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Final Report

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Renewable Fuels of Non-Biological Origin Certification Pilot Study on Hydrogen Derivatives Produced in Australia

Rijksdienst voor Ondernemend Nederland

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Abbreviations

Abbrev.	Full name
AUS	Australia
BESS	Battery Energy Storage System
BOG	Boil-off Gas
DEU	Germany
DR	Delegated Regulation
DRC	Delta Rhein Corridor
EF	Emission Factor
EHB	European Hydrogen Backbone
ELY	Electrolyzer
EU	European Union
FLH	Full Load Hour
GHG	Greenhouse Gas
GWP	Global Warming Potential
H2	Hydrogen
HB	Haber Bosch
HDY	Handysize
HFO	Heavy Fuel Oil
ISCC	International Sustainability & Carbon Certification

Abbrev.	Full name
LCOA	Levelized Cost of Ammonia
LCOH	Levelized Cost of Hydrogen
LGC	Large Gas Carrier
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
MGC	Medium Gas Carrier
NDL	Netherlands
NEM	National Electricity Market
NH3	Ammonia
PPA	Power Purchase Agreement
PtX	Power-to-X
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Bon-Biological Origin
SWIS	South West Interconnected System
VLGC	Verg Large Gas Carrier
WA	Western Australian
WEM	Wholesale Electricity Market

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Executive Summary

The primary objective of this study was to evaluate the feasibility of producing ammonia and hydrogen in Australia, for consumption in Germany, while ensuring the products meet the criteria for certification as Renewable Fuels of Non-Biological Origin (RFNBO) as per the European Union's (EU) Renewable Energy Directive (RED) II/III. The certifications and standards applicable, detailed in the delegated regulations DR 2023/1184 and DR 2023/1185, and the International Sustainability & Carbon Certification (ISCC) schemes (EU 202-6 and EU 205-1), set the regulatory framework for this analysis.

To qualify as RFNBO, two main criteria must be met: first, the electricity utilized in the production process must be entirely sourced from renewable energy; and second, the total greenhouse gas (GHG) emissions across the entire value chain must not exceed 28.2 gCO_2eq/MJ.

This certification study was divided into two phases: cradle-to-gate (production in Australia) and gate-to-grave (transportation and usage in Germany). Fichtner constructed two reference projects for the cradle-to-gate analysis, focusing on liquid hydrogen and ammonia production, both targeting equivalent hydrogen production levels. The analysis included three power sourcing scenarios ranging from fully renewable production, which achieved the lowest emission intensity (0.3 gCO_2eq/MJ), to economically optimized conditions, which far exceeded the permissible emissions threshold.

The gate-to-grave analysis covered the logistic processes from export in Australia to consumption in Germany. This phase examined various transportation methods from Rotterdam to Duisburg after the oceanic tanker transport from Australia to Rotterdam. The analysis revealed that, even under worst-case conditions using heavy fuel oil (HFO), the emissions from this phase constituted about 30% of the total permissible emissions (approximately 7.3 gCO_2eq/MJ).

The findings of this comprehensive study suggest that producing RFNBO in Australia for consumption in Europe is technically and environmentally feasible, provided that the production harnesses renewable electricity sources only.

This study encapsulates the pivotal insights and conclusions derived from the RFNBO certification study, guiding stakeholders on the vital conditions that must be satisfied to ensure the sustainable production and distribution of renewable energy sources internationally.

1 Introduction

The objective of this project is to perform a pilot study for Renewable Fuels of Non-Biological Origin (RFNBO) certification, focusing specifically on hydrogen derivatives produced in Australia, with an emphasis on potential production sites in the Oakajee region. The primary aim of the study is to assess the eligibility of these projects to export their products to the Netherlands and to Germany.

An important component of the study is the analysis of the entire supply chain, as depicted in **Figure 1**. This includes an examination of the implications of employing renewable energy sources for production of hydrogen (H_2) or ammonia (NH_3), storage at the Australian port of departure, transportation to the port of entry in the Netherlands, storage at the port of entry, and subsequent transportation to end-users in either the Netherlands or Germany.

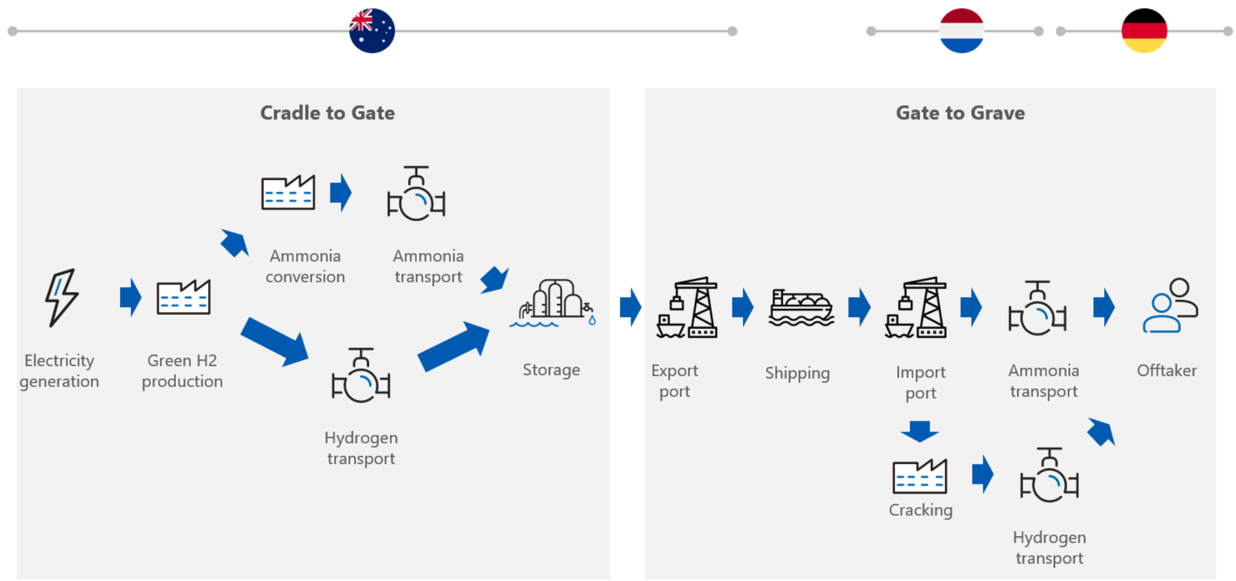


Figure 1: Supply chain from cradle to grave

The steps in the value chain vary depending on the target production product, be it liquid hydrogen or ammonia. Liquid hydrogen involves fewer production steps, thereby presenting a lower potential for emissions. However, the transportation of liquid hydrogen entails higher losses by e.g. boil off gases during shipping while it does not require being cracked at the point of destination. Both scenarios are investigated in this study.

In the absence of concrete project information or transport details from project developers, Fichtner established **two typical reference production projects** for both cases and identified typical transport methods to simulate technically feasible and realistic scenarios.

Based on these assumptions and settings, Fichtner conducted the certification study in four phases:

- Understanding the certification scheme, specifically from ISCC - **Section 2**;
- Analysis of emissions from cradle to gate, inclusive of the electricity source - **Section 3**;
- Analysis of emissions from gate to grave - **Section 4**;
- Compilation of overall evaluation results and issuing recommendations - **Section 5**.

2 RFNBO Certification Regulation

The goal of this section is to understand the certification scheme from International Sustainability & Carbon Certification (ISCC) and its legal base, i.e., RED and related delegated regulations as guidance for the certification process that is subject to the analysis in this project.

The Renewable Energy Directive (RED) II/III sets the European regulatory framework on the sustainability of renewable fuels of non-biological origin (RFNBO). Based on the RED, two delegated regulations (DR) are detailing the regulatory requirements on RFNBO: DR 2023/1184 on RFNBO production and DR 2023/1185 on greenhouse gas (GHG) emissions calculations.

Based on these EU documents, the ISCC provides the certification scheme (ISCC EU 202-6 and EU 205-1) relating to RFNBO. The ISCC scheme used in the project is still in the draft stage and is considered confidential within the project. It may undergo changes before the final official version is released. The project takes the ISCC certification scheme as a foundation, but in cases of uncertainty, it also considers the RED and the two DRs. ISCC was involved for clarification issues regarding the certification scheme.

2.1 Background

Renewable Energy Directive (RED)

The first Renewable Energy Directive (RED I) of 2009, sets ambitious targets to increase the share of renewables in its total final energy consumption to 20% by 2020. The EU exceeded those targets, thereby setting the stage for more ambitious aims with a second version, RED II, in 2018. After, RED II became the governing framework, delineating various requirements to ensure that 32% of the energy consumed within the EU comes from renewable sources by 2030.[1] It outlined specific policy amendments, known as delegated regulations, to offer clarity on various aspects of renewable energy for the production and certification of RFNBO and on GHG emission reduction targets and the calculation methodology. Two delegated regulations have been adopted.[2,3] Among the most notable aspects of RED II was that RFNBOs had to achieve greenhouse gas emissions savings of 70% compared to fossil fuels.[4]

Following the approval of RED III by the EU Council of Ministers on October 9, 2023, the regulation has been advancing the EU's commitment towards an increased usage of renewable energy and setting ambitious targets across various sectors.[5] RED III transitions from a provisional agreement to being actively incorporated into EU legislation, requiring member states to align their national laws with its provisions. Until then, the detailed provisions of RED II, including the newly ratified delegated regulations will remain in force.[6] However, RED III specifications should already be considered for upcoming projects, as there is only an 18-month window for member states to implement the directive into national laws from the time of its implementation.[7]

[1] Directive - 2018/2001 - EN - EUR-Lex (europa.eu) (RED II)
[2] EUR-Lex - 32023R1185 - EN - EUR-Lex (europa.eu)
[3] EUR-Lex - 32023R1184 - EN - EUR-Lex (europa.eu)
[4] Article 25 EUR-Lex - 32018L2001 - EN - EUR-Lex (europa.eu)
[5] Directive - EU - 2023/2413 - EN - Renewable Energy Directive - EUR-Lex (europa.eu) (RED III)
[6] Council and Parliament reach provisional deal on renewable energy directive - Consilium (europa.eu)
[7] Article 19 Directive - EU - 2023/2413 - EN - EUR-Lex (europa.eu)

A consolidated version of RED II/III is available, however, can be used purely as a documentation tool and has no legal effect yet.[8]

Delegated Regulations Related to RFNBO

The Delegated Regulations (DRs) of RED II, which are technically referred to as "Commission Delegated Regulations", are enacted by the European Commission under the mandate granted by the EU's main legislative bodies: the European Parliament and the European Council. Unlike Directives, Regulations are binding in their entirety and are directly applicable in all EU countries.

The RED II Delegated Regulations hold pivotal significance, not just for the existing RED II framework but also for RED III.[9] To clarify the intricate process that gave rise to these Delegated Regulations, it is helpful to trace their journey through RED II background:

- Initially, the European Commission drafted the proposed Delegated Regulations in May 2022. Following a period of intense debate and partial rejection by the European Parliament, revised drafts were presented in December 2022.[10]
- On February 13, 2023, the European Commission officially adopted the final versions of these DRs, fulfilling the mandate specified under article 27.3 of the RED II.[11]
- The acts then underwent scrutiny by both, the European Parliament and the Council, culminating in their formal approval on June 20, 2023.
- They were subsequently published in the Official Journal of the EU on the same day and came into effect 20 days later, on July 10, 2023.[12]
- Once in effect, EU Member States are still required to transpose these regulations (except for two delegated regulations on hydrogen) into national law.[13]

DRs of RED II related to RFNBO specifically focus on two key areas: Requirements on the use of renewable electricity for production and GHG emissions assessment methodology:

1. Commission Delegated Regulation (EU) 2023/1184 of February 10, 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a **methodology setting out detailed rules for the production** of renewable liquid and gaseous transport fuels of non-biological origin (DR 2023/1184):[14]
   This DR 2023/1184 to Article 27 of RED II/III sets out detailed requirements to consider renewable electricity used in production of RFNBO as “fully renewable”.[15] Renewable electricity can either be supplied via a direct connection or via the public power grid. The grid-derived electricity must meet certain criteria, such as a high share of renewables or GHG intensity in the grid, to be considered renewable. This applies both to products produced within the EU and those imported.[16]
2. Commission Delegated Regulation (EU) 2023/1185 of February 10, 2023 is supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum

[8] EUR-Lex - 02018L2001-20231120 - EN - EUR-Lex (europa.eu) (Consolidated version REDII/REDIII)
[9] Renewable energy directive (europa.eu)
[10] EU rules for renewable hydrogen (europa.eu)
[11] Commission sets out rules for renewable hydrogen (europa.eu)
[12] Renewable hydrogen production: new rules formally adopted (europa.eu)
[13] National transposition - EUR-Lex (europa.eu)
[14] EUR-Lex - 32023R1184 - EN - EUR-Lex (europa.eu)
[15] Article 27 EUR-Lex - 32018L2001 - EN - EUR-Lex (europa.eu)
[16] Recital (3) EUR-Lex - 32023R1184 - EN - EUR-Lex (europa.eu)

threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a **methodology for assessing greenhouse gas emissions savings** from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels (DR 2023/1185):[17] This DR 2023/1185 to Article 28 of RED II/III specifies the methodology for GHG emissions calculation and assessment of RFNBO along the entire value chain.[18] For any RFNBO to be certified, it must achieve a minimum of 70% GHG emissions saving compared to conventional fuels.

