups are sensitive to RES PPA, which would change the net-LCOH with 20-30 pct. depending on the setup. However, it is important to note the likeliness of each cost component to either decrease or increase, and further, if additional cost components were included, the sensitivity towards the individual components would be reduced.

Zooming in on the four onshore-solar setups (top of Table 7), there is not one parameter that stands out as being significant regarding sensitivity. Contrary, BTM setups are obviously more exposed to changes in the PPA as they rely on one RES electricity source.

In general, the sensitives identified in this exercise are significant, indicating that the changes in LCOH caused by the DA temporality requirements must be considered relatively insignificant.

7.2.3.1 Capacity Factor in BTM Setups

A sensitivity analysis was done on capacity factor of the electrolysis in the BTM setups to evaluate the net-LCOH's sensitivity towards changes in utilisation rate at monthly matching. These analyses was done by either increasing or decreasing the capacity of the electrolysis, hence, making the capacity ratio smaller or bigger. The analyses were conducted in EnergyPRO. This was only done in the setups applying monthly matching to check feasibility of the capacities identified using linear optimization, to examine whether the BTM monthly matching setups benefited from a higher capacity factor.

The results from the exercise are displayed in Figure 16. The setups applied in the previous are marked with bold, and the capacity of the electrolysis [MWe] are displayed on the x-axis, descending. The sensitivity analyses did decrease the capacity of the electrolysis, as it was presumed a setup with monthly matching would benefit from a higher capacity factor by taking advantage of the flexibility provided at monthly matching. With one exception being at *BTM Solar* where a larger capacity was checked.

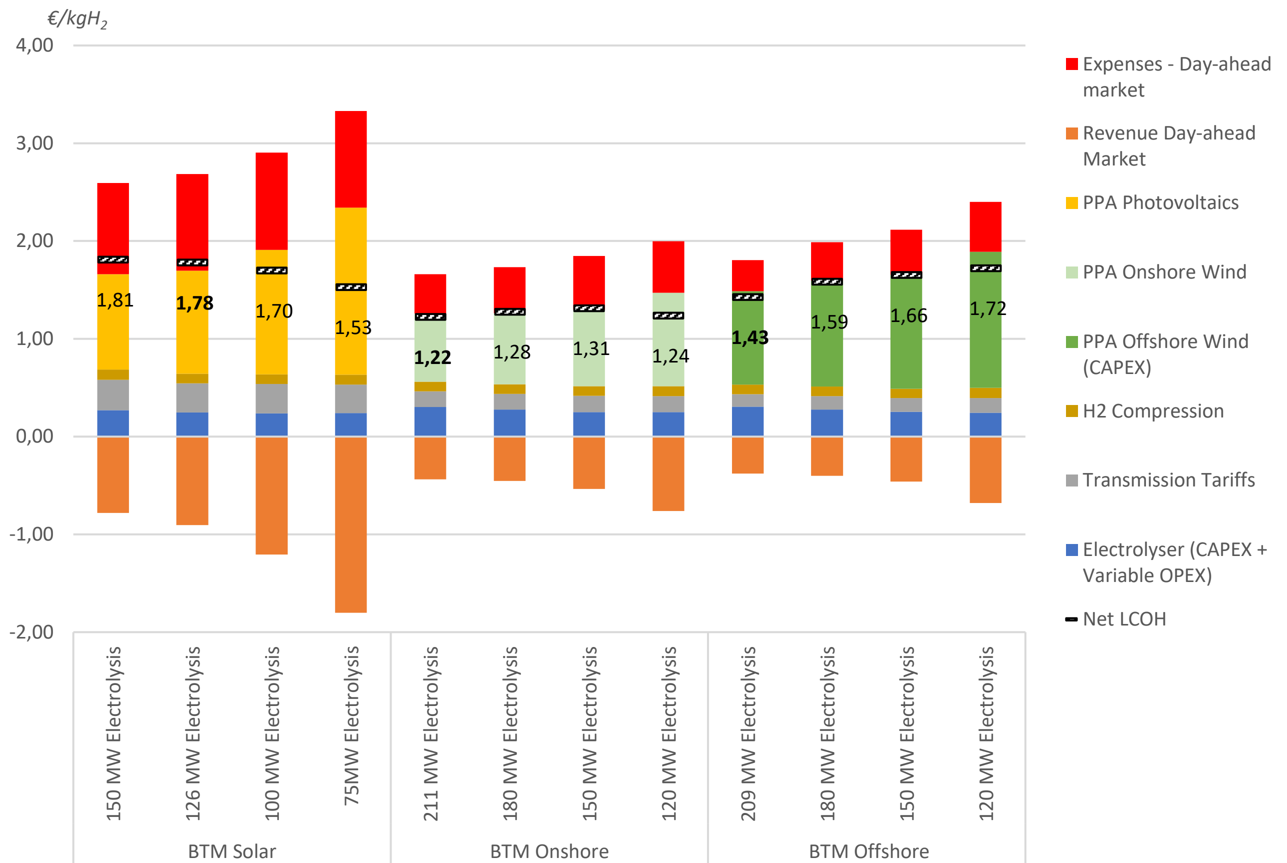

Figure 16 BTM Setups Sensitivity to the Capacity Factor

Notes The figure illustrates the three BTM setups sensitivity to changes of the electrolyser capacity. All the setups are at monthly matching. The X-axis shows the capacity of the electrolysis (descending) at the three BTM setups. BTM Onshore and BTM Offshore does not benefit from a smaller electrolysis capacity, hence, increased capacity factor. This is contrary to BTM Solar.

Source Own calculations based on EnergyPRO and Excel.

The capacity factors go from and up to:

- BTM Solar: 0.73-0.84
- BTM Onshore 0.59-0.80
- BTM Offshore 0.59-0.82

There is a clear pattern when focusing on the development of the net-LCOH in the three BTM setups. At *BTM Onshore* and *BTM Offshore* setup the net LCOH increases as the capacity of the electrolysis decreases, hence, increasing the utilisation rate is disadvantageous. The trend is clearer at *BTM Offshore* experiencing a 20 pct. increase in net-LCOH. In contrast, the net-LCOH at *BTM Onshore* remains rather stable and takes a drop to the initial level when going to a 120 MWe electrolysis, the drop is due to the increasing revenue from excess electricity. The opposite happens for solar, where the net LCOH decreases with the reduced electrolysis capacity, however, it is clear this is driven by an increasing revenue from excess electricity. The LCOH drops by 15 pct, when halving the electrolysis capacity.

The identified changes in LCOH and the proportions between the three BTM setups should not be interpreted as exact figures, as the costs do not consider the additional costs of such a BTM setup, as the interconnection varies in both length and capacity this is especially the case for the *BTM Offshore* setup that presumably entail excessive extra costs compared to the two other setups.

The magnitude of the changes in LCOH when increasing the capacity factor in all three BTM setups illustrates that the production costs are more sensitive to changes in utilization rate than the changes observed when going from monthly to hourly matching requirements by 2030. However, the sensitivity varies between RES technology, with a *BTM Onshore* setup being the least sensitive, while the *BTM Solar* setup is the most sensitive.

7.3 Impact on the RNFBO Production Facility Setup

Following the assessment of the DA's impact on cost when moving towards hourly matching, it is evident to examine the potential impact on the design of the RNFBO facilities beyond the RES electricity supply and electrolysis. This will be examined by drawing on literature and the interview with BPP especially.

From the point of view of the BPP interviewee, the DA is not likely to drive any change in electrolysis technology, as the common technologies i.e., Alkaline, PEM, and SOEC are able to respond to power signals quickly enough to comply with hourly matching (Appendix IV BPP). The interviewee added that a shift in technology is only likely to happen if an electrolysis technology with higher efficiency can reduce the sourcing costs, despite its higher CAPEX (Appendix IV BPP). Because electrolysis with higher efficiency can be favourable when facing high sourcing costs in terms of electricity prices or PPAs, this comes down to the relation between increased CAPEX and potential gains by increasing efficiency (Appendix IV BPP). A higher efficiency can also be achieved by using thinner membranes, though this comes with a trade-off as it increases the shorter lifetimes; increasing OPEX (IRENA, 2020, p. 42).

