Risk-Aware Contracting Strategies for Electrolytic Hydrogen Projects Facing Grid Congestion

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***Abstract*—Electrolytic hydrogen is expected to play a key role in decarbonizing energy systems in Europe. However, such projects face uncertain grid access due to congestion and struggle with financial viability. To address growing grid congestion in the Netherlands, different types of non-firm connection and transport agreements (CTAs) and capacity restriction contracts (CRCs) were introduced, enabling client curtailment in exchange for tariff discounts or per-MW compensation. This paper investigates investment and contracting decisions for electrolyzer projects under these novel contracts using a two-stage risk-aware stochastic optimization model that captures uncertainty in electricity prices and grid access. Results show that risk-averse clients prefer non-firm CTA-85 contracts, which balance tariff discounts with curtailment compensation, while risk-neutral clients favor standard non-firm CTAs. The new contract types can lower the break-even hydrogen price by approximately €0.50/kg compared to firm contracts outside congested areas, and thus improve the business case for electrolytic hydrogen in the Netherlands.**

***Index Terms*—Congestion management, bilateral contracts, electrolyzers, grid connection, stochastic optimization.**

List of Abbreviations

CTA	Connection and transport agreement
CRC	Capacity restriction contract
FA	Firm CTA
NFA	Non-firm CTA
NFA85	Non-firm CTA-85

I. Introduction

Hydrogen produced by electrolyzers is increasingly recognized to be key in decarbonizing European energy systems. The Netherlands alone requires the development of 16 to 45 GW of domestic electrolysis capacity to become carbon neutral by 2050. However, electrolytic hydrogen currently presents a weak business case compared to fossil-based alternatives, which is exacerbated by (financial) uncertainties such as future electricity prices, making it difficult to secure financial close for such projects. On top of that, in the Netherlands, electrolytic hydrogen projects are hampered due to congestion issues in the Dutch power grids, that require costly and time intensive grid reinforcements, resulting in extensive waiting lists for new connection and transport agreements (CTAs) [1].

To address these waiting lists, the Dutch regulator introduced new contract types to the grid code between 2022 and 2024, namely capacity restriction contracts (CRCs) and non-firm CTAs, that allow grid operators to temporarily limit the contracted capacity of clients to mitigate anticipated congestion [2]. Under non-firm CTAs, clients receive flexible (non-firm) transport capacity instead of guaranteed (firm) capacity. Clients with non-firm CTAs receive discounts on their annual transport tariffs, while clients with CRCs are compensated by the network operator for each MW of reduced power from their contracted capacity. Thus, by choosing non-firm CTAs or CRCs, a client might improve the business case of electrolytic projects through e.g. tariff discounts; However, these contracts also introduce additional uncertainty as future grid access is no longer guaranteed, impacting future revenue. Currently, it is unclear which of the novel contracts are attractive to clients and whether these contracts improve, or hamper the business case of electrolytic hydrogen projects. Previous studies have analyzed or optimized the business case of electrolytic hydrogen projects under uncertainty. For instance, [3] assessed the techno-economic performance of solar PV-electrolyzer systems under various electricity market configurations in California. [4] proposed a two-stage stochastic optimization model for risk-conscious asset sizing of an electrolytic hydrogen-PV plant under uncertain future electricity prices and PV generation. [5] developed a hybrid stochastic–robust optimization framework for sizing electrolyzers in industrial parks, accounting for uncertainties in electricity prices, renewables, and hydrogen demand. However, these studies did not consider uncertainty in future grid access. Other research has highlighted the role of non-firm CTAs in facilitating grid access [6], supporting renewable development [7], or analyze and formulate congestion management strategies [8], [9]. Yet, to the best of the authors' knowledge, no studies have evaluated the business case of electrolytic hydrogen projects under uncertain future grid conditions: particularly in the context of novel contracts emerging in congested power grids. To address this gap, this study proposes a two-stage risk-aware stochastic planning model for an electrolytic hydrogen plant in the Dutch power grid. In the first stage, the plant owner decides on the size of the electrolyzer and ancillary infrastructure size, and the CTA. In the second stage, operational decisions are made once uncertainties in electricity prices and grid capacity are realized. This is the first study to explore how a risk-aware, flexible client, such as an electrolyzer operator, would choose among emerging CTA and CRC types, and whether such contracts can enhance the business case of electrolytic hydrogen projects. The remainder of this paper is organized as follows. Section II briefly introduces novel non-

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firm CTAs and CRCs in the Dutch power system. Section III mathematically describes the stochastic risk-aware planning model for a hydrogen plant. Section IV introduces the case study. Section V gives and discusses numerical results. Section VI concludes the study.