In terms of accounting for GHG emissions resulting from the supply of electricity for RFNBO or RCF production, the two DRs are closely linked, as described in further detail in the relevant sections of this report.

Target

The RED III enhances the binding target that at least **42.5% of the EU's total energy consumption is derived from renewable sources by 2030** and requires the Member States to make efforts to achieve 45%.[19]

RED III also specifies minimum **sector targets** for buildings, industry, heating and cooling, district heating and cooling and the transport sector. The figure below provides an overview of **sector targets relevant for RFNBOs** and including ReFuelEU aviation targets.[20]

Sector	Sub sector	Renewable	RFNBO		
		Renewable target	**RED III sub-target, Art. 22a (1)**	**RED III sub-target, Art. 25 b**	**ReFuelEU aviation target[2]**
Industry[1]		**RE-share 1.6% increase per year** Art. 22a (1)	**42% RFNBO** (of total hydrogen)		
Transport	Road transport	**RE-share 29%** or **GHG intensity reduction 14.5%** Art. 25 (1)		**1% RFNBO**	
	Rail transport				
	Aviation				**0,7% RFNBO**
	Maritime[3]			**1.2% RFNBO**	

[1] For member states with maritime ports
[2] (EU) 2023/2405 (ReFuelEU Aviation), Annex I
[3] For „industry" defined under Article 2 Definitions of RED III

Figure 2: EU RED III Sector Targets with Relevance for RFNBO (incl. ReFuelEU Aviation Target)

RED III **significantly broadens the definition and application of Renewable Fuels of Non-Biological Origin (RFNBOs), extending beyond transportation to include industrial uses, thereby creating new markets for renewable energy sources.** Additionally, RED III sets specific mandates, **including minimum quotas for RFNBOs in the transport sector and an annual 1.6% increase in renewable energy usage within the industry**.[21] By 2030, 42% of industrial hydrogen shall come from RFNBOs, with an increase to 60% by 2035.[22] However, while non-renewable hydrogen imports generally remain

[17] EUR-Lex - 32023R1185 - EN - EUR-Lex (europa.eu)
[18] Article 28 Directive - 2018/2001 - EN - EUR-Lex (europa.eu)
[19] Article 3 (1) Directive - EU - 2023/2413 - EN - Renewable Energy Directive - EUR-Lex (europa.eu)
[20] Regulation - EU - 2023/2405 - EN - EUR-Lex (europa.eu)
[21] Article 25 Directive - EU - 2023/2413 - EN - Renewable Energy Directive - EUR-Lex (europa.eu)
[22] Article 22a Directive - EU - 2023/2413 - EN - EUR-Lex (europa.eu)

permissible into the EU, it does not contribute towards renewable energy quotas, which emphasizes the **importance for exporters to align with RED III's requirements through investments in renewable energy production and certification processes, ensuring their offerings are sustainable and traceable according to the EU standards**.[23] Therefore, to leverage these opportunities, it's critical that RFNBO imported to Europe meets RED III's rigorous criteria related to the renewable nature of electricity used in its production, along with rules ensuring additionality, geographical correlation, and temporal correlation as well as GHG emissions calculation considering traceability and sustainability.[24]

ISCC Certification Scheme

In RED II/III, it is stated that national schemes or international voluntary schemes may be used to certify the compliance of renewable liquid and gaseous transport fuels of non-biological origin (RFNBO) and recycled carbon fuels (RCF) with the sustainability and GHG emissions saving criteria.[25]

Voluntary schemes and national certification schemes of EU countries help to ensure that biofuels, bioliquids and biomass fuels as well as renewable hydrogen and its derivatives (renewable fuels of non-biological origin or RFNBOs), and recycled carbon fuels (RCF) are sustainably produced by verifying that they comply with the EU sustainability criteria, as well as the relevant methodologies for RFNBOs and RCF. So far EU recognized three certification schemes: ISCC, CertifHy and REDcert. All three certification scheme can be applied for RFNBO certification.

ISCC is one of the certification scheme owners and was chosen as reference. ISCC offers a sustainability certification for all feedstocks across various markets. Depending on the target market for a sustainable product, a specific certification from ISCC is required. The systems, ISCC EU, ISCC CORSIA (PLUS) and ISCC PLUS, are mostly aligned, meaning that a single audit can yield three certificates.

Two documents from ISCC are relevant for RFNBO certification:

- ISCC EU 202-6
  - Reflecting DR Commission Delegated Regulation (EU) 2023/1184;
  - Definition of RFNBO and requirement of inputs and production to certify as RFNBO;
  - Detailed requirements to consider renewable electricity sourced in production of RFNBO as "fully renewable";
- ISCC EU 205-1
  - Reflecting DR Commission Delegated Regulation (EU) 2023/1185;
  - Completing ISCC 202-6 on methodology for assessing greenhouse gas emissions savings;

The two reference projects assessed within this study are one for ammonia production and another one for liquid hydrogen production (**Section 3.2**). Based on the requirements listed by EU and ISCC, there are two main criteria that should be fulfilled to certify as RFNBO:

- Green electricity sourcing: The electricity used to contribute to the product heating value (electricity used for electrolyzer) should be fully renewable from qualified renewable sources. If the input

[23] EU rules for renewable hydrogen (europa.eu)
[24] (90) EUR-Lex - 32018L2001 - EN - EUR-Lex (europa.eu)
[25] Article 30(4) Directive - 2018/2001 - EN - EUR-Lex (europa.eu)

electricity is not fully renewable, the product should be separated. In this section, Fichtner investigated the production of ammonia in Australia, especially the sourcing of electricity.

- GHG emission reduction: The cradle to grave GHG emissions should be at least 70% lower than the comparable conventional fuel. Fichtner calculated the emission of two system boundary definitions: 1) gate to grave and 2) cradle to gate as displayed in **Figure 1**.

2.2 Electricity Sourcing

ISCC EU 202-6 defines the principles and rules to count electricity for RFNBO production as "fully renewable". The electricity used for RFNBO production must be produced exclusively from renewable sources excluding bioenergy. Depending on the renewable electricity supply option further conditions apply to prevent increased electricity productions from fossil sources: additionality, temporal correlation and/or geographical correlation.

2.2.1 Renewability

As a principle, RFNBO produced from electricity is considered renewable only when the electricity is renewable for electricity demand that enhances the heating value of the fuel. The criteria of DR 2023/1184 do not apply for electricity that does not enhance the fuel's heating value.

Electricity consumption qualified as fully renewable under ISCC EU 202-6 shall be attributed zero GHG emissions in the GHG emissions calculation according to ISCC EU 205-1. For electricity used for processes that do not enhance the heating value of the fuel, the emission intensity factors apply as defined in ISCC EU 205-1. Hence, using not qualified electricity under ISCC EU 202-6 impacts the GHG emissions intensity of the output. Therefore, two main options for renewable electricity supply of an RFNBO production plant are defined (see **Figure 3)**.[26]

- Option 1: direct connection between the RFNBO production facility and the renewable energy plant.
- Option 2: sourcing renewable energy from a grid/bidding zone that meets certain renewable energy and emission intensity benchmarks, sub-divided to the following sub-options:
  - Option 2a: >90% RES-E share in the grid/bidding zone
  - Option 2b: <18 gCO_2eq/MJ GHG intensity in the grid/bidding zone
  - Option 2c: electricity taken from the grid reduces temporal grid imbalance
  - Option 2d: Others than above but fulfilling all further conditions plus PPA principles (details see below)

An overview of the options and requirements that qualify for "fully renewable electricity" is given in **Figure 3** presenting the underlying principles set out in ISCC EU 202-6. The detailed requirements for all options are outlined in **Figure 4**. The figure also contains references to PPA principles as well as additional conditions to prevent the use of fossil fuels as a source of electricity. The stipulations on these additional conditions comprising additionality, temporal correlation and geographical correlation are described in more detail below.

[26] Articles 3-4 Delegated regulation - 2023/1184 - EN - EUR-Lex (europa.eu)

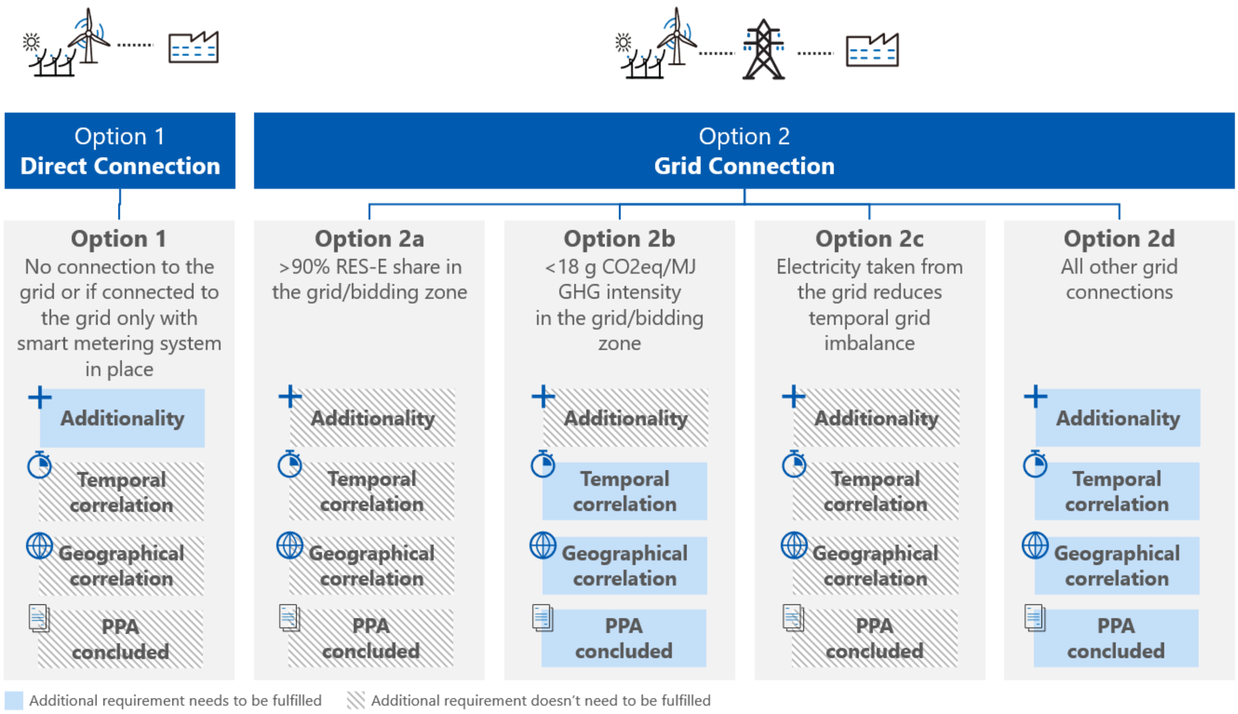


Figure 3: Overview of Renewable Electricity Options for RFNBO Production

Whereas fully renewable electricity shall be attributed zero GHG emissions, the GHG emissions values for **electricity taken from the grid that does not fully qualify as fully renewable** shall be calculated by one of three alternative methods:

- Take the GHG emissions from ISCC 205-1, Table 5 (EU country only)
- Assess the operation of the electrolyzer operation (via full load hours, FLH)
  - 0 gCO_2eq/MJ when where the number of FLH's the electrolyzer is producing is equal or lower than the number of hours in which the marginal price of electricity was set by installations producing renewable electricity or nuclear power plants;
  - 183 gCO_2eq/MJ, otherwise;
- Take the GHG emissions value of the marginal unit generating electricity at the time of the production of RFNBOs and RCFs in the bidding zone may be used if this information is publicly available and originates from the national transmission system operator

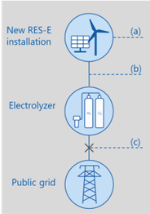
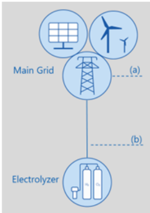
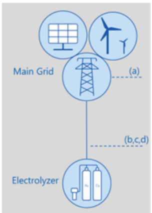
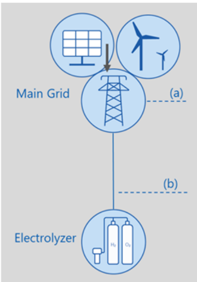
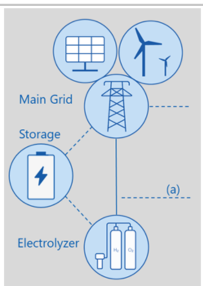
Renewability options		Conditions	Additional conditions
1: **Direct connection** Electricity produced off-grid		• RES-E facilities directly connected to the RFNBO production facility or within the same installation (a). • RES-E facilities not connected to the electrical grid, but if grid-connected, a smart metering system must confirm no electricity is drawn for RFNBO production (c).	Additionality (b)
2a: **Grid connection /** >90% RES-E share in the grid/bidding zone		Grid-sourced electricity may account fully renewable if: • The grid's average share of renewable electricity was above 90% in on of the last six years (a). • AND the number of full load hours of RFNBOs production is limited to the share of renewable electricity in the bidding zone (b).	*No additional requirements*
2b: **Grid connection /** <18 g CO2eq/MJ GHG intensity in the grid/bidding zone		Grid-sourced electricity is considered entirely renewable if: • The GHG intensity of the grid is below 18 g CO2eq/MJ. (a) • AND Fuel producers must have established one or more **PPAs** for renewable electricity. The quantity of renewable electricity sourced through these PPAs must be at least equal to the amount claimed and used for RFNBO production (b)	Temporal correlation (c) Geographical correlation (d)
2c: **Grid connection /** Electricity taken from the grid reduces temporal grid imbalance		Electricity is consumed during an imbalance settlement period during which the fuel producer can demonstrate, • a) power-generating installations using renewable energy sources were redispatched downwards during that time (a). • b) the electricity consumed for the production of RFNBOs reduced the need for redispatching by a corresponding amount (b).	*No additional requirements*
2d: **Grid connection /** Others than above but fulfilling all additional conditions & PPA principles		• Power Purchase Agreements **(PPAs)** involving Renewable Electricity Sources (RES-E) plants—other than biomass—are considered to provide fully renewable electricity for the amount consumed and claimed if all three additional conditions are met (a) • Electricity via PPA can be directly sourced from the RES producer or via intermediaries	Additionality Temporal correlation Geographical correlation

Figure 4: Requirements of Renewable Electricity Options for RFNBO Production

2.2.2 Additionality, Temporal Correlation, Geographical Correlation

Additional conditions are defined to prevent increased electricity production from fossil sources and govern the categorization of electricity as fully renewable for RFNBO production. These are,

- additionality,
- geographical correlation, and
- temporal correlation.