The BPP interviewee argues that the capacity factor of the electrolysis will still mainly be determined by the potential offtake agreement. Nevertheless, pointing out that the DA will likely result in offtake agreements spanning over longer periods e.g., monthly, quarterly, or yearly as the temporal matching requirements reduce the flexibility of operation (Appendix IV BPP).

The RES sourcing combination and electrolysis design do also heavily depend on the later arrangements e.g., is the electrolysis fed into a grid, storage, or converted to an e-fuel. If the electrolytic hydrogen is used as an intermediary produced to produce e-fuels, serving the need of the downstream process e.g., methanol synthesis is the priority (Appendix IV BPP). Afterwards, the operation of the electrolysis can be optimized against the Day-ahead market and potentially intraday market (Appendix IV BPP). The BPP interviewee, thus, emphasised that the DA will not speed up this development as this is important to consider regardless (Appendix IV BPP Though strict temporal matching can potentially speed up the deployment of hydrogen storage to provide flexibility, though, this is highly project-specific (Appendix IV BPP).

This is backed by developer 2, that explains that one of their projects is a methanol project, where the electrolytic hydrogen is directly fed into the methanol synthesis (Appendix III Developer 2). Developer 2 further explains that feeding the hydrogen directly into the methanol synthesis where it is combined with CO_2, and the methanol is then stored together with water, functioning as a storage. Then the methanol and water are separated via distillation, which is the most inflexible part of the process when converting hydrogen to methanol, hence, also the biggest barrier for operating flexible (Appendix III Developer 2). The intermediary storage of raw methanol can provide flexibility and buffer and enable dispatching the electrolyser while still running the distillation process (Appendix III Developer 2). Developer 2 added that they are exploring the feasibility of including hydrogen storage in future projects. Asked to fixed offtake agreements, Developer 2 stated that they had integrated flexibility in the monthly offtake volumes to mitigate risks off variable RES production (Appendix III Developer 2.

In summary, the impact of the DA on the RNFBO production setup goes beyond electricity supply and electrolysis. Existing electrolysis technologies can adjust the load quickly enough to operate under hourly matching. The capacity factor of electrolysis depends on the offtake agreement, likely spanning longer periods due to especially the hourly matching requirement. Considerations for downstream processes and flexibility, such as methanol synthesis and hydrogen storage, are project-specific and highly dependent on the potential flexibility provided by the RES supply or offtake agreement and not necessarily accelerated by the DA.

7.4 Preliminary Conclusion

The present analysis purpose was to answer the following sub-question: *How will the delegated act on RNFBOs impact the production costs and production facility setup?* This was examined by analysing electrolyser system supplied by various RES electricity combinations contracted via Physical or BTM PPAs with a Pay-as-produced structure.

In conclusion, the findings suggest that the impact of the DA on production costs and facility setup for RNFBOs is relatively insignificant when transitioning from monthly to hourly matching. The analysis reveals that the transition from monthly to hourly matching requirements has a trivial impact on the production costs of RNFBOs. This holds true for both fixed monthly offtake setups and setups without a fixed monthly offtake.

When applying granular matching requirements, onshore wind and solar are identified as the most cost-efficient combination, with the majority produced from wind. Applying a fixed monthly offtake increase the share of solar to benefit from the intra-annual variabilities. Further, the results show that a fixed monthly demand when hourly matching is valid requires a diversified supply.

Regardless of the offtake and matching requirements, the production costs in the all setups remain economically viable compared to a grid-electricity setup. The use of pay-as-produced PPAs combined with the derogations diminishes the economic differences between monthly and hourly matching. Furthermore, the sourcing cost from the contracted PPA RES assets is essential for the feasibility of utilizing the feasibility provided at monthly matching and by the derogations allowing grid electricity to be claimed renewable.

Regarding the impact on BTM setups, the reliance on wholesale market revenues is more pronounced in BTM Solar setups due to the high capacity ratio between RES assets and electrolysis. The shift from monthly to hourly matching does not show a clear tendency in terms of the LCOH. Pay-as-produced structures create unfavourable conditions for trading electricity at the Day-ahead market, often leading to a net loss. The changes in LCOH caused by the DA's temporality requirements are considered relatively insignificant, with larger impacts observed from changes in utilization rates. BTM Onshore setups are the least sensitive to such changes, while BTM Solar setups are the most sensitive.

The trivial impact on the LCOH when going from monthly to hourly matching emphasise the sensitivity towards OPEX and the electrolysis' capacity factor. This is caused by the relatively small impact of the electrolyser CAPEX as 2030 estimates are applied. The impact of temporal matching will depend on the CAPEX share of LCOH, as a high share would require a higher utilisation rate, and vice versa. In relation, the applied dataset on Day-ahead prices was identified as critical for the analysis and the results.

Furthermore, the impact of the DA extends beyond electricity supply and electrolysis, encompassing downstream processes and flexibility considerations such as methanol synthesis and hydrogen storage. The potential flexibility provided by the RES supply or offtake agreement, rather than the DA, influences project-specific decisions regarding these aspects. Overall, the DA's influence on RNFBO production setup goes beyond electricity supply and requires careful consideration of various project-specific factors.

7.5 Limitations

It is important to emphasise that there are substantial limitations associated to the present analysis. The following will unfold the key limitations and their implications.

The main limitation stems from linear optimization conducted in Excel, as the model was not able to optimize the electrolytic hydrogen production but only the RES supply while modifying the electrolysis capacity, but not the production. However, this was partly mitigated by investigating several setups and testing for sensitives, and further by simulating the operation in EnergyPRO. Thus, the capacity ratio between RES assets and electrolysis pivotal for the LCOH, as displayed in Subsection 7.2.3. This finding challenges the identified changes in LCOH when going from monthly to hourly matching and when allowing counting grid electricity mix renewable. This also goes for the exclusion of electrical and hydrogen storage systems. Nevertheless, the analysis was still able to identify general trends and single out key assumptions to adequately draw some conclusion on the DA's impact on cost.

The model is set to optimise hydrogen production by utilising the RES available, which means that at monthly matching the excess RES sold from the contracted PPA assets are consumed in hours with relative high price due to the derogation. This is in line with the DA's provisions, however, an RNFBO producer might not decide to utilise all the RES available. If not, this could magnify the cost-premium when applying hourly matching. This will be context-specific and will determined by the obligations in the offtake agreement.

Furthermore, this approach does not consider the aspect of additionality, and if there exists a difference in PPA tariff between existing and new RES plants. The present thesis is not able to assess the impacts of the additionality aspect of the DA, though, one may presume that the difference and issues related to concluding PPAs with new and additional assets is caused by the permitting deadlines, and not necessarily a difference in price. It is critical to note, that this is not backed by any of the interviewees, as they were not able to share any information in relation to the level price level of PPAs.

8 Discussion

This discussion will place the findings of the present thesis in the context of existing literature to identify similarities and differences. This serves to validate the robustness and reliability of the findings. Consistency or divergence from previous studies can indicate the strength and generalizability of the present thesis. Further, this chapter will address limitations and the implications of the research and discuss how and to what extent the results from a stand-alone electrolyser system can be used to answer the research question regarding RNFBOs in general. Furthermore, the findings of the two analyses will be discussed by applying the theoretical framework *Choice Awareness*.

8.1 Optimising RES supply for RNFBOs

This subsection will discuss the RES electricity supplies for RFNBOs and compare the optimised RES supplies in the present thesis with the literature. A few studies include an explicit cost-optimised combination of RES electricity generation at various temporal matching levels for electrolysers, this being Zeyen et al. (2022), Ricks et al. (2023), and Ruhnau & Schiele (2022).

Zeyen et al. (2022, p. 20) identifies solar as the favourable source of renewable electricity at annual matching requirements, and when applying hourly matching levels, both solar and onshore wind is needed with more wind production than solar. The findings cannot be transferred directly to the present thesis as Zeyen et al. (2022) optimise on a different scale with capacity constraints. Ricks et al. (2023, p. 8) do similarly identify the cost-optimal RES combination for electrolysers across various states in the U.S.. One of the findings is that more strict matching requirements lead to a combination of solar and wind, with wind favoured. Similar to Zeyen et al. (2022). However, the exact combination varies between locations, which highlights the importance of considering the geographical context (Ricks et al., 2023). A similar share between onshore wind and solar is found in the present thesis at hourly matching, where around ¾ of the electricity is generated by onshore, though this changed when a fixed monthly demand was applied. This substantiates the results in the present thesis.