II. Novel Contracts in Dutch Energy System

For a detailed explanation on novel contracts in the Dutch energy system, the reader is referred to [10]. The contracts will be briefly explained here.

Starting April 1, 2025, clients can choose between three types of CTAs. The firm CTA (FA) guarantees the client full access to their contracted capacity at all times. The non-firm CTA-85 (NFA85) allows the network operator to reduce transport capacity up to 15% of the hours in the year. The non-firm CTA (NFA) allows the network operator to reduce the contracted capacity at all times. Clients choosing an NFA85 or NFA receive discounts on their transport tariffs. There are two transport tariffs for large clients, kW-contracted and kW-peak, which will be denoted by T^1 and T^2. For non-firm CTAs, T^1 is lowered while T^2 remains fixed. Network operators will provide forecasts on future residual network capacity to help clients assess risks. Capacity restrictions are announced before the closing of the day-ahead market.

CRCs are a congestion management tool introduced in 2022. Before refusing new connections in congested areas, network operators must spend at least €1.02/MW on congestion management. Under CRCs, network operators can curtail a client's transport capacity, compensating the client with fixed or dynamic payments. In congested areas, clients over 1 MW must participate in congestion management if their CTA allows it, which is the case for FA and NFA85 contracts (while NFA holders are exempt). Therefore, clients with an FA or NFA85 are assumed to be automatically enrolled in CRCs. The network operator can simultaneously curtail via a CRC and NFA85, but the same capacity cannot be curtailed twice.

III. Model Formulation

This study considers the planning of a grid-connected hydrogen plant consisting of an alkaline electrolyzer, a hydrogen storage vessel, and a compressor. The plant needs to meet an hourly minimum demand $D_t^{\mathrm{H_2}}$. During hours of congestion, the electrolyzer cannot produce hydrogen and the hydrogen storage vessel is used to meet the hydrogen demand. The plant owner must decide on the sizing of plant components and their preferred CTA contract in the first stage, before uncertainties in future grid access and electricity prices are realized in the second stage. Although the NFA offers the highest tariff discount, it also involves the greatest risk: if future residual network capacity is low, the plant may face frequent curtailments without compensation.

A. Mathematical Description

In the following, Greek letters and uppercase symbols denote parameters; lowercase symbols denote variables. Indices and sets are defined as follows: $t \in \mathcal{T}$ for hours, $i \in \mathcal{I}$ for years, $\omega \in \Omega$ for scenarios, and $c \in \mathcal{C}$ for CTAs, where $\mathcal{C} = \{\mathrm{FA}, \mathrm{NFA85}, \mathrm{NFA}\}$. Symbols indexed by c (e.g., $r_{c,t}$) correspond to FA (c=1), NFA85 (c=2), and NFA (c=3) contracts.

The risk-averse optimal sizing and contracting problem was formulated as a multi-objective, two-stage stochastic problem. A compact formulation of the objective function is given in (1):

$$\max_{\mathbf{x}} \quad (1-\beta)\mathbb{E}[NPV(x,\omega)] + \beta \mathrm{CvAR}_{\alpha}[NPV(x,\omega)] \quad (1)$$

Herein, $NPV(x,\omega)$ is the electrolyzer plant's net present value in some scenario ω, $\mathbb{E}_{\omega}\{NPV(x,\omega)\}$ the expected value of the net present value over all scenarios with realization probability π_{ω}, and $\mathrm{CvAR}_{\alpha}[NPV(x,\omega)]$ is the conditional value at risk of the net present value, and $\mathbf{x}$ represents the set of variables. The net present value in some scenario ω, $NPV(x,\omega)$, is given by:

$$\begin{aligned} NPV = & -C^{\mathrm{el}}\bar{p}^{\mathrm{el}} - C^{\mathrm{c}}\bar{p}^{\mathrm{com}} - C^{\mathrm{v}}\bar{v} - \sum_{i\in\mathcal{I}}\delta_i \sum_{c\in\mathcal{C}} T_{c,i}\bar{p}_c \quad (2) \\ & - \sum_{i\in\mathcal{I}}\delta_i \sum_{t\in\mathcal{T}} \lambda^{\mathrm{e}}_{t,i,\omega}(p^{\mathrm{el}}_{t,i,\omega} + p^{\mathrm{com}}_{t,i,\omega}) \\ & . + \sum_{i\in\mathcal{I}}\delta_i \sum_{t\in\mathcal{T}} \Big(\lambda^{\mathrm{H_2}} f^{\mathrm{sold}}_{t,i,\omega} + \lambda^{\mathrm{crc}}(s_{1,t,i,\omega} + s_{2,t,i,\omega})\Big) \end{aligned}$$

Herein, $\bar{p}^{\mathrm{el}}$ is the capacity of the electrolyzer, $\bar{p}^{\mathrm{com}}$ the capacity of the compressor, $\bar{v}$ the capacity of the hydrogen storage tank, with upfront investment costs C^{el}, C^{c}, and C^{v}. $\bar{p}_c$ is the capacity contracted in CTA c, and $T_{c,i}$ is the corresponding aggregated grid tariff (T^1 and T^2), for contract c and year i. $p^{\mathrm{el}}_{t,i,\omega}$ and $p^{\mathrm{com}}_{t,i,\omega}$ are, respectively, the power consumed by the electrolyzer and compressor, bought at electricity price $\lambda^{\mathrm{e}}_{t,i,\omega}$ at hour t, year i, and in scenario ω. $f^{\mathrm{sold}}_{t,i,\omega}$ is the hydrogen sold to an offtaker at hour t, year i and in scenario ω at price $\lambda^{\mathrm{H_2}}$. $s_{1,t,\omega,i}$ and $s_{2,t,\omega,i}$ are the power curtailed through the CRC contracts on the FA contract (1), and NFA85 contract (2), for which the client receives compensation λ^{crc}. Future cash flows at year i are discounted by factor δ_i. In this study, the client is only allowed to choose one of the CTAs, which is enforced by making the contract capacities $\bar{p}_c$ special order sets of type 1 (SOS1) variables:

$$\{\bar{p}_1, \bar{p}_2, \bar{p}_3\} \in \mathrm{SOS1}. \quad (3)$$

The following set of constraints describes the hydrogen balance of the plant:

$$f_{s,t,i,\omega} \leq B_s p^{\mathrm{el}}_{t,i,\omega} + C_s \bar{p}^{\mathrm{el}}, \quad \forall s,t,i,\omega, \quad (4)$$
$$f^{\mathrm{sold}}_{t,i,\omega} = f_{s,t,i,\omega} + f^{\mathrm{fromst}}_{t,i,\omega} - f^{\mathrm{tost}}_{t,i,\omega}, \quad \forall s,t,i,\omega \quad (5)$$
$$f^{\mathrm{sold}}_{t,i,\omega} \geq D^{\mathrm{H_2}}_t, \quad \forall t,i,\omega \quad (6)$$
$$v^{\mathrm{H_2}}_{t,i,\omega} = v^{\mathrm{H_2}}_{t-1,i,\omega} + f^{\mathrm{tost}}_{t,i,\omega} - f^{\mathrm{fromst}}_{t,i,\omega}, \quad (7)$$
$$\alpha^{ves}\bar{v} \leq v^{\mathrm{H_2}}_{t,i,\omega} \leq \bar{v}. \quad (8)$$

Herein, $f_{s,t,w,i}$ is the hydrogen produced at timestep t, year i and scenario ω. B_s and C_s are the slopes and intercepts segments s used to approximate the hydrogen production curve, as explained in [11]. Constraint 5 defines the hydrogen sold, $f^{\text{sold}}_{t,i,\omega}$, as the combined hydrogen produced by the electrolyzer, and by the storage vessel $f^{\text{fromst}}_{t,i,\omega}$, minus the hydrogen flow to the storage tank, $f^{\text{tost}}_{t,i,\omega}$, at hour t, year i and scenario ω. Constraint 6 ensures that the demand of the hydrogen offtaker at hour t, $D^{\text{H}_2}_t$, is always met. Constraint 7 defines the hydrogen mass stored in the storage vessel $v^{\text{H}_2}_{t,i,\omega}$ at hour t, year i and in scenario ω. Lastly, the amount of hydrogen stored is bounded by its maximum capacity $\bar{v}$, and a minimum storage threshold defined by the ratio α^{ves}. The power consumption of the electrolyzer is constrained by its rated power and minimum load ratio as:

$$\alpha^{\text{el}}\bar{p}^{\text{el}} \leq p^{\text{el}}_{t,i,\omega} \leq \bar{p}^{\text{el}}, \quad \forall t,i,\omega. \tag{9}$$

The power consumption of the compressor is defined as:

$$p^{\text{com}}_{t,i,\omega} = K^{\text{com}} f^{\text{tost}}_{t,i,\omega}, \quad \forall t,i,\omega, \tag{10}$$

$$p^{\text{com}}_{t,i,\omega} \leq \bar{p}^{\text{com}}, \quad \forall t,i,\omega, \tag{11}$$

and is constrained by its rated capacity through (11). The total contracted CTA capacity is limited from below by the electrolyzer and compressor capacity, as follows:

$$\sum_c \bar{p}_c \geq \bar{p}^{\text{el}} + \bar{p}^{\text{com}}. \tag{12}$$

The available transport capacity on the hydrogen plant's connection is constrained by the residual capacity of the network, as:

$$\sum_c \bar{p}_c - \sum_{c\in\{1,2\}} \left(s_{c,t,i,\omega} + r_{c,t,i,\omega}\right) \leq \bar{S}_{t,i,\omega}, \quad \forall t,i,\omega \tag{13}$$

where $\sum_{c\in\{1,2\}} r_{c,t,i,\omega}$ is the curtailment under the NFA85 and NFA contracts, and $\sum_{c\in\{1,2\}} s_{c,t,i,\omega}$ the curtailment via their respective CRCs. $\bar{S}_{t,i,\omega}$ is the residual capacity of the network (excluding consumption by the hydrogen plant) at time t, year i, and in scenario ω. The total power consumption of the electrolyzer and compressor is subject to an upper bound, as:

$$p^{\text{el}}_{t,i,\omega} + p^{\text{com}}_{t,i,\omega} \leq \sum_c \bar{p}_c - \sum_{c\in\{1,2\}} \left(s_{c,t,i,\omega} + r_{c,t,i,\omega}\right), \ \forall t,i,\omega. \tag{14}$$

The time-budgeted curtailments under the NFA85 contract are described by:

$$r_{2,t,i,\omega} \leq \bar{p}_2, \quad \forall t,i,\omega, \tag{15}$$

$$r_{2,t,i,\omega} \leq b_{t,i,\omega} P^{\text{grid}}, \quad \forall t,i,\omega, \tag{16}$$

$$\sum_{t\in\mathcal{T}} b_{t,i,\omega} \leq B^{\text{NFA85}}|\mathcal{T}|, \ \forall i,\omega, \tag{17}$$

$$r_{2,i,t,\omega} \geq \left(\bar{p}_2 - \bar{S}_{t,i,\omega}\right) b_{t,i,\omega}, \quad \forall i,t,\omega \tag{18}$$

$$b_{t,i,\omega} \in \{0,1\}, \quad \forall t,i,\omega. \tag{19}$$

Herein, $b_{t,i,\omega}$ is a binary variable indicating curtailment activations for the NFA85 contract (with a value of one indicating the activation of curtailment and zero otherwise) for hour t, year i and scenario ω, $|\mathcal{T}|$ denotes the number of hours in the given time horizon, and $B^{\text{NFA85}}|\mathcal{T}|$ is the NFA85 compliance budget, which enforces an upper bound on the number of curtailment events over $|\mathcal{T}|$. Constraint 18 ensures that when the NFA85 contract is activated, power curtailed via the NFA85 contract is never smaller than what is necessary to keep the network within its limits (and therefore has precedence over CRC activation). Curtailments under the NFA contract are constrained by the NFA contract capacity:

$$r_{3,t,i,\omega} \leq \bar{p}_3, \quad \forall t,i,\omega. \tag{20}$$

The following set of constraints describe the curtailment decisions under CRC contracts by the network operator:

$$\sum_t \sum_{c\in\{1,2\}} s_{c,t,i,\omega}\lambda^{\text{crc}} \leq B^{\text{CM}}, \quad \forall i,\omega, \tag{21}$$

$$\sum_{c\in\{1,2\}} s_{c,t,i,\omega} \leq \left(\sum_{c\in\{1,2\}} \bar{p}_c - \bar{S}_{t,i,\omega}\right) b^{aux1}_{t,i,\omega}, \ \forall i,t,\omega, \tag{22}$$

$$s_{2,t,i,\omega} \leq b^{aux2}_{i,\omega} M, \quad \forall i,t,\omega, \tag{23}$$

$$\sum_t b_{t,i,\omega} b^{aux2}_{i,\omega} = b^{aux2}_{i,\omega} B^{\text{NFA85}}, \quad \forall i,t,\omega, \tag{24}$$

$$b^{aux1}_{t,i,\omega}, b^{aux2}_{i,\omega} \in \{0,1\}, \quad \forall t,i,\omega. \tag{25}$$

Constraint (21) ensures that the amount spent on congestion management in year i and scenario ω does not exceed the budget B^{CM} that the network operator is obliged to spend on congestion management in the network. Constraint (22) ensures that curtailment under the CRC contracts does not exceed that what is necessary to keep the network within its power limit. That is, the network operator will not incur more congestion management costs than necessary. Constraints (23) and (24) ensure that the CRC contract on the NFA85 is activated only when the NFA85 budget is insufficient. Otherwise, curtailment through the NFA85 contract, which does not impose costs on the network operator, takes precedence.

IV. Case Study

We consider a hydrogen plant owner seeking connection to a medium- to high-voltage substation. The net present value of the project is evaluated over the plant's assumed lifetime of 15 years, starting in 2024. A discount rate of 10% is applied throughout the analysis.

Techno-economic specifications of the hydrogen plant are specified in table I [1]. Grid tariffs for medium- to high-voltage substations were taken from [12] for the year 2024. For FA contracts, T^1 and T^2 are respectively 42 €/kW and 53.76 €/kW in 2024, resulting in tariff $T_{1,1}$ of 95.7 €/kW for 2024. Both grid tariffs are expected to increase by 5.8% on average each year, resulting in a total grid tariff $T_{1,15}$ of 211 €/kW for FA contracts in the year 2049. For NFA85 and NFA contracts, T^1 is reduced by 80% and 100%, respectively, resulting in lower total tariffs $T_{2,i}$, $T_{3,i}$.

Dutch network operators make prognoses on hourly electricity profiles on their assets for up to 15 years based on

[1] In calculating the parameters, a storage pressure of 200 bar was assumed, and the electrolyzer was assumed to operate at a pressure of 15 bar and temperature of 80 °C.

demand growth scenarios. For every year i and scenario ω, future hourly profiles $pb_{t,i,\omega}$ were simulated as:

$$pb_{t,i,\omega} = A_\omega i + pb_{t,0}, \quad \forall t, i, \omega, \tag{26}$$

where A_ω is a scenario-dependent positive constant, and $pb_{t,0}$ represents the measured substation electricity profile for each hour t, as taken from [13] for the year 2024. The residual capacity of the network was calculated as:

$$\bar{S}_{t,i,\omega} = \min(\bar{S} - pb_{t,i,\omega}, 0), \quad \forall t, i, \omega, \tag{27}$$

where $\bar{S}$ is the maximum network capacity. Figure 1 shows the residual capacity for a winter and summer day in the years 2031 and 2049, across all scenarios. In total, five equiprobable scenarios are considered, representing a range of demand growth expectations, from low to high. For each ω, the spread between the profiles $pb_{t,i,\omega}$ widens over the years, reflecting increasing uncertainty in the predictions. Day-ahead electricity prices were taken from [14] for the year 2021[2]. A small correlation was assumed between electricity prices $\lambda^{e}_{t,i,\omega}$ and load profiles $pb_{t,i,\omega}$, with peak prices diverging ±7.5% from 2021 levels by the end of the project: decreasing in the lowest and increasing in the highest demand growth scenario.