The extent to which these conditions must be assigned to the various renewability options is presented in the overviews in **Figure 3**.

The first condition, "**additionality**" refers to the obligation for RFNBO manufacturers to ensure that the electrical power consumed in generating RFNBO is counterbalanced by the creation of renewable energy. This can be achieved by self-producing an equivalent amount of renewable electricity at an additional facility directly connected to the RFNBO production facility (Option 1) or for renewable electricity taken from the grid through a contract to purchase renewable energy (known as a PPA, contracted directly or via intermediaries) with entities that generate additional renewable electricity (Option 2d). An additional installation for renewable electricity production should neither have been in operation for more than 36 months before the RFNBO production plant nor have received governmental operating or investment aid.[27] Financial support that is repaid or financial support for land or grid connections for the renewable power generation facility should not been considered as operating aid or investment aid.[28] If electricity is sourced via a direct connection (Option 1) no PPA needs to be concluded.[29] To encourage the early adoption of RFNBO production, the regulation introduces a transitional phase. This exempts installations that come online before January 1, 2028, from adhering to the additionality criteria (a) (36 months period) and (b) (receiving support) until 1 January 2038.

Next, the "**temporal correlation**," specifies that RFNBO production should temporally align with renewable electricity availability. In doing so, RFNBO production supports the integration of renewable electricity generation into the electricity system and reduces the need for dispatching renewable energy. Up until December 31, 2029, RFNBO must be produced in the same calendar month as the renewable electricity. Starting January 1, 2030, this window narrows to just one hour. Member States may choose to enforce this one-hour rule as early as July 1, 2027, provided they notify the Commission in advance.

The third condition, "**geographical correlation**", requires the renewable energy installation to be in the same or interconnected bidding zones as the RFNBO production plant. Member States can introduce further conditions to this rule to ensure it aligns with national energy policies and grid plans.

To maintain transparency and accountability, RFNBO producers are obliged to submit hourly information about their electricity usage by quantity and sources (types of renewable sources as detailed above as well as non-renewable sources, if any), the amount of renewable electricity generated and RFNBO output quantities. This data and compliance with DR 2023/1184 can be certified through national schemes or international voluntary schemes recognized by the Commission.

2.3 GHG Emission Calculation

The GHG emissions savings threshold for RFNBO is laid down in the RED: "*Energy from RFNBO shall be counted towards Member States' shares of renewable energy and the targets referred to in … only if the GHG emissions savings … are at least 70%.*"[30] The same threshold applies for RCF.[31] The Commission Delegated Regulation (EU) 2023/1185 of 10 February 2023 (hereafter referred to as Delegated Regulation DR 2023/1185) sets out rules on how to calculate the GHG emissions savings for RFNBO and RCF. Main

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[27] Article 5 EUR-Lex - 32023R1184 - EN - EUR-Lex (europa.eu)
[28] Recital 9 EUR-Lex - 32023R1184 - EN - EUR-Lex (europa.eu)
[29] EU Q&A No. 13 Q&A implementation of hydrogen delegated acts (europa.eu)
[30] Article 29a (1) Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (europa.eu)
[31] Article 29a (2) Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (europa.eu)

provisions are described in the sections below. The fossil fuel comparator for RFNBO and RCF is set at 94 gCO_2eq/MJ (transportation), 183 gCO_2eq/MJ (electricity generation), and 80 gCO_2eq/MJ (heat production) indicated by Annex V of RED II[32]. The GHG emissions savings must be at least 70% compared to this fossil fuel comparator value.

In consultation with ISCC, the GHG reduction threshold of 70% is confirmed and the only conventional emission reference is considered with 94 gCO_2eq/MJ regardless of the end application.

The total **GHG emissions from the production and use of RFNBO** shall be calculated according to the following equation:

$$E = e_i + e_p + e_{td} + e_u + e_{ccs}$$

where:

- E = total emissions from the use of the fuel;
- e_i = emissions from elastic inputs + emissions from rigid inputs - emissions from inputs' existing use or fate;
- e_p = emissions from processing;
- e_{td} = emissions from transport and distribution;
- e_u = emissions from combusting the fuel in its end-use;
- e_{ccs} = emissions savings from carbon capture and geological storage;

All emissions shall be expressed in the units of gCO_2eq/MJ fuel, where all types of fuel shall be considered to have the same emissions intensity if a fuel is a mix of RFNBO, RCF and other fuels.

To elaborate on each element included in the calculation of the total emissions from the fuel, emissions from inputs are explained in detail under the sub-sections below.

The GHG emissions intensity can then be calculated by dividing the total emissions of the process by the total amount of fuel produced from the process. This GHG emissions intensity may be calculated as an average for the production of fuels occurring for a maximum period of at most one calendar month (however, may be calculated for shorter time intervals).

Lastly, the **GHG emissions savings** from RFNBO or RCF shall be calculated using the following equation:

$$Savings = \frac{E_F - E}{E_F}$$

where:

- E = total emissions by using from the use of RFNBO;
- E_F = total emissions from the fossil fuel comparator (94 gCO_2eq/MJ);

[32] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001

2.3.1.1 Emissions from inputs (e_i)

The total emissions of inputs (e_i) equals to the sum of emissions from rigid inputs (e_{rigid}) and elastic inputs ($e_{elastic}$) minus the emissions from existing use or fate (e_{ex-use}). Emissions attributed to inputs e_i shall include emissions from their associated transport and storage.

2.3.1.1.1 Emission from Elastics and Rigid Inputs ($e_{elastic}$, e_{rigid})

Emissions from the supply of inputs shall be categorized into elastic inputs and rigid inputs. **Rigid inputs refer to those that cannot be expanded to meet extra demand,** such as all inputs qualifying as a carbon source for the production of RCF as well as outputs that are produced in fixed ratio by an incorporated process which represents less than 10% of the economic value of the output. If the supply represents more than 10% of the economic value, it shall be classified as an elastic input. In principle, **elastic inputs are supplies that can be increased to meet extra demand**. For instance, petroleum products from refineries would be classified as an elastic input, because refineries can change the ratio of their products.

An incorporated process refers to processes that take place in the same industrial complex, that are supplied via a dedicated supply infrastructure, or that supply more than half of the energy of all inputs to the production of RFNBO or RCF.

The emissions of the elastic input from an incorporated process should consider all emissions arising due to their production over the whole supply chain. In the case of elastic inputs that are not obtained from an incorporated process, the GHG emissions values are determined in ISCC EU 205-1, Annex I, Table 1&2, with inputs such as natural gas. If the input is not included in the list, information of the emission intensity may be drawn from the latest version of the JEC-WTW report, the ECOINVENT database, official sources such as the IPCC, IEA or government, other reviewed sources such as the E3 and GEMIS database and peer reviewed publications.

Emissions from rigid inputs should include the emissions resulting from the diversion of those inputs from a previous or alternative use, taking into account the loss of production of electricity, heat, or products, as well as the emissions that arise from additional treatments that are needed for using this rigid input. The emissions resulting from the diversion of rigid inputs shall be determined by multiplying the lost production of electricity, heat, or other products with the relevant emission factor. The average amount of electricity or heat that was produced from the rigid input over the last three years before starting to produce the RFNBO can be used as the value for the loss of production of electricity or heat for the first 20 years of RFNBO production. After that, these values will be determined based on the minimum energy performance standards assumed at that time as best available technology.

Hence, the categorization of an input (rigid or elastic) may depend on circumstances. Waste heat from processes might fall under rigid inputs. Elastic inputs comprise for instance petroleum products, electricity, natural gas and CO_2. **In case of doubt an input should be considered elastic**.

Relevance for the Project

The main input for the Project, the electricity, as well as water for hydrogen production will be accounted for as elastic input.

In case fully renewable electricity is used for RFNBO production the GHG emission is zero. If electricity is sourced from spot market, grid emission intensity in Western Australian (WA) bidding zone is applied.

2.3.1.1.2 Emissions from Existing Use of Fate (e_{ex-use}) (eligible CO_2 input)

Emissions from existing use of fate refer to emissions avoided when the input is used for fuel (RFNBO) production. **To elaborate, the avoided emissions are subtracted from the total emissions of the inputs**, as the carbon incorporated in the chemical composition of the fuel would have otherwise been emitted as CO_2 into the atmosphere. The CO_2 can be considered eligible if at least one of the conditions set out in the figure below is met and none of the exclusions apply. According to these conditions CO_2 qualifies for e_{ex-use} if the captured CO_2 is:

- from activities as listed under Annex I of Directive 2003/87/EC (emissions trading directive) and having been **taken into account in an effective carbon pricing system**
  - before 2036 for combustion of fuel for electricity production ("**fossil CO_2**");
  - extended to 2041 for other cases ("**unavoidable CO_2**");
- from the air (direct air capture – "DAC");
- from production/combustion of biofuels, bioliquids, or biomass fuels complying with RED ("**biogenic CO_2**") (i.e. that comply with the sustainability criteria which have not received credits for emissions savings, as set out in Annex V and VI of Directive (EU) 2018/2001 (RED II));
- from combustion of RFNBO complying with RED, ("**CO_2 from qualified RFNBO or RCF**"); or
- from geological source of CO_2 where the CO_2 was previously released naturally ("**geological CO_2**").

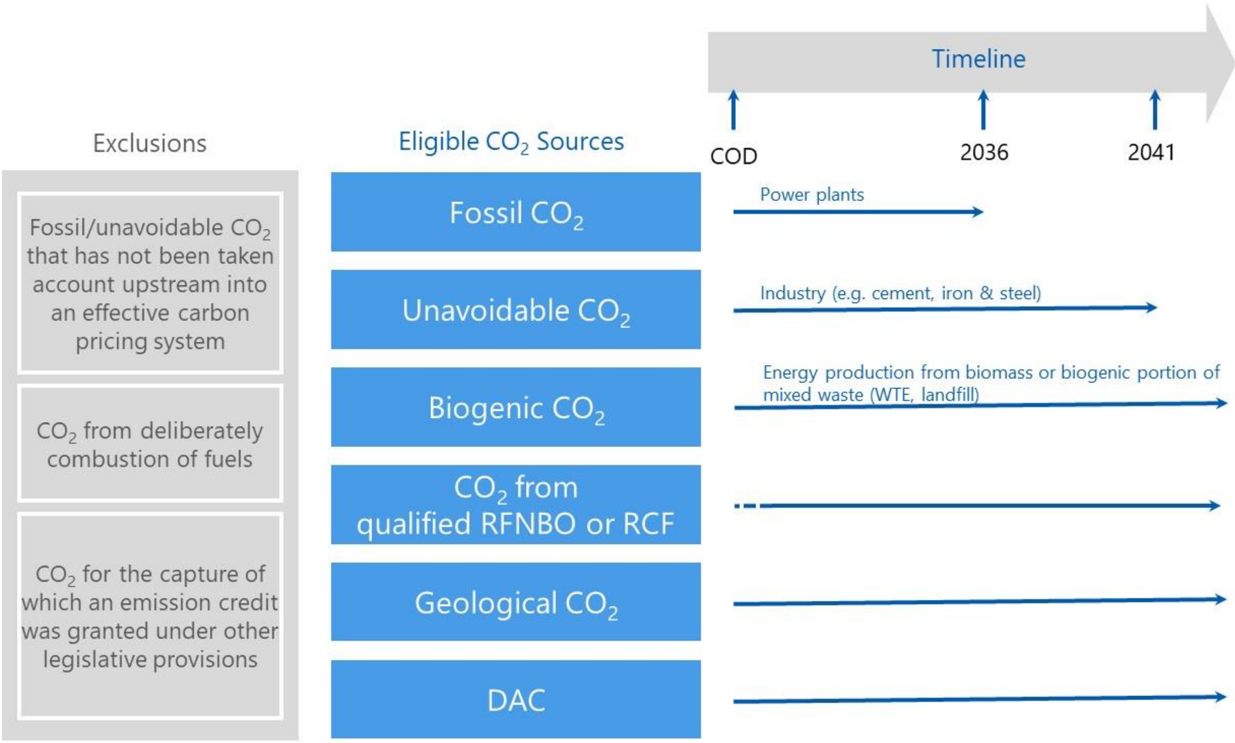

Figure 5: Eligible CO_2 Sources and Exclusions

According to the EU regulation related to the production of RFNBO the use of fossil carbon dioxide (CO_2) captured from power generation after 2036 is not compliant. In 2042, the production of RFNBOs using CO_2 captured from so-called 'unavoidable' industries, such as cement or steel making, must have been phased out. The implication of this EU RFNBO legislation is **that biogenic CO_2 and CO_2 from direct air capture (DAC) are the favored long-term sources of carbon for RFNBO**.