Further, this suggests that it is cost-efficient to source from complementary RES technologies at strict temporal matching requirements taking advantage of the non-linear correlation between solar and wind (Jacobson, 2021). This is also backed by Brauer et al. (2022, p. 23) highlight the importance of considering several RES technologies and not limiting the analysis only to include one or two technologies, as seasonal differences in resource availabilities between technologies can be neglected. That is also why solar, onshore wind, and offshore wind is considered in the present thesis. Though a pure BTM setup with offshore wind cannot compete on cost with a BTM Onshore setup, nonetheless, given the pace of deploying wind turbines relying on offshore wind is seemingly more realistic. It is not likely to deploy the capacities needed onshore at one location to provide enough electricity for a large-scale electrolyser system with a BTM setup. Pure BTM solar setups do likewise seem unrealistic, given the high capacity ratio identified and the poor performance at hourly matching. Hence, wind PPAs would likely supplement a BTM solar setup. Therefore, offshore and combined solar-wind setups are more realistic.

In relation, Zeyen et al. (2022) find that the ratio of onshore wind and solar depends on the operational flexibility of the electrolysis. Ruhnau & Schiele (2022, p. 15) similarly find that flexible operation without temporality would decrease the capacity ratio between the RES unit and electrolysis in the respective study of an onshore wind turbine and electrolysis setup. Additionally, since Ruhnau & Schiele (2022, p. 15) also examine the inter-annual variation of weather patterns, they find that the variation in the cost-optimal size of the electrolyser and of the hydrogen storage is substantially reduced relative to an islanded setup and hourly matching. But the optimal size of the wind turbine varies from year to year. So, lenient matching requirements, e.g., annual, mean that one system configuration is likely cost-optimal for all years, contrary to a case with hourly matching. This indicates that hourly matching requirements will entail additional costs for RNFBO producers due to inter-annual weather variations (Ruhnau & Schiele, 2022, p. 15). The significance of this is difficult to estimate. Nonetheless, it highlights the importance of considering inter-annual variability when optimising the RNFBO setup and further the importance of integrating flexibility in terms of storage.

8.2 Integrating Electrical or Hydrogen Storage to Unleash Flexibility

This subsection will delve into the DA's impact on RNFBO production facility setups and, more specifically, storage availability and production flexibility.

Two obvious ways of providing flexibility to the RNFBO production facility are by integrating storage facilities in the form of an electrical or hydrogen storage system. An electrical storage system can provide flexibility for electrolysis and can further increase the utilisation at peak RES electricity generation. Hydrogen storage can likewise provide flexibility for the electrolysis and the downstream processing of the electrolytic hydrogen e.g., via a methanol synthesis.

The model used in the present thesis does not consider an electrical storage system, which is a methodological delimitation, as the DA allows such if located behind the meter cf. Article 6 (*Commission Delegated Regulation C(2023) 1087 Final*, 2023). An electrical storage system could help utilise peak hour RES production, which is likely more feasible with a setup with a high RES and electrolysis capacity ratio, as the case is with solar. Even in the strictest case modelled by Brauer et al. (2022, p. 18) did not result in investments in electrical storage, which is substantiated by Zeyen et al (2022). Therefore, the general feasibility of investing in electrical storage systems is highly questionable, even at hourly matching. The investment in electrical storage should be compared with the cost of over-investing in RES electricity generation capacity. Hydrogen storage, however, indicates to be more economically feasible.

The literature shows that CAPEX and OPEX for hydrogen storage technologies are decisive for feasibility. The impact of LCOH varies and depends on the design of the model. Brauer et al. (2022, p. 23) finds that the most economical storage, Liquid Organic Hydrogen Carriers, is deployed even in the case of annual matching requirements. Brauer et al. (2022, p. 18) find that the impact on LCOH varies between 0.04-0.30 €/kgH_2, which is rather small. In addition, Zeyen et al. (2022, p. 7) show that the LCOH is highly sensitive to the flexibility provided by storage, especially the associated costs. Hydrogen storage is disregarded in the present thesis, as the recent announcements of hydrogen pipelines potentially can obviate onsite storage (Klima-, Energi- og Forsyningsministeriet, 2023b, 2023a). However, the literature illustrates that storage is essential when cost-optimising a specific facility to counter imbalances between RES supply and a potential hydrogen offtake agreement. The dataset applied in the present thesis substantiated this, as September was a challenging month to meet the fixed monthly demand at hourly matching, which is why storage or contractual flexibility can counter such events. Optimisations based on one weather year risk missing such vulnerabilities. Hydrogen storage could have turned out to be more feasible than increasing the investments in RES generation capacity in the setups with a fixed monthly offtake, which could have diminished the cost premium associated.

Since the present thesis and the identified literature only assess an electrolyser system and not downstream processing to synthetic fuels, the impacts of imposing monthly and especially hourly matching might be underestimated, as the electrolyser is a highly flexible component compared to more inflexible processes like methanol synthesis and green ammonia production, or as a constant flow in industrial processing (Energistyrelsen, 2023b, pp. 212, 290)

In addition to the considerations related to the economic feasibility, there are also some considerations regarding permits. Developer 2 explained that they do not include a hydrogen storage system in their initial RNFBO production setup as this would entail a substantial load of additional security and environmental permits, risking delaying the project (Appendix III Developer 2). However, Developer 2 did emphasise that they were monitoring the economic feasibility of integrating a hydrogen storage system to provide operational flexibility (Appendix III Developer 2).

8.3 Production Costs in the Context of Existing Literature

This subsection will discuss the present thesis' findings on production cost in relation to the literature covered in Subsection 2.3 and by including a policy memo comparing studies on renewable hydrogen in the U.S. published by Ricks & Jenkins (2023).

The present thesis finds trivial impacts on cost when going from monthly to hourly matching, whereas the literature, in general, identifies a cost premium when a fixed hydrogen demand is applied. This becomes more prominent as a more expensive hydrogen storage technology is applied (Brauer et al., 2022, p. 17; Zeyen et al., 2022, p. 25). Further, Zeyen et al. (2022, pp. 8, 25) identifies 3-5 pct. higher cost at monthly matching compared to annual matching, and a similar cost-premium when going from monthly to hourly in setups with flexible demand. The latter is substantiated by the present thesis, which similarly finds equal LCOHs at monthly and hourly matching in setups with flexible, though with the exception of BTM Solar.

In addition, the present thesis similarly identifies a more prominent cost premium when applying a fixed monthly demand relative to no demand. The present thesis differs from Zeyen et al. (2022) and Brauer et al. (2022, p. 11) as they both apply a continuous daily demand, whereas the present thesis applies a monthly demand. However, it is evident from Zeyen et al. (2022, p. 25) that the type of storage can have a substantial impact on the cost, especially at hourly matching, underlining the importance of integrating flexibility in the production process. This is further emphasised as Brauer et al (2022) apply hydrogen storage in the form of LOHC, hence, hydrogen storage remains a rather insignificant cost component regardless of the temporal matching requirements (Brauer et al., 2022, p. 18; Zeyen et al., 2022, p. 11). This indicates that the production cost is more sensitive to the hydrogen demand and storage availability than going from monthly to hourly matching. In addition, the sensitivity is more prominent in hourly matching than monthly. This suggests that the cost impact of the DA varies and depends on storage availability.

In the present thesis, it is evident that the inclusion of the derogations allowing accounting the grid electricity mix as renewable when <20 €/MWh and <0.36xEUA further diminishes the potential cost premium when going from monthly to hourly matching. The derogations are not included in the two papers by Brauer et al (2022) and Zeyen et al (2022), which can, amongst others, explain the insignificant and diverging cost premiums found in the present thesis relative to the two studies. The two derogations allowing claiming grid electricity mix renewable have a relatively small impact on the LCOH. The results suggest that the effect is further diminished by the pay-as-produced PPA structure, and in some cases, the two derogations increase the LCOH, depending on the level of the agreed PPA price.