V. Numerical Results and Discussion

Figure 2 shows optimal CTA capacities and expected NPV against factor β. $\beta = 0$ corresponds to optimal decisions made by a risk-neutral client and $\beta = 1$ corresponds to a risk-averse client. Shown are contracting decisions for a hydrogen price λ^{H_2} of 5 €/kg and 5.5 €/kg, and a congestion management budget B^{CM} of 1 and 1.5 million euros per year, resulting in four cases. At a λ^{H_2} of 5 €/kg and B^{CM} of 1 million euros, a risk-neutral client chooses the NFA contact. The contract capacity decreases with β and, at $\beta > 0.4$, the client switches to an NFA85. At a hydrogen price of 5 €/kg and B^{CM} of 1.5 million euros, both a risk neutral and a risk-averse client choose an NFA85, while the contract capacity decreases slightly as β approaches 1. At a λ^{H_2} of 5.5 €/kg and B^{CM} of 1 million euros, the NFA85 contract is only chosen for $\beta > 0.9$, while at a B^{CM} of 1.5 million euros, the client switches to an NFA85 at $\beta > 0.3$.

Figure 3 shows the optimal grid connection capacity against λ^{H_2} for two cases: (1) a client that can choose between all

[2]We take 2021 instead of 2024, to not include the distorted 2022 - 2024 price rise in electricity spot prices for generalizability

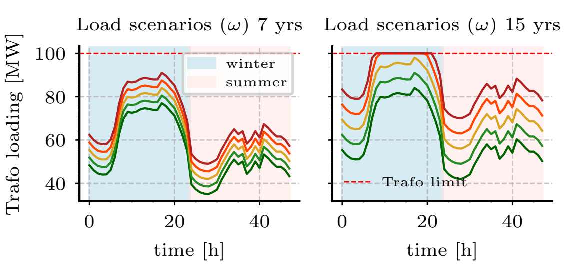

Fig. 1. Simulated load profiles for scenarios ω for a winter and summer day in 7 years and 15 years time.

TABLE I
Techno-economic parameters

Parameter	Value	Unit
C^{el}	1000	k€/MW
C^{c}	10	k€/kg/h
C^{v}	0.25	k€/kg
α^{el}	0.2	-
α^{ves}	0.1	-
K^{com}	2.2	kWh/kg

three CTAs, and (2) a client that can only choose an NFA. For both cases, the grid connection capacity is shown for a risk neutral and risk-averse client. The hydrogen plant becomes profitable at a λ^{H_2} of around 4.50 €/kg for the risk neutral and 4.70 for the risk-averse client. At this price, the risk neutral client chooses an NFA, while at a λ^{H_2} between 4.60 €/kg and 5.10 €/kg, the client chooses an NFA85, switching back to an NFA at prices above 5.10 €/kg. The risk-averse client chooses an NFA85 between a λ^{H_2} of 4.70 €/kg and 6.50 €/kg, and chooses an NFA when the price increases further. In general, the risk-averse client chooses a lower grid-connection capacity than the risk neutral client. Figure 3 also indicates the hydrogen price at which the plant becomes profitable in the base case, where the client can only select an FA contract and no grid congestion is present. In this scenario, the break-even price is 5 €/kg for a risk-neutral client and 5.2 €/kg for a risk-averse client: approximately 0.50 €/kg higher than when the client chooses non-firm contracts in a congested area.

Figures 2 and 3 show that, in general, as clients become more risk-aware, they tend to hedge against scenarios involving low residual grid capacity, and thus frequent curtailments, by opting for an NFA85 contract. This allows them to participate in congestion management and receive compensation for curtailments through their CRC when the budget B^{NFA85} has been spent. In none of the cases, the client chooses an FA. By choosing an FA the client could receive more compensation through CRC activations (instead being curtailed via the NFA85). However, this additional income does not outweigh the tariff discounts on the NFA85. In general, tariff discounts are more attractive than congestion management income, and the B^{NFA85} budget is sufficiently small to give risk-averse client hedging opportunities. It is observed that at higher hydrogen prices, the client tends to choose an NFA, as they are more secure that future revenue is sufficient to cover initial investment costs. As shown in 3, non-firm CTAs and CRCs lower the break-even price of electrolytic hydrogen projects by about 0.50 €/kg, with respect to projects outside congested areas with firm contracts. Hence, although future grid access remains uncertain, the novel CTAs and CRCs can strengthen the business case and support the development of hydrogen projects in the Netherlands–and in Europe as a whole.