Captured CO_2 stemming from a fuel that is deliberately combusted for the specific purpose of producing CO_2, for which the capture has received an emissions credit under other provisions of the law shall not be qualified.

Furthermore, with regard to **biogenic CO_2 sources** the following has been clarified under the EU Q&A procedure: In accordance with the European regulations as defined in the Renewable Energy Directive (RED III) and the related Delegated Regulations biogenic CO_2 comprises CO_2 that stems from the production or the combustion of biofuels, bioliquids or biomass fuels. **CO_2 from the treatment of biogenic wastes is also eligible.** In order to be eligible to count as emissions from existing use or fate $e_{ex\text{-}use}$, biogenic CO2 must comply with the sustainability and greenhouse gas saving criteria and must not have received credits for emission savings from CO_2 capture and replacement, set out in Annex V and VI to Directive (EU) 2018/2001. Biogenic CO_2 stemming from processes which are out of the scope of the sustainability and greenhouse gas saving criteria are also eligible (e.g. if the installation has a rated thermal input below the applicable threshold).

Emissions associated with the inputs like electricity and heat and consumable materials **used in the capture process of CO_2 shall be included in the calculation of emissions attributed to inputs.**

The credit for eligible CO_2 input sources ($e_{ex\text{-}use}$) and CO_2 emissions from the use of RFNBO (e_u) can balance each other out.

Relevance for the Project

As the end product is ammonia/hydrogen, there is no need to use CO_2 as input. Therefore, the $e_{ex\text{-}use}$ is not relevant in this project.

2.3.1.2 Emissions from Transport and Distribution (e_{ts})

Emissions from transport and distribution shall include the emissions from storage and distribution of finished fuels. Transportation and storage related emissions of inputs e_i shall be included in the emissions attributed to the inputs. Transport emission can include several different transportation methods in the same analysis, e.g., pipeline and shipping. The methodology and formulas described in ISCC EU System Document 205 and based on RED II shall be applied.

ISCC EU System Document 205 **Section 4.3.4** defines the methods and database of calculation. There are two main methods of calculation.

- Fuel consumption based. The method is more accurate for more significant emission process, e.g., transoceanic tanker, or for emission factor in ton-km that is not available, e.g. hydrogen pipeline:

$$\frac{Amount_{fuel}\ [ton] \times Ef_{fuel}[\frac{kg\ CO_2eq}{ton}]}{Amount\ transported\ material\ in\ transport\ type\ [ton]}$$

- Based on transported distance and transported material, as the alternative:

$$\frac{Amount_{transported\ material\ in\ transport\ type}\ [ton] \times distance_{transported}\ [km] \times Ef_{transport\ type}\ [\frac{kg\ CO_2eq}{t\ km}]}{Amount_{transported\ material\ in\ transport\ type}\ [ton]}$$

where *Ef* = Emission factor.

The emission factor is provided by ISCC EU 205 and EU 205-1. Detailed assumptions are shown in **Section 4.4**.

2.3.1.3 Further GHG emissions parameter (e_p, e_u)

Further GHG emissions parameters to be considered in the GHG emissions calculation are e_p and e_u.

The emissions from processing e_p shall include direct atmospheric emissions from the processing itself, from waste treatment processes and leakages.

The EU Q&A clarifies that H_2 leakages should be considered as an energy loss (leading to proportional increase of the emission intensity). The global warming potential (GWP) of emitted H_2 should be considered as soon as a value for the GWP of H_2 is added in the relevant Annex.[33] However, according to ISCC EU 205-1, the greenhouse gases to be considered are CO_2, N_2O and CH_4, not including H_2.

Emissions from combustion of the fuel e_u refer to the total combustion emissions of the fuel in use.

Relevance for the Project

With hydrogen or ammonia as the product, there is no emission in use. Therefore, the e_u is zero in this project.

Hydrogen leakage is considered not to have GHG emissions.

2.3.1.4 Emissions from carbon captured and stored (e_{ccs})

e_{ccs} is subtracted from the total emissions, as this refers to the carbon emissions that are permanently stored in accordance with Directive 2009/31/EC from the production process for RFNBO. The emissions arising due to the storage operation, however, should be included under e_p. Hence, the applicability depends on the end use of the produced RFNBO. Probably this is not relevant within short- and medium-term.

Relevance for the Project

No CCS is considered. Therefore, the e_{ccs} is zero in this project.

2.3.1.5 Other rules

2.3.1.5.1 Rules, if output is not entirely qualifying as RFNBO

In the case that the output of a process is not entirely qualifying as RFNBO, the share of RFNBO from that process can be determined by dividing the relevant renewable energy input into the process by the total relevant energy inputs into the process. For electricity inputs that are used to enhance the heating value of the fuel or intermediate products the relevant energy is the energy of the electricity. In simple terms, the portion of renewables in the energy input of the whole process represents the portion of the entire output that would qualify as RFNBO.

[33] EU Q&A No. 64 Q&A implementation of hydrogen delegated acts (europa.eu)

Relevance for the Project

Due to the absence of actual planned projects, Fichtner constructed two typical reference projects for evaluation (one for ammonia production, one for liquid hydrogen). A sensitivity analysis was conducted to assess the impact of utilizing fully renewable electricity in RFNBO production on GHG emissions. Specifically, the analysis focused on how variations in the share of fully renewable electric power input for electrolyzers affect the proportion of RFNBO in the total product output.

2.3.1.5.2 Rules, if a process yields multiple co-products

For a process that yields multiple co-products such as fuels or chemicals, including energy co-products (e.g. heat, electricity or mechanical energy), the GHG emissions shall be allocated to these co-products. This is to be conducted at the end of the process that produces the co-products. The total emissions calculation should include the value chain up to the emissions of the process step at which these co-products are produced and shall comprise emissions from input e_i, production e_p, transport and distribution e_{td} and carbon capture and storage e_{ccs}. Where the ratio of the products is fixed and each product has an energy content, the allocation of GHG emissions shall be done **by energy content**. If one or more products are materials with no energy content, the allocation shall be done **by the economic value**. The economic value considered shall be the average factory-gate value of the products over the last three years. If such data is not available, the value shall be estimated from commodity prices minus the cost of transport and storage.

As an example, if oxygen from an electrolyzer facility is used in other processes and not released to the atmosphere, the products hydrogen and oxygen shall be allocated based on economical allocation. If the hydrogen is composed of products to which are attributed the same emission intensity (RCF and RFNBOs), an average price (weighted arithmetic average) can be applied.

Furthermore, it is possible to allocate emissions to heat (if used as a product). The allocation should be based on a Carnot efficiency.

These rules on multiple co-products apply on top of the specific rule for a production step yielding only energy products: If a produced fuel is a mix of RFNBO, RCF and other fuels, all (fuel) types shall be considered to have the same emission intensity unless the exception for co-processing apply. If for instance a process yields next to RFNBOs, RCF and other fuels also materials with no energy content, a first allocation should be done based the economic value of the co-products as set out under Annex, Part A (15(f)), while for the energy products the allocation rule set out under Annex, Part A (1) applies.

Relevance for the Project

For the Project and as a basis for the study it shall be assumed that O_2 and heat will be released into the atmosphere. Thus, the Project does not yield multiple co-products.

3 Cradle to Gate

The objective of this section is to analyze whether an emission factor from cradle to gate to achieve more than 70% total emission savings is feasible. It is crucial to ascertain the source of the electricity utilized by the projects and verify compliance with the standards prescribed by ISCC. Specifically, the hydrogen used in ammonia production should be sourced from renewable energy as much as possible.

A significant challenge encountered in identifying fully renewable sources is when a project is integrated with the grid. Initially, this section examines the bidding zone where the two projects are located, evaluating the renewable share and emission intensity of each zone. The findings indicate that the grid does not sufficiently meet renewable standards. Therefore, if the project relies on grid connectivity, it must fulfill additional criteria such as additionality, geographical correlation, temporal correlation, and securing a Power Purchase Agreement (PPA).

Due to the lack of existing planned projects, Fichtner developed two typical reference projects for this evaluation—one for ammonia production and another for liquid hydrogen. A sensitivity analysis was then conducted to determine how the integration of fully renewable electricity into RFNBO production influences GHG emissions. This analysis specifically focuses on the variation in the proportion of fully renewable electric power inputs for electrolyzers and its impact on the RFNBO share in the total product output.

3.1 Australian Power Market/ Bidding Zone

The Australian Energy Market Operator (AEMO) is responsible for managing Australia's electricity and gas systems and markets. AEMO administers two major wholesale electricity markets in Australia, as shown in **Figure 6**:

- National Electricity Market (NEM): This market operates in Eastern and Southeastern Australia.
- Wholesale Electricity Market (WEM): This market operates in Western Australia.

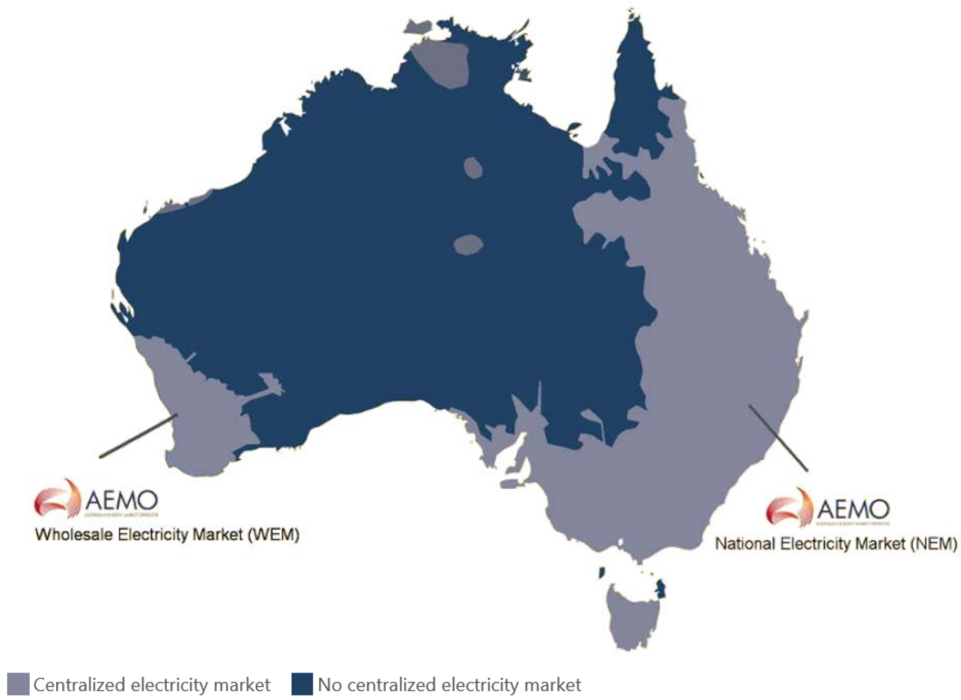

Figure 6: Bidding zone in Australia

It is important to note that the NEM and WEM are not interconnected. The Wholesale Electricity Market (WEM) functions within the South West Interconnected System (SWIS), making SWIS the bidding zone where the reference projects are located, with WEM serving as the operator of this bidding zone. The WEM facilitates wholesale electricity transactions between generators, retailers, large-scale consumers, and demand-side participants.

As defined in ISCC 202-6 Annex III, which stipulates that "the establishment of hourly prices for electricity within a geographic area allows it to be considered a bidding zone equivalent," the WEM qualifies as its own distinct bidding zone. This classification is essential for understanding the regional market dynamics and the compliance of the electricity used in projects with sustainability criteria.

Figure 7 shows the share of renewable and emission intensity in the Western Australian (WA) bidding zone. Due to low share of renewables (with 35% well below the required 90%) and high GHG emission (about 150 gCO_2eq/MJ well above the required 18 gCO_2eq/MJ) within the WEM grid, the only possible options to certify as fully renewable remain option 2c and 2d for grid-connected projects (see **Figure 3**).