One of the clear differences between the present thesis and the study designs of Zeyen et al. (2022) and Brauer et al. (2022, p. 11) is that the present thesis applies a Pay-as-produced structure to the PPAs. Brauer

et al. (2022) and Zeyen et al. (2022) do include additional RES generation capacity similar the present thesis. However, the pay-as-produced structure eliminates the advantage of the flexibility provided at monthly matching, as the excess electricity can be sold with a loss if the agreed price is higher than the Day-ahead price, whereas this is not the case in the study designs applied by Brauer et al. (2022) and Zeyen et al. (2022). This explains the trivial results in the analysis and further indicates that the PPA structure is pivotal for the feasibility of over-procuring RES supply. Nonetheless, over-procuring solar can be more economical than over-procuring offshore wind, as solar is more cost-efficient, hence, lower agreed offtake price, more likely to provide revenue when excess electricity is sold Day-ahead with a pay-as-produced PPA. However, this does not consider the cannibalisation effect of the respective technologies, which is higher for solar, and could reverse the claim (López Prol et al., 2020).
Again, this is highly geographically dependent on the price level in the respective bidding zone but also shows the sensitivities towards changes in the Day-ahead price. In this context, it is also relevant to note that the applied Day-ahead dataset has a steep cost increase in a relatively short time, 10 days, the Day-ahead price increase from 60 to 80 €/MWh, at around hour 5600. Hence, capacity factors over 0.60 can potentially result in substantially higher marginal Day-ahead prices, which is seen in the *Monthly* and *Monthly (fixed offtake)* (see Table 5 on page 44). This can potentially explain the slight difference in LCOH seen when going from monthly to hourly matching in the solar-onshore setup. The model could not avoid the relatively expensive hours by investing in storage or the like, which is a methodological limitation. This fact complicates generalisation to other geographical contexts and bidding zones.

The LCOH has been proven to be sensitive towards the utilisation rate of the electrolysis as explored in Subsection 7.2.3. Figure 11 on page 49 shows the clear relation between Day-ahead price and the resulting LCOH. This finding is further backed by Ricks & Jenkins (2023), who compare a broad range of studies assessing the cost of producing hourly matched electrolytic hydrogen. They find that high electrolysis CAPEX needs a higher utilisation rate to bring the LCOH down, while the expected electrolysis CAPEX in 2030, similar to the present thesis, is less sensitive to the utilisation rate (Ricks & Jenkins, 2023, pp. 6–8).

The present thesis did investigate the cases where additionality, geographical, and temporal correlation were imposed, however, the DA would likely have a smaller impact if the >90 pct. RES share or <18 gCO2/MJ thresholds are met. These cases are beyond the scope of the present thesis to assess.

8.4 Choice Awareness: Enabling a Radical Technological Change

This subchapter will apply the theoretical framework *Choice Awareness* as presented in Chapter 4 to contextualize the results, and further help the understanding of RNFBOs in relation to radical technological changes. This is useful to frame the analyses and its findings. It is evident that a shift from fossil fuels etc. to RNFBOs has required a shift in all five constituents of technology: 1) Technique, 2) Knowledge, 3) Organisation, 4) Products, and 5) Profits (Lund, 2014b, p. 20),.

The shift in technique is clear when going from hydrogen based on natural gas using steam methane reformation to hydrogen produced from electrolysis based on renewable electricity. This further necessitates new knowledge, as the production process is radically different. The organisational changes happened as a new regulatory framework was needed to define when a fuel could be an RNFBO, hence, claimed renewable. The supply chain of the product is substantially changed, but this does not necessarily change the end-product, as an RNFBO can have the same properties as the fossil counterpart. Lastly, profits, the economic viability of RNFBO production is key for deploying the production at scale. This consideration for profits is also apparent in the published DA, as a transitional phase is included regarding additionality for RNFBO production facilities coming online before 2028 remains exempt until 2038.

Furthermore, hourly matching will be introduced by 2030 due to technological barriers, as stated in Recital 16 in the DA, as there is a lack of infrastructure to provide a constant supply for the end users relying on such (*Commission Delegated Regulation C(2023) 1087 Final*, 2023). Recital 19 furthermore states that monthly matching was chosen in the short-term to enable a ramp-up of RNFBO production, in other words, with consideration for the feasibility. This illustrates that deploying technology is not only a matter of technological readiness but also relies on a rightful regulatory framework and economic viability, hence, technology cannot be perceived as a one-dimension phenomenon.

The subsequent changes in the latter four constituents underline the point made by Lund (2014b, p. 20) that the technological shift to electrolytic hydrogen would not happen if at least one of the other constituents followed. In the case of RNFBOs, a shift in several of the constituents was needed.

The case of RNFBOs, further substantiates the point made by Lund (2014b, p. 22) that the change to renewable energy systems is to be regarded as radical technological change - a radical technological change prerequisite substantial changes in existing organizations and institutions.

9 Conclusion

The present thesis aim was to examine the following research question: *How will the European Commission's delegated act on RNFBOs impact the production of RNFBOs?* The research was conducted via two sub-questions related to the impact of the European Commission's DA on RNFBOs. The first sub-question examined how renewable electricity can be traced and accounted for on a granular basis, and the implications of the DA on the design of renewable PPAs for RNFBO production. The second sub-question focused on the impact of the DA on production costs and facility setup. By integrating the findings from both sub-questions and the discussion a conclusion can be drawn.

A GO scheme plays a crucial role in tracing and accounting for renewable electricity, ensuring compliance and avoiding double claiming. Granular GOs can effectively track and account for grid-sourced electricity contracted from renewable PPAs, providing the necessary information for RNFBO producers to claim compliance. However, it is essential to emphasize the importance of the revised RED enabling granular GOs, as they are essential for compliance with hourly correlation requirements. The implementation of granular tracking and accounting of electricity can be done through the use of metering data and a reliable platform. Additionally, proving the contractual connection between the claimed RES electricity and PPAs is necessary, and further additional information of the grid mix is needed to claim grid electricity mix as renewable.

Clear directions were identified on how the DA impacts the design of PPAs for RNFBO production. The requirement of hourly matching by 2030 implies a shift towards pay-as-produced structures for PPAs concluded with - or supplemented by - assets off-site. Shaped PPA structures are likely achieved by combining multiple pay-as-produced PPAs with different generation technologies, such as wind and solar to increase the utilisation rate. However, this approach carries the risk of over-procurement, necessitating the sale of excess electricity in the Day-ahead market. The additionality provision suggests RES PPAs are more likely to be concluded with solar and offshore wind, this is, however, highly geographically dependent.

Furthermore, the impact of the DA on production costs and facility setup for RNFBOs is relatively insignificant when transitioning from monthly to hourly matching. The results indicate that the transition to hourly matching requirements has a trivial impact on production costs. Regardless of the offtake and matching requirements, all setups remain economically viable compared to grid-electricity setups. Pay-as-produced PPAs combined with derogations help mitigate economic differences between monthly and hourly matching. The sourcing cost from contracted RES assets is crucial for the feasibility of utilising the advantages provided by monthly matching and derogations.

The impact of the DA on BTM setups varies depending on the capacity ratio between RES assets and electrolysis. BTM Solar setups rely more on wholesale market revenues, while the changes in LCOH caused by the DA's temporality requirements are relatively insignificant compared to changes in utilisation rates. The sensitivity towards OPEX and electrolysis capacity factor highlights the importance of carefully considering these factors in relation to the impact of temporal matching. Downstream processes and flexibility considerations, such as methanol synthesis and hydrogen storage, are influenced by RES supply or offtake agreements rather than the DA itself. Nonetheless, hourly matching requirements can precipitate the need for hydrogen storage, the consequence of this is highly dependent on the availability of storage technology.