VI. Conclusion

This study analyzes investment and contracting decisions of an electrolytic hydrogen plant in the Netherlands, under novel non-firm CTAs and CRCs, and under uncertain grid access and

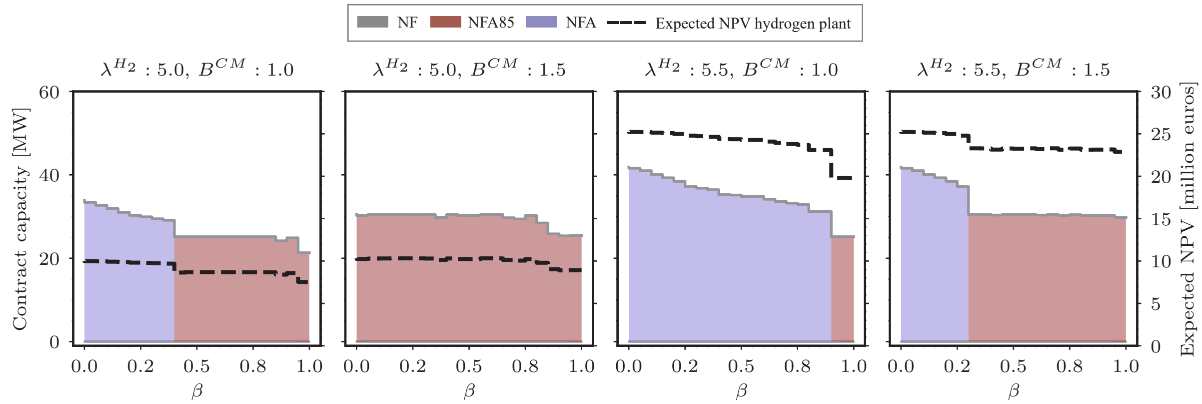

Fig. 2. Optimal grid connection and CTA capacities are shown against factor β, where $\beta = 0$ corresponds to a risk-neutral client and $\beta = 1$ corresponds to risk-averse client. The figure also displays the expected NPV against β.

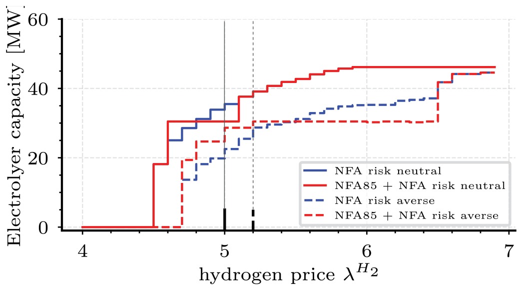

Fig. 3. Optimal grid connection capacity shown against hydrogen price λ^{H_2}. The red lines correspond to a client that chooses between all three CTAs, and the blue lines to a client that can only choose an NFA. The vertical black lines indicate the hydrogen price at which the hydrogen plant becomes bankable for a risk neutral client (solid line) and risk-averse client (dashed line) in a scenario without non-firm contracts and without grid congestion.

electricity prices. To this end, the study proposes a two-stage, risk-averse stochastic planning model, with investment (sizing) and contracting decisions in the first stage, and operational decisions in the second stage. Risk-neutral clients tend to choose NFAs with high discounts but no curtailment compensation, while more risk-aware clients tend to choose NFA85 contracts that allow them to participate in congestion management to hedge against frequent future curtailments. Results show that tariff discounts on non-firm contracts are more attractive than congestion management participation with FA contracts. In congested areas, the hydrogen plant becomes profitable at a hydrogen price of €4.50/kg for a risk-neutral client and €4.70/kg for a risk-averse client:€0.50/kg lower than the break-even price for a project with an FA outside a congested area. Thus, despite uncertainty in future grid access, the introduction of non-firm CTAs and CRCs improves the business case for electrolytic hydrogen and supports the development of hydrogen projects in the Netherlands. Although this study focused on the Netherlands as a case area, the conclusions are relevant to European countries more generally, given the rising prevalence of grid congestion across the continent.

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