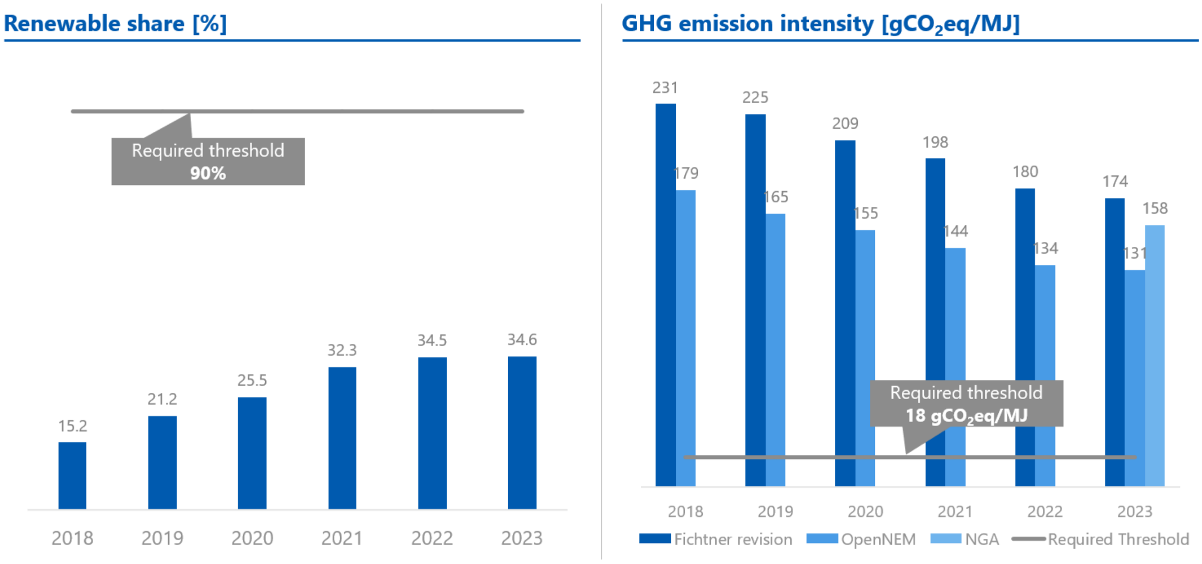

Figure 7: Renewable share (left) and GHG mission (right) in WA bidding zone, 2018-2023

The share of renewable power generation data is sourced from OpenNEM, an open platform that also provides information on the emission intensity for the SWIS bidding zone.[34] However, upon reviewing the emission intensity per generation type, Fichtner identified discrepancies when compared with the standards set forth in ISCC EU 205-1 Annex I and II.

To reconcile these discrepancies, Fichtner proceeded to calculate the emission intensity of the grid. This calculation was based on the generation data obtained from OpenNEM and the emission factors (both upstream and combustion) specified in ISCC EU 205-1, tables 3 and 4. The values derived from this calculation were then adopted as reference points for subsequent emissions calculations in the analysis. This adaptation ensures the compliance with the ISCC's stringent environmental criteria and substantiates the integrity of the project's emissions reporting. The values are compared with the NGA[35] values.

3.2 Reference Project Setting and Scenarios

The original plan was to base the calculation on real projects in Australia. However, discussions with the respective developers revealed that the projects were at a very early stage of development and therefore could not provide the required information. Fichtner therefore used the limited available information combined with the own knowledge in Power-to-X (PtX) to generate a reference project with realistic scenarios (direct connect and grid connection, shown in **Table 1**) and production type (ammonia and liquid hydrogen, shown in **Table 2**) for analysis. The assumption and scenarios will be the input for the inhouse optimization tool for PtX projects (*H_2-Optimizer*). The optimizer will give required facility capacity and electricity consumption by facility, e.g., electrolyzer. Electricity consumption is the key parameter within the GHG emission calculations.

The direct connection scenario based on the assumption has zero GHG emission from cradle to gate. The study focuses on the second grid connection scenario.

[34] OpenNEM
[35] Australian National Greenhouse Accounts Factors

Scenario No	Scenario name	Description
1	Direct connection	▪ All electricity used for RFNBO production are directly from renewable generation site via direct line ▪ No connection with grid
2	Grid connection	▪ RFNBO production facility requires electricity from grid ▪ **Grid electricity can be used for all RFNBO production steps depending on power supply case indicated in Table 2** ▪ Battery storage can be possible ▪ Wastewater treatment plant is external facility and using grid power ▪ Additionality fulfilled ▪ Geographical correlation fulfilled ▪ Renewable electricity generation - No constraint of PV/wind production capacity - Typical wind/solar profile in Western Australia - Green electricity PPA contract

Table 1: Scenario definition

The Grid connection scenario considers two production processes (**Table 2**): ammonia as product or liquid hydrogen. The Ammonia scenario is assumed to have the production target of 900 kTPA ammonia considering the prefeasibility study of BP for project GERI[36]. This requires approximately 159 kTPA hydrogen equivalent. Therefore, the liquid hydrogen production target is assumed to be the same amount of hydrogen. Under each production process, there are three ways to source electricity for production:

- **Fully green**: 100% fully renewable electricity is used for electrolyzer (ELY) and other production facilities;
- **Green power for ELY only**: 100% fully renewable electricity is used for ELY (excluding standby), other facilities sources electricity completely from spot market;
- **Economical optimal**: Grid electricity can be freely used for all production facilities;

Process No	Process type	Description	Power supply
2.1	Ammonia production	▪ Ammonia as target product ▪ Production target: 900 $kTPA_{NH3}$ ▪ Production facility: PV, Wind, Desalination, Electrolyzer, H_2 storage, Haber Bosch, Air Separation Unit, NH_3 storage	▪ Fully green ▪ Green for ELY only ▪ Economical optimal
2.2	Hydrogen production	▪ Liquid Hydrogen as target product ▪ Production target: 159 $kTPA_{H2}$ ▪ Production facility: PV, Wind, Desalination, Electrolyzer, H_2 storage, Liquefaction	▪ Fully green ▪ Green for ELY only ▪ Economical optimal

Table 2: PtX production type and power supply cases

Figure 8 shows the block diagram of ammonia/hydrogen production facility. Production supply chain is considered from material sourcing to the target product that is ready for loading to tanker. Therefore,

[36] Renewable Hydrogen and Ammonia Commercial Study (arena.gov.au)

storage facilities are considered part of the production process. The ammonia production scenario requires electrolyzer, desalination plant, air separation unit, Haber Bosch, hydrogen storage and ammonia storage. The Hydrogen production scenario needs less facilities: air separation unit, Haber Bosch and ammonia storage will not be required. But liquefaction facility is required to convert gaseous hydrogen to liquid hydrogen.

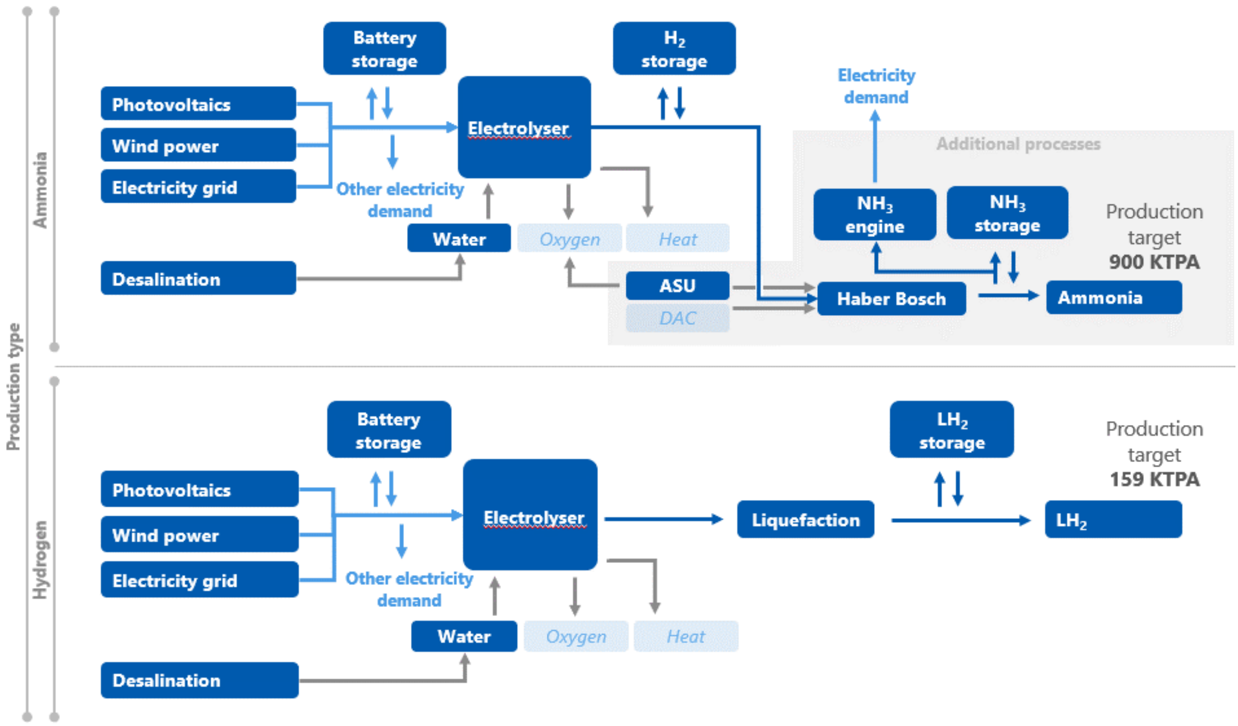

Figure 8: Block diagram of production facility by production type (grid connect scenario)

3.3 GHG Emission Calculation

3.3.1 Assumptions/ Inputs

To calculate the optimal system sizing and the corresponding mass and energy balances, several input information are required. These can be separated into technical assumptions, general economic assumptions and technology specific cost and performance data to be considered for this project. The main assumptions for these are summarized in the following paragraphs.

Technical assumptions

Basic technical assumptions for the optimization are displayed in Table 3.

Parameter	Assumption
Timeseries for Renewable power production (Wind & PV)	Data from renewables.ninja[37] for the location of the Oakajee strategic area resulting in a capacity factor of 19% (PV) and 42% (Wind)

[37] https://www.renewables.ninja

Parameter	Assumption
Offtake profile	Ships are expected to offload the Ammonia approximately every 3 weeks, and a storage system of suitable size is included for this purpose. On the other hand, the storage system for liquid H_2 is significantly costlier and highly depending on the offtake profile that is not known today. The basic LCOH calculation is therefore done considering a constant offtake without the need for a storage system. A sensitivity analysis is run considering that an offload of H_2 will be every 4.5 days. Thereby it is more frequently compared to ammonia to maintain economic feasibility.
Water information (availability limitations and quality)	It is assumed, that water can be generated via desalination on-site in sufficient quantities

Table 3: Technical assumptions.

General Economic assumptions

Those are assumptions made about the economic conditions and factors that may impact on the project costs and its financial performance and are important to consider as they can have a significant impact on the accuracy of the estimates. These assumptions include factors such as inflation rates, interest rates, exchange rates, as well as market conditions and are derived from the extrapolation of current key figures, when required, and input from external specialists.

Parameter	Unit	Value	Remark
Inflation	%	2.00	Inflation rate
WACC nominal	%	8.70	Before tax
WACC real	%	5.95	After tax
Project Lifetime	a	25	Lifetime of all equipment and installations and replacements must be considered in the costs
TICA 1 (non-chemicals)	%	25.4	Indirect cost adder for mature and mass production products[38]
TICA 2 (chemicals)	%	36.9	Indirect cost adder for non-mature and/or individual production products
Planned production target	$kTPA_{NH3}$ $kTPA_{H2}$	900.0 158.0	No specific demand profile considered
Proposed plant availability	%	97.0	Valid for overall plant availability
Grants or subsidies	-	None	-
Carbon credit sales	-	None	-
Electricity purchase price	USD/MWh	53.5	Yearly average price from WEM[39]

Table 4: Economic and project execution assumptions.

[38] It is assumed that the renewable energy generation technologies such as solar PV and wind as well as further technologies including battery energy storages, seawater reverse osmosis, water pipeline and power transmission lines have higher technology maturity level than for the technologies of the green industry. Hence, the EPCM effort and the contingencies associated with these technologies are expected to be lower than that for green industry technologies.
[39] AEMO | WEM data dashboard

Technology specific cost and performance data

Costs are estimated based on up-to-date experience gained from utility-scale projects in the region and worldwide. This includes information gathered from complete tender projects, bid evaluation, bid engineering services, technical due diligences and feasibility studies. By utilizing this experience, the cost estimates can be more accurate and reflective of current market conditions and trends. The estimated direct costs of each individual technology option are presented in the following tables. Therefore, it is important to understand that these cost estimates represent today's expected direct costs. To consider potential future cost savings (e.g., based on increased efficiency or improved processes) at the time of the actual purchase, learning rates will be applied.

As the focus of this study is not a full techno-economical evaluation of a project, the values used are based on Fichtner experience and are not aligned with the client beforehand. The aim is to have a solid cost estimate as a basis to compare the change in the LCOH for the different scenarios considered. For a more reliable estimate of costs, a proper feasibility study is recommended.