In conclusion, the present thesis demonstrates that the DA's influence extends beyond electricity supply and electrolysis, encompassing various project-specific factors. The GO scheme enables granular tracking and accounting of renewable electricity, supporting compliance and avoiding double claiming. The DA's impact on the design of renewable PPAs for RNFBO production involves a shift towards pay-as-produced structures and the potential use of combining PPAs to increase full-load hours. This is especially driven by the hourly matching requirements. However, careful consideration is required to mitigate the risk of over-procurement. The impact of the DA on production costs and facility setup is relatively insignificant, with greater sensitivity observed in utilization rates rather than the transition from monthly to hourly matching. The impact of the DA ultimately depends on geographical context, as the DA’s provisions are determined by the renewable electricity penetration in the grid to which the RNFBO production facility is connected.

10 Reference list

Bjørn, A., Lloyd, S. M., Brander, M., & Matthews, H. D. (2022). Renewable energy certificates threaten the integrity of corporate science-based targets. *Nature Climate Change*, *12*(6), 539–546. https://doi.org/10.1038/s41558-022-01379-5

Brauer, J., Villavicencio, M., & Trüby, J. (2022). Green hydrogen – How grey can it be? *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4214688

Brinkmann, S., & Tanggaard, L. (2010a). 1. Interviewet: Samtalen som forskningsmetode. In *Kvalitative Metoder—En Grundbog* (1st ed., Vol. 5, pp. 29–55). Hans Reitzels Forlag.

Brinkmann, S., & Tanggaard, L. (2010b). Introduktion. In *Kvalitative Metoder—En Grundbog* (1st ed., Vol. 5, pp. 17–20). Hans Reitzels Forlag.

Brintbranchen. (2023a, May 16). *European Energy tager spadestik til e-metanol-anlæg i Kassø*. Brintbranchen. https://brintbranchen.dk/european-energy-bygger-verdens-stoerste-e-metanol-anlaeg-i-kassoe/

Brintbranchen. (2023b, May 23). *Brintprojekter i Danmark kortlagt i Brintbranchens statistikbank Brint i tal*. Brintbranchen.dk. https://brintbranchen.dk/brintprojekter-i-danmark/

Christensen, A. (2020). *Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe*. International Council on Clean Transportation.

Council of the EU and the European Council. (2023, March 30). *Council and Parliament reach provisional deal on renewable energy directive*. https://www.consilium.europa.eu/en/press/press-releases/2023/03/30/council-and-parliament-reach-provisional-deal-on-renewable-energy-directive/

Creswell, J., W. (2009). *Research Design—Qualitative, Quantitative, and Mixed Methods Approaches* (3rd ed.). SAGE Publications, Inc.

Danish Energy Agency. (2021). *Technology Data for Renewable Fuels*. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels_0.pdf

EMD. (2022). *User's Guide energyPRO*. https://www.emd-international.com/energyPRO/Tutorials%20and%20How%20To%20Guides/energyPROHlpEng-4.8%20Jun%2022.pdf

Energinet. (n.d.-a). *Energy Origin—GRANULAR CERTIFICATES FOR ENERGY ORIGIN*. Retrieved April 21, 2023, from https://en.energinet.dk/energy-data/datahub/energy-origin/

Energinet. (n.d.-b). *Projekt Energioprindelse*. Retrieved March 31, 2023, from https://energinet.dk/energidata/datahub/energioprindelse/

Energinet. (2023). *Aktuelle tariffer*. https://energinet.dk/el/elmarkedet/tariffer/aktuelle-tariffer/

Energistyrelsen. (2021). *Vejledning i samfundsøkonomiske analyser på energiområdet*.

https://ens.dk/sites/ens.dk/files/Analyser/vejledning_i_samfundsoekonomiske_analyser_paa_energiomraadet_2021.pdf

Energistyrelsen. (2022a). *Samfundsøkonomiske analysemetoder—Regneark med tabeller*. Energistyrelsen. https://ens.dk/service/fremskrivninger-analyser-modeller/samfundsoekonomiske-analysemetoder

Energistyrelsen. (2022b). *Teknologikatalog—Dataark for produktion af el og fjernvarme*. Energistyrelsen. https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-produktion-af-el-og

Energistyrelsen. (2022c, October 7). *Energiø Bornholm*. Energistyrelsen. https://ens.dk/ansvarsomraader/energioeer/energioe-bornholm

Energistyrelsen. (2023a). *Analyseforudsætninger til Energinet*. Energistyrelsen. https://ens.dk/service/fremskrivninger-analyser-modeller/analyseforudsaetninger-til-energinet

Energistyrelsen. (2023b). *Teknologikatalog for fornybare brændstoffer—Datablade for produktion af fornybare brændstoffer*. https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-fornybare

EnergyTag. (n.d.). *How we work*. EnergyTag. Retrieved March 31, 2023, from https://energytag.org/how-we-work/

EnergyTag. (2021). *EnergyTag and granular energy certificates: Accelerating the transition to 24/7 clean power*. https://energytag.org/wp-content/uploads/2022/03/210830-ET-Whitepaper.pdf

Erhvervsstyrelsen. (2021). *Green Fuels for Denmark one-pager*. https://erhvervsstyrelsen.dk/sites/default/files/2021-03/Green%20Fuels%20for%20Denmark%20one-pager_0.pdf

European Commission. (n.d.). *Hydrogen*. Ec.Europa.Eu. Retrieved May 28, 2023, from https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

European Commission. (2023a). *COM(2023) 156 final on the European Hydrogen Bank*. https://energy.ec.europa.eu/system/files/2023-03/COM_2023_156_1_EN_ACT_part1_v6.pdf

Commission Delegated Regulation C(2023) 1087 final, European Commission (2023) (testimony of European Commission). https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf

European Commission. (2022, May 23). *Commission launches consultations on the regulatory framework for renewable hydrogen*. https://commission.europa.eu/news/commission-launches-consultations-regulatory-framework-renewable-hydrogen-2022-05-23_en

European Commission. (2023b). *Commission sets out rules for renewable hydrogen* [Text]. European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_594

European Commission, DG ENER. (2023). *Technical assistance to assess the potential of renewable liquid* *and gaseous transport fuels of non-biological origin (RFNBOs) as well as recycled carbon fuels (RCFs), to establish a methodology to determine the share of renewable energy from RFNBOs as well as to develop a framework on additionality in the transport sector: Final report. Task 1, Assessment of the potential of RFNBOs and RCFs over the period 2020 to 2050 in the EU transport sector*. Publications Office of the European Union. https://data.europa.eu/doi/10.2833/195142

European Energy. (2023, March 1). *I GW-skala: Her kommer de 7 største PtX-anlæg i Danmark til at ligge*. Ingeniøren. https://ing.dk/artikel/gw-skala-her-kommer-de-7-stoerste-ptx-anlaeg-danmark-at-ligge-266486

Renewable Energy Directive 2018/2001, European Union (2018) (testimony of European Union). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG#d1e1159-82-1

Fernández, A. A. (2021, November 28). *(Carbon) Contracts for Difference*. The European Roundtable on Climate Change and Sustainable Transition (ERCST), Brussels. https://ercst.org/wp-content/uploads/2022/04/20220528-CCfDsv2.pdf

Ghiassi-Farrokhfal, Y., Ketter, W., & Collins, J. (2021). Making green power purchase agreements more predictable and reliable for companies. *Decision Support Systems*, *144*, 113514. https://doi.org/10.1016/j.dss.2021.113514

Glenk, G., Holler, P., & Reichelstein, S. (2023). Advances in Power-to-Gas Technologies: Cost and Conversion Efficiency. *TRR 266 Accounting for Transparency Working Paper Series*, *2022*(109). https://doi.org/10.2139/ssrn.4300331

Glenk, G., & Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. *Nature Energy*, *4*(3), Article 3. https://doi.org/10.1038/s41560-019-0326-1

Hamburger, Á. (2019). Is guarantee of origin really an effective energy policy tool in Europe? A critical approach. *Society and Economy*, *41*(4), 487–507. https://doi.org/10.1556/204.2019.41.4.6

Hydrogen Europe & Renewable Hydrogen Coalition. (2023). *Industry Letter on RNFBO DA*. Hydrogen Europe. https://hydrogeneurope.eu/wp-content/uploads/2022/10/2022.10.6_Industry-letter-on-RFNBO-DA.pdf

IEA. (2019). *The Future of Hydrogen—Seizing today's opportunities*. International Energy Agency.