Item	Unit	Reference size [unit]	Specific direct cost [USD/unit]	EoS exponent [-]
Wind power (onshore)	MW	500	937,000	1.00
Solar PV	MW_p	500	435,000	1.00
Battery (capacity)	MWh	200	163,000	1.00
Battery (charge, discharge)	MW	100	70,500	1.00
Desalination unit	m^3/d	1,000	6,600	0.80
Electrolyzer	MW	500	1,389,330	0.89
H2 storage (100 bar_g)	kg	1,164	824	0.95
Air separation	t/h	49	1,020,400	0.45
Haber Bosch	t/h	63	2,285,700	0.66
Ammonia storage	kt	20	1,575	0.74

Table 5: Direct cost estimations for main technologies

In the context of energy conversion technologies, the size of the project, in terms of MW, has a significant impact on specific costs. Therefore, economy of scales is incorporated in the optimization.

3.3.2 Capacity and Electricity Consumption of Reference Projects

The optimization results regarding installed capacities of the main component for each scenario are presented in **Table 6** (ammonia production) and **Table 7** (hydrogen production).

To achieve a production output of 900 kTPA of ammonia, it is necessary to produce 159 kTPA of hydrogen as an input for the Haber-Bosch process. Consequently, both production scenarios are aligned in terms of their hydrogen production targets. This alignment is reflected in the similarities in the sizing of the photovoltaic (PV) and wind installations, the desalination plant, and the electrolyzer.

Optimization considerations indicate that with the availability of grid power purchases, there is no requirement for power storage. Instead, storage is solely designated for the end products (either ammonia or hydrogen). This is due to the logistical setup where tankers are not continuously present to load the product, but rather arrive every specified number of days (~every 23 days). This intermittent loading schedule necessitates sufficient storage capacity to maintain continuous production and ensure availability of the product for scheduled shipments.

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Production rate	kTPA		900 NH_3 (~159 H_2)	
Solar PV	GWp	2.1	2.0	1.4
Wind	GW	2.1	2.0	1.4
Battery storage	MWh	95	0	0
Electrolysis plant	GW	1.3	1.3	1.0
Air Separation Unit	MW	111	107	88
Haber Bosch plant	t_{NH3}/h	24	23	19
H_2 storage	t_{H2}	50	47	
NH_3 storage	kt_{NH3}	64	64	64
Desalination plant	t_{H2O}/h	305	295	234

Table 6: Installed capacity of ammonia production project

The Hydrogen production reference project has similar sizing as the ammonia production project, since the H2 equivalent target of the ammonia project is also 159 kTPA. Since the additional electricity required for liquefaction exceeds the electricity demand of the HB and other ammonia production facilities, the overall electricity consumption is slightly lower in the case of ammonia production and thus, the installed capacity of wind and PV is lower.

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Production rate	kTPA		159	
Solar PV	GWp	2.3	2.2	1.5
Wind	GW	2.2	2.1	1.5
Battery storage	GWh	1.0	0	0
Electrolysis plant	GW	1.3	1.3	1.0
Desalination plant	t_{H2O}/h	309	303	234

Table 7: Installed capacity of hydrogen production project

3.3.3 Electricity consumption and wastewater generation

In analyzing the GHG emission drivers from cradle to gate, electricity and generated wastewater have been identified as the primary factors. The production of ammonia or hydrogen predominantly relies on electricity as the main input. The detailed consumption numbers are shown in **Table 8**.

Our findings reveal that a significant portion of this electricity is consumed by the electrolyzer, which stands as the largest power consumer in the process. Following closely, the liquefaction process emerges as the second most significant power consumer. Additionally, it is important to note that the electricity utilized for desalination and water treatment processes is consistently sourced from the grid. This assumption plays a critical role in understanding the overall power consumption and emission landscape.

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Production rate	$kTPA_{NH3}$	900 (H_2 equivalent 159)		
Power consumption				
Electrolyzer – Production	GWh	9,154	9,108	9,108
Electrolyzer – Standby	GWh	274	266	211
Desalination	GWh	9	9	9
H2 storage	GWh	2	2	0
Haber Bosch	GWh	320	312	270
NH3 storage	GWh	5	0	0
Air Separation Unit	GWh	147	144	131
Total	GWh	9,910	9,840	9,729
Wastewater production				
Electrolyzer	kTPA	240	239	239
Desalination	kTPA	3,558	3,540	3,540

Table 8: Electricity consumption and wastewater generation of ammonia production project

In the context of liquid hydrogen production, a similar trend is observed. The most significant variation is that the liquefaction facilities demand more electricity compared to the combined requirements of ammonia production facilities, which include Haber-Bosch (HB), Air Separation Unit (ASU), and NH3 Storage. Consequently, this makes liquid hydrogen production predominantly dependent on electricity, thereby heightening its sensitivity to the characteristics of the sourced electricity.

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Production rate	$kTPA_{H2}$	159		
Power consumption				
Electrolyzer – Production	GWh	9,123	9,108	9,108

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Electrolyzer – Standby	GWh	278	273	211
Desalination	GWh	9	9	9
H2 storage	GWh	-	-	-
Liquefaction	GWh	1,197	1,195	1,195
Total	GWh	10,607	10,584	10,523
Wastewater production				
Electrolyzer	kTPA		239	
Desalination	kTPA	3,546	3,540	3,540

Table 9: Electricity consumption and wastewater generation of liquid hydrogen production project

3.3.4 Emission results

Based on the electricity demand, wastewater generation, share of fully renewable power (defined by power sourcing cases), GHG emission from cradle to gate is calculated. **Table 10** (ammonia production) **Table 11** (hydrogen production) show the emission by category and process.

In general, when more power is sourced from the spot market, the emissions associated with the project increase. The scenarios "Fully renewable production" and "Green power for ELY only" consider the use of fully renewable electricity for the electrolyzer, which enhances the low heating value of the end product, excluding the standby load of the electrolyzer. Consequently, the share of RFNBO is 100%.

Elastic input emissions are the primary source of emissions, as electricity is the main input for the electrolyzer, Haber-Bosch and liquefaction processes. Thus, elastic input emissions are highly sensitive to the emission intensity of the sourced electricity. The second power sourcing case, "Green power for ELY only" results in approximately 28 gCO_2eq/MJ in production emissions for ammonia, even when less than 10% of the electricity for the electrolyzer is not fully renewable. Achieving RFNBO certification criteria in terms of emissions with this scenario is therefore possible, if the transport doesn't add additional emissions.

While the project developer can achieve economic optimality, meaning the lowest cost across the entire lifespan of the project, only 73% of the product can be theoretically classified as RFNBO. Moreover, the overall emissions amount to approximately 100 gCO_2eq/MJ, significantly surpassing the threshold of 28.2 gCO_2eq/MJ. Consequently, none of the end product qualifies as RFNBO under this scenario.

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Power consumption - Fully renewable (PV/Wind)	GWh	10,239	9,743	7,274
Power consumption - Spot market	GWh	-	414	2,685

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Share of RFNBO	GWh	100%	100%	73%
Emission				
GHG emission	gCO_2eq/MJ	0.3	28.1	99.9
Emission by category				
Input - Elastic	gCO_2eq/MJ	-	27.8	99.6
Input - Rigid	gCO_2eq/MJ	0	0	0
Input - Existing use of fate	gCO_2eq/MJ	0	0	0
Process	gCO_2eq/MJ	0.3	0.3	0.3
Emission by process				
Electrolyzer	gCO_2eq/MJ	0.02	10.1	95.5
Desalination	gCO_2eq/MJ	0.27	0.6	0.4
H2 storage	gCO_2eq/MJ	0	0.06	0
Haber Bosch	gCO_2eq/MJ	0.0	11.9	2.8
ASU	gCO_2eq/MJ	0.0	5.5	1.3

Table 10: GHG emission of ammonia production project by power sourcing cases

In terms of liquid hydrogen production, liquefaction facilities require more electricity than ammonia production facilities. Therefore, it is crucial to have a high share of qualified renewable electricity for liquefaction as well.

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Power consumption - Fully renewable (PV/Wind)	GWh	9,723	9,474	6,975
Power consumption - Spot market	GWh	-	222	2,574
Share of RFNBO	GWh	100%	100%	73%
Emission				
GHG emission	gCO_2eq/MJ	0.25	49.4	94.6
Emission by category				
Input - Elastic	gCO_2eq/MJ	0	49.1	94.4
Input - Rigid	gCO_2eq/MJ	0	0	0
Input - Existing use of fate	gCO_2eq/MJ	0	0	0
Process	gCO_2eq/MJ	0.3	0.3	0.0.3

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
Emission by process				
Electrolyzer	gCO_2eq/MJ	0.02	9.1	83.6
Desalination	gCO_2eq/MJ	0.24	0.5	0.3
H2 storage	gCO_2eq/MJ	0	0	0
H2 liquefication	gCO_2eq/MJ	0	39.8	10.7

Table 11: GHG emission of liquid hydrogen production project by power sourcing cases

3.4 Sensitivity analysis

Based on the emission intensity results from typical power sourcing cases, it can be concluded that the sourcing of electricity plays a pivotal role in meeting the RFNBO emission criteria. However, the sensitivity of the electricity input in terms of its share of fully renewable sources necessitates further examination.

In this analysis, Fichtner considered the "Economical Optimal" scenario as the baseline, focusing on sizing and power consumption. The approach involved altering the share of electricity input for the electrolyzer (ELY) and other facilities separately, to observe how emissions from cradle to gate respond to these changes.

Figure 9 presents the results of the sensitivity analysis for the ammonia production scenario. It reveals that the majority of the power demand for RFNBO (ammonia) production is attributable to the electrolyzer, accounting for over 90% of the total consumption. The impact of the power source for other facilities is comparatively less significant. The full renewability of power for the electrolyzer proves to be crucial, not only in determining the share of the product classified as RFNBO but also in contributing to the majority of greenhouse gas (GHG) emissions. The recommended production scenario entails using fully renewable power input for the electrolyzer, albeit not 100% because it is assumed that electricity for desalination and water treatment is consistently sourced from the grid.

Share of fully renewable power for **other production facilities** \ Share of fully renewable power for **electrolyzer**[1)]	0%	10%	20%	40%	60%	80%	90%	93%	95%	98%	100%
0%	374.1	339.5	304.9	235.7	166.5	97.3	62.7	54.1	45.4	36.8	28.1
10%	371.3	336.7	302.1	232.9	163.7	94.5	59.9	51.3	42.6	34.0	25.3
20%	368.5	333.9	299.3	230.1	160.9	91.7	57.1	48.5	39.8	31.2	22.5
30%	365.8	331.2	296.6	227.4	158.2	89.0	54.4	45.7	37.1	28.4	19.8
40%	363.0	328.4	293.8	224.6	155.4	86.2	51.6	42.9	34.3	25.6	17.0
50%	360.2	325.6	291.0	221.8	152.6	83.4	48.8	40.1	31.5	22.8	14.2
60%	357.4	322.8	288.2	219.0	149.8	80.6	46.0	37.4	28.7	20.1	11.4
70%	354.6	320.0	285.4	216.2	147.0	77.8	43.2	34.6	25.9	17.3	8.6
80%	351.9	317.3	282.7	213.5	144.3	75.1	40.5	31.8	23.2	14.5	5.9
90%	349.1	314.5	279.9	210.7	141.5	72.3	37.7	29.0	20.4	11.7	3.1
100%	346.3	311.7	277.1	207.9	138.7	69.5	34.9	26.2	17.6	8.9	0.3

Emission below 28.2 gCO2eq/MJ Emission above 28.2 gCO2eq/MJ

1) Excluding standby load of electrolyzer

Figure 9: Sensitivity analysis of fully renewable share (ammonia project)

In the case of liquid hydrogen production (**Figure 10**), trends similar to those observed in ammonia production are evident. However, due to the higher power demand of the liquefaction facilities, the feasible area for optimization predominantly lies in the lower right part of the analysis. This indicates that liquid hydrogen production requires stricter power sourcing measures.

The recommended production strategy involves utilizing fully renewable power inputs for both the electrolyzer and liquefaction processes. By adhering to this approach, it ensures that the liquid hydrogen production aligns with sustainability goals and minimizes greenhouse gas emissions. This shift towards fully renewable sources is critical in maintaining the environmental integrity of the production process and in meeting stringent emission criteria.

Share of fully renewable power for **electrolyzer**[1)]

Share of fully renewable power for **other production facilities**	0%	10%	20%	40%	60%	80%	90%	93%	95%	98%	100%
0%	350.1	319.8	289.5	229.0	168.4	107.9	77.6	70.0	62.5	54.9	47.3
10%	345.4	315.1	284.8	224.3	163.7	103.2	72.9	65.3	57.8	50.2	42.6
20%	340.7	310.4	280.1	219.6	159.0	98.5	68.2	60.6	53.0	45.5	37.9
30%	335.9	305.7	275.4	214.8	154.3	93.7	63.5	55.9	48.3	40.8	33.2
40%	331.2	301.0	270.7	210.1	149.6	89.0	58.8	51.2	43.6	36.1	28.5
50%	326.5	296.3	266.0	205.4	144.9	84.3	54.1	46.5	38.9	31.4	23.8
60%	321.8	291.6	261.3	200.7	140.2	79.6	49.4	41.8	34.2	26.6	19.1
70%	317.1	286.8	256.6	196.0	135.5	74.9	44.6	37.1	29.5	21.9	14.4
80%	312.4	282.1	251.9	191.3	130.8	70.2	39.9	32.4	24.8	17.2	9.7
90%	307.7	277.4	247.2	186.6	126.1	65.5	35.2	27.7	20.1	12.5	5.0
100%	303.0	272.7	242.4	181.9	121.4	60.8	30.5	23.0	15.4	7.8	0.3

Emission below 28.2 gCO2eq/MJ Emission above 28.2 gCO2eq/MJ

1) Excluding standby load of electrolyzer

Figure 10: Sensitivity analysis of fully renewable share (hydrogen project)

3.5 Financial impact

The analysis of previous sections underscores the importance of considering both financial and environmental factors when planning a new project in the energy sector. Achieving RFNBO certification, which requires at least 90% of electricity consumption to be from renewable sources, is crucial but comes with increased costs. Strategic options such as enhancing renewable generation capacity, aligning generation with consumption patterns, or incorporating battery storage can help meet this criterion.