IEA. (2021). *The cost of capital in clean energy transitions – Analysis*. https://www.iea.org/articles/the-cost-of-capital-in-clean-energy-transitions

IEA, Nuclear Energy Agency, & OECD. (2020). *Projected Costs of Generating Electricity*. International Energy Agency. https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf

IRENA. (2020). *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal*. International Renewable Energy Agency.

IRENA. (2023). *The cost of financing for renewable power*. International Renewable Energy Agency.

Jacobson, M. Z. (2021). On the correlation between building heat demand and wind energy supply and how it helps to avoid blackouts. *Smart Energy*, *1*, 100009. https://doi.org/10.1016/j.segy.2021.100009

Jain, S. (2022). Exploring structures of power purchase agreements towards supplying 24x7 variable renewable electricity. *Energy*, *244*, 122609. https://doi.org/10.1016/j.energy.2021.122609

Juul, S., & Pedersen, K. B. (2012). *Samfundsvidenskabernes videnskabsteori: En indføring* (1st ed.). Hans Reitzels Forlag.

Klima-, Energi- og Forsyningsministeriet. (2023a). *Ny aftale: Vigtig milepæl i brinteventyret er nu på plads*. https://kefm.dk/aktuelt/nyheder/2023/maj/ny-aftale-vigtig-milepael-i-brinteventyret-er-nu-paa-plads

Klima-, Energi- og Forsyningsministeriet. (2023b). *Samarbejdsaftale skal bane vej for brintrørledning mellem Danmark og Tyskland*. https://kefm.dk/aktuelt/nyheder/2023/mar/samarbejdsaftale-skal-bane-vej-for-brintroerledning-mellem-danmark-og-tyskland

Kurmayer, N. J. (2023, February 11). LEAK: France wins recognition for nuclear in EU's green hydrogen rules. *Www.Euractiv.Com*. https://www.euractiv.com/section/energy-environment/news/leak-france-wins-recognition-for-nuclear-in-eus-green-hydrogen-rules/

Kvale, S., & Brinkmann, S. (2009). *InterView—Introduktion til et håndværk* (2nd ed., Vol. 6). Hans Reitzels Forlag.

LDES Council & McKinsey. (2022). *A Path towards full grud decarbonization with 24/7 clean power purchase agreements*.

López Prol, J., Steininger, K. W., & Zilberman, D. (2020). The cannibalization effect of wind and solar in the California wholesale electricity market. *Energy Economics*, *85*, 104552. https://doi.org/10.1016/j.eneco.2019.104552

Lund, H. (2014a). Chapter 1—Introduction. In *Renewable Energy Systems* (pp. 1–14). Elsevier. https://doi.org/10.1016/B978-0-12-410423-5.00001-8

Lund, H. (2014b). Chapter 2 - Theory: Choice Awareness Theses. In H. Lund (Ed.), *Renewable Energy Systems (Second Edition)* (pp. 15–34). Academic Press. https://doi.org/10.1016/B978-0-12-410423-5.00002-X

Lund, H., Arler, F., Østergaard, P. A., Hvelplund, F. K., Connolly, D., Mathiesen, B. V., & Karnøe, P. (2017). *Simulation versus Optimisation: Theoretical Positions in Energy System Modelling*.

Mason, A. J. (2012). OpenSolver—An Open Source Add-in to Solve Linear and Integer Progammes in Excel. In D. Klatte, H.-J. Lüthi, & K. Schmedders (Eds.), *Operations Research Proceedings 2011* (pp. 401–406). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-29210-1_64

Mendicino, L., Menniti, D., Pinnarelli, A., & Sorrentino, N. (2019). Corporate power purchase agreement: Formulation of the related levelized cost of energy and its application to a real life case study.

Applied Energy, *253*, 113577. https://doi.org/10.1016/j.apenergy.2019.113577

Miller, G. (2020). Beyond 100 % renewable: Policy and practical pathways to 24/7 renewable energy procurement. *The Electricity Journal*, *33*(2), 106695. https://doi.org/10.1016/j.tej.2019.106695

NREL. (2017). *DTU 10MW 178 RWT v1—NREL/turbine-models power curve*. https://nrel.github.io/turbine-models/DTU_10MW_178_RWT_v1.html

NREL. (2019). *5MW 126_RWT — NREL/turbine-models power curve*. https://nrel.github.io/turbine-models/NREL_5MW_126_RWT.html#power-curve

Ørsted. (2021). *Ørsted og HOFOR indgår aftale om grøn strøm til banebrydende brintprojekt*. https://orsted.dk/presse/nyheder/2021/05/537308985671172

Perner, J., & Peichert, P. (2021). *Effects of RED II sustainability criteria for H2 production on CO2 emissions [Auswirkungen der Ausgestaltung der RED II Grünstromkriterien für die H2-Erzeugung auf CO2- Emissionen]*. Frontier Economics.

Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., & Stolten, D. (2017). Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Applied Energy*, *200*, 290–302. https://doi.org/10.1016/j.apenergy.2017.05.050

Ricks, W., & Jenkins, J. (2023). *The Cost of Clean Hydrogen with Robust Emissions Standards: A Comparison Across Studies*. Zenodo. https://doi.org/10.5281/zenodo.7948769

Ricks, W., Xu, Q., & Jenkins, J. D. (2023). Minimizing emissions from grid-based hydrogen production in the United States. *Environmental Research Letters*, *18*(1), 014025. https://doi.org/10.1088/1748-9326/acacb5

Ruhnau, O., & Schiele, J. (2022). Flexible green hydrogen: Economic benefits without increasing power sector emissions. *EconStor*. https://www.econstor.eu/handle/10419/258999

Schlecht, I., Maurer, C., & Hirth, L. (2023). Working Paper—Financial Contracts for Differences. *ZBW - Leibniz Information Centre for Economics, Kiel, Hamburg*.

Schlund, D., & Theile, P. (2022). Simultaneity of green energy and hydrogen production: Analysing the dispatch of a grid-connected electrolyser. *Energy Policy*, *166*, 113008. https://doi.org/10.1016/j.enpol.2022.113008

Simon, F. (2022, February 16). Key lawmaker tables radical overhaul of EU's renewable energy directive. *Www.Euractiv.Com*. https://www.euractiv.com/section/energy/news/key-lawmaker-tables-radical-overhaul-of-eus-renewable-energy-directive/

Sotos, M. (2015). *GHG Protocol Scope 2 Guidance—An amendment to the GHG Protocol Corporate Standard*. World Resources Institute. https://ghgprotocol.org/corporate-standard#supporting-documents

Stöckl, F., Schill, W.-P., & Zerrahn, A. (2021). Optimal supply chains and power sector benefits of green hydrogen. *Scientific Reports*, *11*(1), 14191. https://doi.org/10.1038/s41598-021-92511-6

Tang, C., & Zhang, F. (2019). Classification, principle and pricing manner of renewable power purchase agreement. *IOP Conference Series: Earth and Environmental Science*, *295*(5), 052054. https://doi.org/10.1088/1755-1315/295/5/052054

Transport & Environment, Bellona, Client Earth, Ecos, Climate Action Network Europe, Clean Air Task Force, Zero, Ecodes, Global Witness, Deutsche Umwelthilfe, Iberdrola, EnergyTag, EDP, Flexidao, Electricity Maps, Granular, & greenko. (2022). *Joint Letter on RNFBO delegated act*. https://www.transportenvironment.org/wp-content/uploads/2022/10/Joint-letter-RFNBO-DA-September-2022.pdf

U.S. Department of Energy. (2023). *Pathways to Commercial Liftoff: Clean Hydrogen*. https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf

Zeyen, E., Riepin, I., & Brown, T. (2022). Hourly versus annually matched renewable supply for electrolytic hydrogen. *Zenodo*.