Levelized cost of hydrogen (LCOH) and levelized cost of ammonia (LCOA) consider only the process from cradle to gate (Australia), the potentially necessary hydrogen cracking cost in Rotterdam is not included. The financial data presented in **Table 12** indicates significant investments are needed to increase renewable capacity and thereby comply with RFNBO standards. For instance, expanding wind and solar capacity from 2.8 GW to 4.2 GW entails a capital expenditure jump from 4.8 billion USD to 6.9 billion USD for the ammonia production scenario. However, it's noteworthy that the Levelized Cost of Ammonia (LCOA) does not rise in direct proportion to the Capex increase, thanks to reduced dependence on the electricity purchase with higher share of own generated electricity.

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
LCOA	USD/t_{NH3}	816	792	740
Capex	bn USD	6.9	6.4	4.8
Capacity PV	GWp	2.1	2.0	1.4
Capacity wind	GW	2.1	2.0	1.4
BESS[40]	GWh	95	0	0

Table 12: Financial indicators of ammonia production project by power sourcing cases

Similarly, for hydrogen production (**Table 13**), while the initial costs for Capex and LCOH (Levelized Cost of Hydrogen) under high renewable scenarios are relatively close, transitioning to 100% renewable energy sources incurs marginal additional costs if the project already utilizes substantial renewable energy inputs. Since the LCOH calculations do not take into account the size of a hydrogen storage, a sensitivity analysis was conducted, considering a storage size of 2,000 tH2. This was done to evaluate the financial consequences of a constant offtake that requires minimal storage compared to an offtake profile that involves an offtake every 4.5 days. The analysis revealed a substantial 30% rise in LCOH, mainly due to the expensive nature of hydrogen storage.

Overall, precisely assessing and strategically planning energy sourcing to meet RFNBO standards is vital for long-term sustainability and cost efficiency in energy project development. Considering the possible off-take profile is a key to deciding in which form the hydrogen shall be transported as hydrogen storages are more expensive than equivalent ammonia storages. Further analysis with real-world project data could provide more tailored recommendations and a refined financial impact assessment.

	Unit	Fully renewable production	Green power for ELY only	Economical optimal
LCOH	USD/t_{H2}	4,266	4,151	3,989
Capex	bn USD	6.3	6.0	4.4
Capacity PV	GWp	2.3	2.2	1.5
Capacity wind	GW	2.2	2.1	1.5
BESS	GWh	1.0	0	0

Table 13: Financial indicators of liquid hydrogen production project by power sourcing cases

[40] BESS = Battery Energy Storage System

4 Gate to Grave

The objective of this section is to determine the greenhouse gas (GHG) emission factor from the Australian export port to the end-users, covering the span designated as 'gate to grave.' This encompasses the processes from the export port in Australia to the final off-takers in Germany. The gate to grave segment primarily consists of two components: transportation and end usage. Given that the end products in this project are either ammonia or hydrogen, which do not generate emissions during use, the focus of this section is solely on transport emissions. **Table 14** summarizes the transportation methods from Oakajee (production site in Australia) to end users in Duisburg.

	Oakajee (Australia) - Rotterdam (Netherlands)	Rotterdam (Netherlands) - Duisburg (Germany)
Ammonia as transport carrier	▪ Transoceanic tanker (fueled with HFO) ▪ Transoceanic tanker (fueled with biodiesel) ▪ Transoceanic tanker (fueled with NH_3)	▪ Hydrogen pipeline (including cracking) ▪ Ammonia barge tanker ▪ Ammonia train
Liquid hydrogen as transport carrier	▪ Transoceanic tanker (fueled with HFO) ▪ Transoceanic tanker (fueled with biodiesel) ▪ Transoceanic tanker (fueled with NH_3)	▪ Hydrogen pipeline (no cracking)

Table 14: Summary of transport methods

The GHG emission analysis indicates that, in the worst-case scenario using HFO as fuel, the emissions attributable to the gate to grave segment represent approximately 30% of the total permissible emissions (28 gCO_2eq/MJ). This finding suggests that there is considerable potential for project developers to utilize less expensive non fully renewable grid electricity, as long as it is not employed to augment the heating value of the end products.

4.1 Transoceanic tanker: Port of Oakajee to Port of Rotterdam

Exported PtX products have several transportation options, including ammonia, Liquid Organic Hydrogen Carrier (LOHC), or liquid hydrogen. Ammonia, being the most common and established method, serves as the baseline for transportation. RVO recommends considering liquid hydrogen as an additional transportation option. The effects on the production process have been explored in detail in **Section 3**.

This section further investigates the potential impact on transport emissions. Different transport methods may entail varying levels of GHG emissions, influenced by factors such as energy density of the fuel, transportation distance, and the specific handling requirements of each fuel type. The evaluation of these factors is crucial to understanding the overall environmental footprint and efficiency of transporting PtX products from the production sites to the end-users. This analysis aims to provide a comprehensive view of the viable transportation options while mitigating the environmental impact.

Ammonia has been used in various industries for a long time, and the infrastructures for ammonia synthesis are abundant. Also, ammonia can be stored in slightly refrigerated tanks at -33 °C or at ambient temperatures under a pressure of 8-10 bar_g. This makes storing and transporting ammonia relatively straightforward and affordable.

Alternatively, hydrogen can also be transported as Liquid Organic Hydrogen Carrier (LOHC) or liquid hydrogen. The LOHC process is relatively inexpensive and safe. In addition, the LOHC is a diesel-like substance, which can be transported under atmospheric pressure and temperature with regular vehicles for gasoline or diesel. However, dehydrogenation requires heat and thus additional energy. In large-scale use, the costs can therefore mount up considerably. Additionally, the production of LOHC causes extra CO_2 emissions. Exactly how much depends on how long the LOHC lasts and how often it can be reused.

Liquid hydrogen requires extreme cooling, which consumes a lot of energy, and high quality insulation to maintain the extremely low temperature. In addition, a small amount of boil-off gas cannot be prevented over time. Technical advancement is expected to allow liquid hydrogen tanker transport to be possible within the next decade or so.

The only possible option for such a long-distance chemical transportation is transoceanic tanker. **Table 15** shows the characteristics of possible ship classes for transoceanic chemical transportation.

Type	Unit	VLGC	LGC	MGC	HDY
Capacity	t	50,100	40,100	25,000	14,100
Capacity	m^3	75,000	60,000	38,000	21,000
Dimensions: Length	m	227	200	188	160
Beam	m	32.3	32.3	29	25.6
Draft	m	12.0	11.5	10.2	9.0
Speed, laden	kn	16.0	16.0	16.0	16.0
Speed, ballast	kn	16.0	16.0	16.0	16.0
Fuel, laden*	TPD	44	35	33	22.0
Fuel, ballast*	TPD	42	33	33	19.5
Fuel, in port**	TPD	7	6	4.5	7.5
Boil-off rate	%/d	0.04	0.04	0.04	0.04
Loading rate	t/h	2,000	1,800	1,700	950
Discharge rate	t/h	2,000	1,800	1,700	950
Usage rate boil-off	%	100	100	100	100

Table 15: Parameters of transoceanic chemical tankers

Two main variables for choosing the tanker transportation are the distance and the volume. The total distance of the track is estimated as 15,500 nm via Suez Canal. The Ammonia project has a production target of 900 $kTPA_{NH3}$, while the hydrogen project has a production target of 159 $kTPA_{H2}$. Additionally, vessel availability and turnarounds over the year are considered. Based on all above-mentioned criteria, Large Gas Carrier (LGC) is the most technical and feasible option for both ammonia and hydrogen reference projects.

Both LGC and VLGC have three fuel options: HFO, biodiesel or NH_3. NH_3 uses the boil off ammonia as powering fuel for vessel, resulting higher losses of ammonia that can be transported. But this does not require external fuel and has no GHG emission.

4.2 Continental transport: Port of Rotterdam to Duisburg

In general, ammonia can be transported from Rotterdam to Duisburg by using one of the following methods, e.g.,

- Hydrogen: Pipeline
- Ammonia: Ship (barge tanker), Train, and Truck

If hydrogen is the transport form, cracking is needed in the Port of Rotterdam. Cracking is assumed to have the efficiency of 80%. The 20% loss is used to power the cracking process. Therefore, no additional emissions occur in the cracking process.

Barge tankers are considered to be the most feasible transport option due to their technical maturity. There are shipping providers offering ammonia transport.

Hydrogen pipelines represent the most promising solution for green molecule transport in large quantities. The European Hydrogen Backbone (EHB) initiative consists of a group of thirty-three energy infrastructure operators. The EHB suggests the development of hydrogen pipelines (existing and new) in enabling the development of a competitive, liquid, pan-European renewable and low-carbon hydrogen market. The EHB indicates the connection between the Port of Rotterdam to Duisburg with a distance of 297 km.

An ammonia pipeline between Netherlands and Germany was proposed within the Delta Rhein Corridor (DRC) project. The DRC focuses on hydrogen and CO_2 transportation pipeline. The ammonia pipeline is mentioned as a possible additional option. However, no further development has been observed. Therefore, the ammonia pipeline is not further investigated in this project.

A train transport is less favorable than barge tanker and pipeline due to the high volume of ammonia/hydrogen that need to be transported. In our case, frequent transportation is needed. This is contradicting to the complexity of chemical train transport. In Netherlands, ammonia train transport is discouraged; In Germany additional permission is required for toxic chemicals.

Within these constraints, ammonia is more suitable for train transport than hydrogen. Ammonia can be easily transported in liquid form, i.e., higher energy density. If hydrogen is wished to be transported in liquid form, the effort is enormous.

Truck transport is out of scope as it is more suitable for short-distance transport. Like for train transport, even higher transport frequencies are needed.

As a result, the following options are selected as feasible options as transport methods.

- Ammonia landed in Rotterdam
  - Barge tanker carrying ammonia;
  - Hydrogen pipeline, with cracking;

- Freight train carrying ammonia;
- Liquid hydrogen landed in Rotterdam
  - Hydrogen pipeline, no cracking process needed;

4.3 Off-takers

Off-takers are assumed to be industry, power and transportation in Duisburg, Germany.

The end use within the scope of this project is either ammonia or hydrogen. Per ISCC EU-205-1, section 3.1.3, there is no emission for hydrogen and ammonia application. This has been clarified in **Section 2.3.1.3**.

4.4 GHG Emission calculation

4.4.1 Assumptions/ Inputs

The assumptions and inputs for transport emission calculations are summarized in **Table 16**.

Step	Parameter	Value	Unit	Source
General	LHV - Ammonia	18.6	MJ/kg	
	LHV - Hydrogen	120	MJ/kg	
AUS-NDL	Ammonia transported amount, S1	900	kTPA	Fichtner
	Hydrogen transported amount, S2	159	kTPA	Fichtner
	HFO emission factor	87	gCO_2eq/MJ	ISCC EU 205
	Distance (one way)	17,678	km	Searates
NDL-DEU	Distance - Pipeline (one way)	297	km	EHB
	Distance - Barge tanker (one way)	254	km	LogistikInside[41]
	Distance - Train (one way)	225	km	Searates
	EF - Barge tanker (fully loaded)	434.58	$gCO_2eq/t{\cdot}km$	ISCC EU 205-1
	Tanker fuel consumption empty vs. full	46%	%	WupperInst[42]
	EF - Train EU	455.69	$gCO_2eq/t{\cdot}km$	ISCC EU 205-1
	Cracking loss	20%	%	Fichtner
	Emission intensity of grid electricity, NL	99.9	gCO_2eq/MJ	ISCC EU 205-1
	Emission intensity of grid electricity, DE	99.3	gCO_2eq/MJ	ISCC EU 205-1

Table 16: Assumptions for transport emission calculation

[41] https://media1.autohaus.de/fm/3576/sixcms_filename/Download_Rhein_km.pdf
[42] https://epub.wupperinst.org/frontdoor/deliver/index/docId/7412/file/7412_Maritime_Transport.pdf

4.4.2 Calculation methodology and validation

The emission calculated methodology has been explained in **Section 2.3.1.2**. As mentioned, there are two calculations methods. The first one is based on fuel consumption; The second one is based on the transport distance and the amount.