Appendix I: Interview Questions

Interview Questions: Developer 1 + 2

1) Can you introduce yourself and your role?
2) What are your organizations general thoughts on the DA for RNFBOs?
3) What RNFBO projects do you have in the pipeline?
4) Have the new requirements influenced how you approaches PPAs or have buyers changed their strategies in terms of PPA design?
5) How do you approach the procurement of PPAs for RNFBO projects?
6) How do you approach the derogations included in the DA when <90% RES share and <18gCO2/MJ?
7) How has the regulation had an impacted the design future RNFBO facilities?
8) What type of PPAs do you offer for RNFBO facilities, and where does the economic risk lie?
9) How much can you disclose about the settlement PPA prices?
10) How do you address the requirement for additional VE capacity from 2028 (grandfathering until 2038)?
11) Is there anything else you would like to add that you haven't mentioned but may be relevant?

Interview Questions: Blue Power Partners

1) Can you introduce yourself and your role in Blue Power Partners?
2) What role do you/Blue Power Partners play in the development of hydrogen projects?
3) How does Blue Power Partners generally approach the EU Commission's new regulation on RNFBOs, if at all?
4) In your assessment, what impact will the delegated regulation have on hydrogen production?
    a. Business case and production costs.
    b. Operation of electrolysis plants: Number of operating hours - both monthly, hourly, and after reaching a 90% renewable energy share?
5) How will projects be designed?
    a. Choice of electrolysis technology.
    b. Capacity in relation to renewable energy capacity.
    c. Production flexibility?
6) What do you consider to be the most profitable investment choices - or the most likely ones - in light of the regulation?
7) What setups are developers working on?
8) Based on your expertise, how do you assess that the regulation will affect PPA procurement or power sourcing?
9) As you have expertise in modeling PtX production and the associated business case, what do you see as the most interesting issue to shed light on regarding the delegated regulation?
10) Is there anything else you would like to add that may be relevant and hasn't been mentioned?

Interview Questions: EnergyTAG

1) Will you give a brief introduction of yourself and EnergyTag?
2) What are EnergyTags initial thoughts on the delegated act on RNFBOs?
3) As far as I can tell, the DA does not consider losses related storage, contrary to your recommendations on granular certificates. What are your thoughts on this?

4) Can you elaborate on the role of GOs and granular certificates in relation to PPAs and the role they will play in making temporal matching happen?
5) How will trading hourly granular GOs happen?
6) What are the regulatory barriers to overcome to enable hourly (granular) matching?
7) How will the administration and registry of granular certificates be different from GOs today? Need to change practices/regulation etc?
8) Who will be the manage the granular certificates registry?

Interview Questions: Energinet

1) Can you start by giving a brief introduction of yourself and your role in Energinet?
2) What are Energinet's immediate thoughts on the delegated regulation for RNFBOs?
3) Can you tell me more about your work with energy origins?
4) What about your pilot projects with time-based energy origins?
5) How does your project ElOprindelser work?
6) How does it relate to the EU's Guarantees of Origin, now and in the future?
7) Do you expect the revision of the Renewable Energy Directive to allow you to offer time-based energy origins?
8) When do you expect the possibility of time-based energy origins to be introduced in Denmark?
9) Can you explain to me how a system with time-based energy origins will work in practical terms?
10) Are there any unresolved issues that need to be addressed before time-based energy origins and correlation can become a reality?
11) Will it be a significant administrative burden for you or the companies involved?
12) Is there anything you would like to mention regarding time-based energy origins that we haven't discussed yet?

Interview Questions: Danish Energy Agency

1) Can you start by giving a brief introduction of yourself and your role in the Danish Energy Agency?
2) What requirements do you expect to apply in Denmark?
3) What role do you expect the Danish Energy Agency to have in the implementation and enforcement of the delegated regulation?
4) Do you see any areas where clarification is needed in order to implement and comply with the delegated regulation?
5) How do you expect RNFBO producers to document their compliance with the requirements?
6) What is the Danish Energy Agency currently doing on RNFBOs?
7) How will the process be carried out?
8) Will it be administratively burdensome?
9) Specifically, what forms of documentation are required, and what systems should be used to comply with the regulations?

Appendix II: Developer 1 - Interview Summary

- The interviewee mentions the importance of being a company with both PtX projects and renewable generation developer when considering power purchase agreements
- They prefer making internal PPAs for ease and security.
- They suggest that if they were an economic operator focused on electrolysis and not involved in building wind and solar projects, they would opt for a baseload contract to secure an adequate production profile.
- Baseload contracts shift the risk to the producer, who must match the supply with demand.
- The interviewee mentions physical PPAs, which can be either pay as produced or baseload.
- More buyers are leaning towards baseload contracts due to risk compensation and security.
- Monthly matching is currently sufficient for baseload contracts, but hourly matching poses challenges.
- The intervieww explains the process of a baseload contract, where they agree to deliver a certain amount of power at a set price. If their assets cannot produce the agreed amount, they purchase the remaining power from the spot market, which may not be green.
- The additionality requirement complicates the sourcing of green power from the spot market.
- The interviewee expects the problem to arise when hourly matching is required, as it becomes challenging to ensure the electrolysis plant's continuous operation and profile matching.
- Concluding multiple renewable PPAs would be necessary to mitigate the risk of profile mismatch.
- Transaction costs would increase significantly due to the need to enter contracts with uncertain electricity purchases.
- Uncertainty exists regarding the requirement for virtual PPAs and whether they should be considered in the legal act.
- The interviewee questions whether virtual PPAs should be classified as electricity supply contracts or financial derivatives due to their derivative nature.
- They suggest that virtual PPAs may not be counted when considering additionality.

Appendix III: Developer 2 - Interview Summary

- The interviewee mentions that during vulnerable times, 50% of the power comes directly from photovoltaics, while the other 50% comes from the grid.
- There is a socio-economic consideration to source electricity from the grid when abundant.
- Offtake contracts are structured to allow flexibility in operations and avoid full load requirements when not feasible.
- Maintenance and various tasks need to be planned to ensure monthly and quarterly delivery, which limits flexibility and operation time.
- The distillation is the least flexible unit in the plant, and turning it off can be challenging.
- Raw methanol is stored, and it is ideal to have enough raw methanol to feed the distillation process, which is less flexible than the electrolysis unit.
- During periods when the storage is full, the electrolysis can be turned off or and methanol synthesis reduced.
- The contracts provide some flexibility in terms of load operation and full load requirements.
- The decision not to have a hydrogen storage system is due to increased security risks, longer procedures for permits and safety notices. They have an aggressive delivery timeline.
- The current solution is simpler and can be implemented more quickly, with the possibility of considering hydrogen storage for future implementation to enhance flexibility.

Appendix IV: BPP - Interview Summary

Interview with Blue Power Partners

- In terms of sourcing, there is a preference for Pay-as-produced PPAs over shaped products, particularly for base-load products. The market may shift towards Pay-as-produced PPAs for socio-economic reasons, and operating electrolysis when electricity prices are low and not operating when prices are high is suggested.
- The holistic plant perspective requires flexibility in the downstream process, and there is a filtering exercise from generating assets through electrolysis and hydrogen storage.
- The flexibility of the plant depends on the flexibility of the offtake agreement. The more flexibility there is in the offtake agreement, the easier it is to incorporate intermittent resources. A more fixed offtake requires a more stable RES like offshore wind or maybe onshore if possible.
- The Pay-as-produced PPAs can be established either with a third party or directly with a supplier. The process of concluding a PPA can involve participating in a bidding process, where different bids can be submitted. The level of risk tolerance determines whether more variable structures are proposed.
- The choice of Pay-as-produced structure depends on the counter-party involved. There are various options available, including a standard Pay-as-produced PPA with a flat price or an indexed price. Different shaped products can be created, with the most extreme being Base Load. Other options include monthly Base Load profiles, daily profiles, and adjustments within a month. Both indexed prices and fixed prices can be utilized in these agreements.
- The current electrolysis technologies are considered capable of regulating fast enough to handle the variation in both monthly and hourly balancing. The interviewee expresses confidence in the current technology and implies that there is no need to consider other options.
- Technology choice may impact sourcing costs and the design of capital expenditure (capex) relative to efficiency. More efficient electrolysis may be chosen in a high-price market due to its impact on the business case.
- Different types of electrolysis technologies, such as atmospheric alkaline, pressurized alkaline, and PEM, are evaluated based on electricity prices and capex. Supplier selection considers average utilization, ESG rating, and credit rating.
- The contractual design with the offtake agreement influences the number of full load hours. Longer contracts with delivery commitments at monthly, quarterly, yearly, or potentially shorter intervals may be used.
- The decision on who operates the plant depends on the project and conversations. It also considers the allocation of electrolysis green doctor flexibility to the downstream process and its optimization against the day-ahead head market, ancillary services, and intraday market.
- Ensuring stability in the downstream process is critical, followed by considerations for downtime, green product delivery, market participation (ahead, intraday, ancillary), and hourly correlation.
- The choice of operator for the project depends on the specific project and considerations surrounding it.
- It is project-specific how much flexibility is allocated and if the operation of the facilitity can be optimized against the day ahead, ancillary services, and intraday markets.
- The holistic plant design should balance upstream flexibility and downstream stability, filtering out excess variables to meet fixed offtake obligations.