This first method is more accurate for significant emission process, i.e., transoceanic tanker; Or the emission factor ton-km is not reliable, i.e., hydrogen pipeline

- Fuel demand of transoceanic tanker from Fichtner Transport Model
- Electricity demand of hydrogen pipeline from Fichtner H2 Pipeline Model

The following assumptions are considered:

- Round trip (AUS-NDL fully loaded; NDL-AUS empty);
- VLGC and LGC have the same fuel consumption rate (the economy of scale effect is still effective);
- Fully refrigerated ammonia transport;
- BOG units in both ports, none on the vessel;
- Boil off ammonia will be used as vessel fuel to reduce ext. fuel consumption;
- 100% ballast rates, i.e., No triangulation considered;
- Power consumption for BOG units in the port is not considered;
- Electricity consumption of compressor for hydrogen pipeline: grid electricity;
- Compression electricity demand in the beginning of the pipeline (48 to 60 bar_g) and compression station along the pipeline (pressure drop from 60 to 45 bar_g).

The second option is not as exact as the average emission factor in km-ton is provided by ISCC. This makes it reliable and needs no validation.

- Round trip for barge tanker (NDL to DEU fully loaded; DEU to NDL empty);
- Emission factor of empty trip is assumed to be 46% of the reference value (values shown in **Table 16**);
- Train transport is assumed to be one way.

Validation is conducted for emission of transoceanic tanker and hydrogen pipeline to confirm the numbers and limit the uncertainty. The validation results are shown in **Figure 11**.

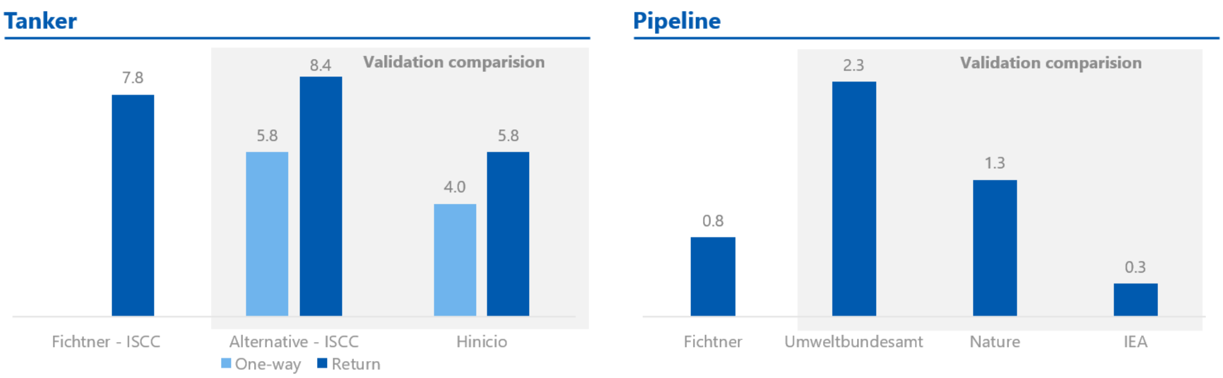

Figure 11: Validation of transoceanic tanker (left) and pipeline (right) CO2eq emission

Generally, an empty tanker is assumed to have 46% fuel consumption as a fully loaded tanker based on a study from Wuppertal Institute and Port of Rotterdam.[43]

The main case is Fichtner-ISCC that is fuel consumption based. Fuel demand of transoceanic tanker is calculated via the Fichtner Transport Model.

An Alternative-ISCC method is a simplified ton-km method. The emission factor of 6.0571 gCO2/ton-km is taken from ISCC EU 205. The fuel type is diesel, but the type of tanker is not clear

The Hinicio study is a fuel consumption method. Hinicio conducted a study of RFNBO in the form of e-methanol for Ministry of Economic Affairs and Climate Policy of the Netherlands. The study gives the following assumption for tanker:

- Fuel consumption: 87.9 kg-fuel oil/nautical mile
- Emissions factor: 3.11 kgCO2/kg-fuel
- Vessel capacity: 35.5 kt

As H_2 pipeline development is still in early phase, data on pipeline transport is not as concrete as for gas pipelines. The number can vary heavily depending on the assumption. Fichtner examines the mainstream updated studies on hydrogen pipeline with the following assumptions:

- Umweltbundesamt (German Environmental Agency)[44]: compression station every 155 km; electricity consumption per compressor: 0.4 kWh/kg_{H2}
- Nature: transported distance[45]: 1,000 km; electricity consumption: 0.45 kWh/kg_{H2}
- IEA: transported distance[46]: 10,000 km; electricity consumption: 3.6 kWh/kg_{H2}

The comparison with other references shows the validity of the study results. However, some studies suggest that transport emissions are even higher, so it is recommended to assess transport emissions on a project-by-project basis, based on the individual components used, such as the type and size of vehicle.

4.4.3 Emission results

The total emission from gate to grave for ammonia project are shown in **Table 17**.

The maximal GHG emission amount of the full value chain would be 28.2 gCO_2eq/MJ. According to the analysis, gate to grave already uses 0.6 to 8.2 gCO_2eq /MJ depending on the transport methods. The reminding allowance for ammonia production is between 10.0 to 27.7 gCO_2eq /MJ in order to certify as RFNBO. The room for production (cradle to gate) is rather big as long as the production is leveraging fully renewable electricity.

[43] https://epub.wupperinst.org/frontdoor/deliver/index/docId/7412/file/7412_Maritime_Transport.pdf
[44] https://www.umweltbundesamt.de/sites/default/files/medien/479/dokumente/uba_welche_treibhausgasemissionen_verursacht_die_wasserstoffproduktion.pdf
[45] https://www.nature.com/articles/s41560-024-01563-1
[46] https://iea.blob.core.windows.net/assets/acc7a642-e42b-4972-8893-2f03bf0bfa03/Towardshydrogendefinitionsbasedontheiremissionsintensity.pdf

Transport				End Use	Gate to Grage
Gate Oakajee - Rotterdam		Rotterdam - Duisburg		Germany	
Method	GHG emission	Method	GHG emission	GHG emission	GHG emission
-	gCO_2eq/MJ	-	gCO_2eq/MJ	gCO_2eq/MJ	gCO_2eq/MJ
Ammonia project					
Transoceanic tanker - HFO	7.33	Barge tanker	0.87	0	**8.20**
		Pipeline	0.79	0	**8.12**
		Train	0.55	0	**7.88**
Transoceanic tanker - Biodiesel	3.96	Barge tanker	0.87	0	**4.83**
		Pipeline	0.79	0	**4.75**
		Train	0.55	0	**4.52**
Transoceanic tanker - Ammonia	0.00	Barge tanker	0.87	0	**0.87**
		Pipeline	0.78	0	**0.78**
		Train	0.55	0	**0.55**
Hydrogen project					
Transoceanic tanker - HFO	6.51	Pipeline	0.78	0	**7.30**
Transoceanic tanker - Biodiesel	3.52	Pipeline	0.78	0	**4.31**
Transoceanic tanker - Ammonia	0.00	Pipeline	0.78	0	**0.78**

Table 17: GHG emission gate to grave

In the project report for the transportation of ammonia or liquid hydrogen from Australia to Rotterdam, three primary options were considered: a Heavy Fuel Oil (HFO) fueled transoceanic tanker, biodiesel fueled transoceanic tanker and an ammonia fueled transoceanic tanker. Due to the need to transport a higher volume of ammonia and the associated economic benefits, a Large Gas Carrier (LGC) was selected.

The sensitivity analysis shows that by replacing HFO with biodiesel the emission of transoceanic tanker can be reduced 42%. The sensitivity analysis is based on the following assumptions:

- HFO: emission factor of 87 gCO_2eq/MJ_{fuel} (source: ISCC) – LHV of 40.2 MJ/kg;
- Biodiesel has emission factor of 47 gCO_2eq/MJ_{fuel} including upstream emission (source: ISCC) – LHV of 37.5 MJ/kg;
- Same heating value is required for tanker despite the difference of fuels;

The ammonia-fueled transoceanic tanker was assessed to lack emissions of CO_2, N_2O, and CH_4, based on ISCC standards, which do not account for such emissions in the combustion of ammonia.

Furthermore, three options were evaluated for transporting ammonia from Rotterdam to Duisburg for ammonia projects: a barge tanker, a hydrogen pipeline that includes ammonia cracking, and a freight train.

Emissions for the transoceanic tanker and hydrogen pipeline were calculated through more accurate fuel consumption using Fichtner's in-house simulation model. Other transportation emissions were estimated based on emission factors derived from the product of distance and transport amount, using ISCC EU 205 as the source for emission factors. The emission intensity remains identical between project 1 and 2 as the key differing factor is distance.

Among the scenarios assessed, the combination of the HFO-fueled tanker from Oakajee to Rotterdam, followed by the barge tanker from Rotterdam to Duisburg, resulted in the highest greenhouse gas (GHG) emissions. HFO contributed significantly to these emissions.

The most optimal transportation solution identified involves using an ammonia-fueled tanker followed by the hydrogen pipeline. This consideration is also in line with the reluctance of the Dutch government regarding the transport of ammonia by train in the Netherlands. This option also takes into account a 20% cracking loss, wherein the cracking process does not require an external fuel source.

Table 18 shows fuel consumption and mass balances as inputs for emission calculation.

Transport section	Transport method	Carrier	Value	Unit
Ammonia project				
Oakajee - Rotterdam	**Transoceanic tanker - HFO fuel**			
	Fuel consumption	HFO	34,577	t/a
	Losses	NH_3	29,582	t/a
	Transoceanic tanker - Biodiesel fuel			
	Fuel consumption	Biodiesel	37,045	t/a
	Losses	NH_3	29,582	t/a
	Transoceanic tanker - Ammonia fuel			
	Fuel consumption	NH_3	88,774	t/a
	Losses	NH_3	118,356	t/a
Rotterdam - Duisburg	**Pipeline**			
	Cracking loss - HFO/biodiesel transoceanic transport	NH_3	171,384	t_{NH3}/a
	Cracking loss - NH3 transoceanic transport	NH_3	153,629	t_{NH3}/a
	H2 output of cracking - HFO/biodiesel transoceanic transport	H_2	120,977	t_{H2}/a
	H2 output of cracking - NH3 transoceanic transport	H_2	108,444	t_{H2}/a

Transport section	Transport method	Carrier	Value	Unit
	Electricity demand compressor - HFO/biodiesel transoceanic transport	Electricity	31,913	MWh/a
	Electricity demand compressor - NH3 transoceanic transport	Electricity	28,458	MWh/a
Hydrogen project				
Oakajee - Rotterdam	**Transoceanic tanker - HFO fuel**			
	Fuel consumption	HFO	35,060	t/a
	Losses	H_2	55,957	t/a
	Transoceanic tanker - Biodiesel fuel			
	Fuel consumption	Biodiesel	37,584	t/a
	Losses	H_2	55,957	t/a
	Transoceanic tanker - Ammonia fuel			
	Fuel consumption	NH_3	90,051	t/a
	Losses	H_2	55,957	t/a
Rotterdam - Duisburg	**Pipeline**			
	Landed H2	H_2	100,954	t_{H2}/a
	Electricity demand compressor	Electricity	26,462	MWh/a

Table 18: Fuel/power consumption of transportation

5 Evaluation Results and Recommendations

The data presented in **Table 19** highlights the significant variability in greenhouse gas (GHG) emissions associated with the production of Renewable Fuels of Non-Biological Origin (RFNBO) depending on the primary energy source utilized. The emissions can vary dramatically from as low as 0.3 gCO_2eq/MJ to as high as 100 gCO_2eq/MJ in the cradle-to-gate phase, which underscores the importance of the energy mix in the production process.

Nevertheless, the study conducted, that the production of RFNBOs (H2 & NH3) in Australia is feasible if certain criteria are met, particularly for renewable electricity share. Due to the low share of renewables and high GHG emissions in the WEM grid, reasonable options for certification as fully renewable are either a direct connection or a grid connection including a PPA and meeting the criteria of additionality, temporal and geographical correlation.

The usage of a high share of renewable power is critical in minimizing GHG emissions during production especially in countries with a high CO2- emission in the Grid such as Australia. Projects that integrate a substantial proportion of fully renewable energy, can maintain lower emission levels, thereby making them more sustainable and environmentally friendly. The contribution of fully renewable electricity to the electrolyser is crucial, not only for the share of the product as RFNBO, but also because it contributes to the majority of greenhouse gas emissions.

The gate-to-grave emissions, which cover the transportation phase, have less variation across the different scenarios. If the electricity source for production is clean enough, the transportation method is flexible without damaging the certification of end product as RFNBO.

GHG emissions in gCO_2eq/MJ		Ammonia production	Hydrogen production
Cradle to gate	Best: Fully renewable	0.3	0.3
	Worst: Economical optimal	99.9	94.6
Gate to grave	Best: Ammonia fueled tanker+train	0.6	0.8
	Worst: HFO tanker+diesel tanker	7.3	6.5
Total	Best	0.9	1.1
	Worst	107.2	101.1

Table 19: Summary of GHG emission of best- and worst-case combination

To make RFNBOs a viable and sustainable alternative, it is crucial for project developers and policymakers to focus on optimizing the energy mix used in the production phase. This may involve leveraging locations with abundant renewable energy resources or investing in technology and infrastructure that increase the proportion of renewable energy used in RFNBO production. This can require higher Capex investment and less production hours. Therefore, significant investments compared to the economical optimum are needed to increase renewable share in the grid and thereby comply with RFNBO standards.