- Plant safety and stability are crucial, requiring measures to ensure the downstream process is well-maintained and avoiding potential hazards.
- Next is to ensure you produce a renewable product along with participation in day-ahead, intraday, and ancillary markets.
- Incorporating more hydrogen storage may be necessary for project-specific productivity and achieving an hourly correlation.

Appendix V: EnergyTAG – Interview Summary

- The interviewee foresees a granular GO system in Europe by 2030 that proves the hourly matching part of the delegated act.
- The regulatory block for member states to implement granular GOs will be removed at the EU level, although member states can choose whether or not to mandate it.
- Industry-level certification for granular GOs is feasible.
- Offshore wind projects are particularly attractive for meeting the hourly matching requirement and achieving a high capacity factor.
- The interviewee advises against using only solar for hourly matching and suggests combining solar with battery storage and offshore wind to ensure a reliable electricity supply.
- The bidding zone geographical matching requirement already ensures physical delivery of power to the same bidding zone as the electrolyzer, reducing price risk and making physical power purchase agreements (PPAs) a viable option.
- There is potential for trading excess volumes and attributes of PPAs between companies within a country to boost the capacity factor of electrolyzers, but such a market does not yet exist.
- The interviewee supports allowing trading and flexibility as long as it meets the criteria of hourly, local, and additionality requirements.
- Currently, there is no market that fully meets all three criteria of hourly, local, and additionality for granular GOs.

Appendix VI: Energinet – Interview Summary

- Energinet is the issuing body for GOs on electricity and gas
- The Project Energy Origins started with a voluntary scheme and has completed market testing.
- Initially, the focus was on improving documentation for gas and later expanded to include Power2X products.
- It quickly appeard to Energinet, that documentation is crucial for using Power2X to scale.
- The Energy Origin prototype system is a website with a login where smart meter points can be added for consumption and production.
- Agreements must be made with parties to transfer granular certificates.
- The system allows for selecting preferred energy sources and establishing agreements with producers.
- Platform: The focus is on ensuring safety, scalability, and trust, with the Energinet acting as a trust anchor.
- Blockchain and other technical solutions are being explored to address challenges.
- Collaboration with Energy Track and Trace aims to enable cross-border transfer of documentation and granular certificates.
- As the platform evolves, it should complement the current GO system rather than replacing it completely.
- The goal is to enable the transfer of granular certificates across EU countries.
- Roles in the future market are to be defined. More clarity is provided when REDII is implemented in national law.

Appendix VII: Danish Energy Agency – Interview Summary

- The Danish Energy Agency is the authority of the Renewable Energy Directive in Denmark.
- There are uncertainties regarding certain aspects of implementation and compliance, such as state aid, repaid state aid, regulation issues with redispatchment in Germany. Who are the certification body, the ones responsible for checking documentation.
- The interviewee expects a system similar to the one for biofuels, where producers are responsible for compliance and voluntary schemes exist, is expected to be established for RNFBOs. The fuel producer can choose a certification "organization".
- Documentation requirements include proving the source of electricity and carbon feedstock. Assessing the GHG emissions in a LCA as prescribed in the second DA.
- The process of documenting compliance and meeting requirements for RNFBO producers is still unclear.
- The Energy Agency is currently waiting for further information and collecting questions from producers.
- Once the rules are finalized, formal guidelines and a handbook, similar to the one for biofuels, will be created by the Energy Agency.

Appendix VIII: LCOH 2018 Day-ahead Spot (DK1)

Costs of Producing Hydrogen from Electrolysis using Grid Electricity – 2018 Day-ahead market.

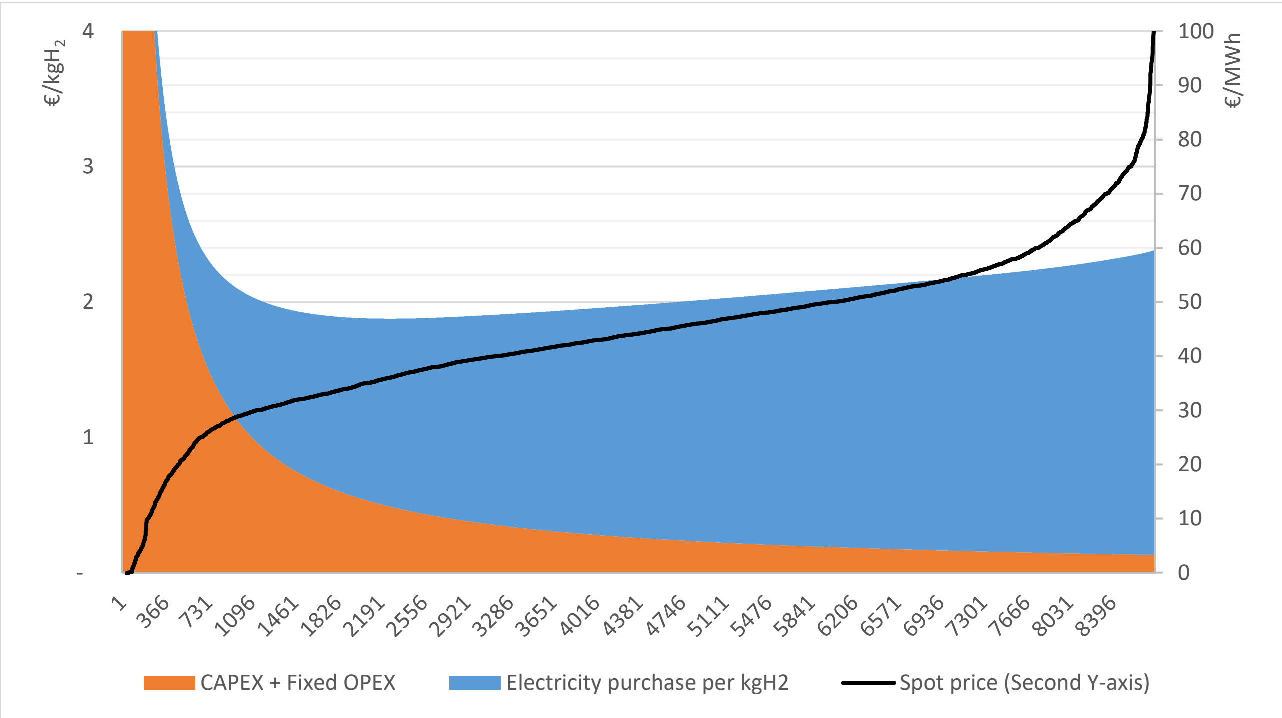

Figure Hydrogen Costs from Electrolysis using Grid-Electricity (2018 Day-ahead market)

Notes The costs of producing electrolytic hydrogen using grid electricity (first y-axis) increase as the utilisation rate increases (hours on the x-axis). CAPEX includes investment costs of the electrolysis, fixed operating costs of the electrolysis, and compression of the hydrogen. Electricity purchase includes transmission tariffs. Cost of capital (WACC) is assumed to 5 pct. The values are stated in chapter x methodology. The Day-ahead spot prices are from the year 2018 DK1, hourly resolution, from Energinet Data Hub.

Source Own calculations inspired by International Energy Agency (2019, p. 48). Assumptions for CAPEX and OPEX can be found in Subsection 5.4.4