Towards Optimal Integrated Planning of Electricity and Hydrogen Infrastructure for Large-Scale Renewable Energy Transport

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Abstract—The imminent advent of large-scale green hydrogen (H₂) production raises the central question of which of the two options, transporting “green” molecules, or transporting “green” electrons, is the most cost-effective one. This paper proposes a first-of-its-kind mathematical framework for the optimal integrated planning of electricity and H₂ infrastructure for transporting large-scale variable renewable energy (VRE). In contrast to most existing works, this work incorporates essential nonlinearities such as voltage drops due to losses in high-voltage alternating current (HVAC) and high-voltage direct current (HVDC) transmission lines, losses in HVDC converter stations, reactive power flow, pressure drops in pipelines, and linepack, all of which play an important role in determining the optimal infrastructure investment decision. Capturing these nonlinearities requires casting the problem as a nonconvex mixed-integer nonlinear program (MINLP), whose complexity is further exacerbated by its large size due to the relatively high temporal resolution of RES forecasts. This work then leverages recent advancements in convex relaxations to instead solve a tractable alternative in the form of a mixed-integer quadratically constrained programming (MIQCP) problem. The impact of other fundamental factors such as transmission distance and RES capacity is also thoroughly analysed on a canonical two-node system. The integrated planning model is then demonstrated on a real-world case study involving renewable energy zones in Australia.

Index Terms—Integrated planning, Hydrogen networks, Linepack, HVDC, HVAC, Renewable energy, MINLP, MIQCP.

I. INTRODUCTION

Due to the variability of renewable energy sources (RES), maximising their utilisation is arguably one of the biggest challenges facing energy system operators in Australia and around the world. Maximising this utilisation requires energy storage, which, in the case of large energy volumes, may be problematic as large-scale battery storage alone is too costly and pumped-hydro storage is limited for geographical reasons [1]. A promising long-term solution for maximising the integration of VRE consists of building a new infrastructure for transporting VRE in the form of electricity and/or H₂. Large-scale renewable energy hubs coupled to H₂ production hubs may unlock substantial economies of scale predicated on building a cost-effective VRE transport infrastructure. Designing a cost-effective infrastructure will need to address the challenging questions of (i) whether VRE hubs and electrolysers should be co-located, (ii) whether to transport VRE as molecules in H₂ pipelines or as electrons in electricity transmission lines, and (iii) the drivers and conditions that favour one investment option over another. Answering the above questions is a massive undertaking that requires an integrated electricity and H₂ system (IEHS) modelling framework to assess costs and benefits of different investment options.

As many of the challenges identified here are relatively new, existing knowledge and modelling tools are inadequate for performing such a large-scale optimal integrated infrastructure design exercise. In particular, existing state-of-the-art literature is either limited in scope to H₂ supply chain only [2–5], i.e., disregarding electricity infrastructure options, or is limited in the variety of considered infrastructure technologies [6–9]. Considering all the relevant transport and storage technologies in an integrated framework can unlock superior design solutions. This is especially true when considering the specific features associated with RES, and in particular when they are clustered in large-scale renewable energy hubs where wind and solar farms may be located far from the location of H₂ utilisation.

Other essential aspects that are ignored in the literature include voltage drops due to losses in transmission lines, pressure drops in pipelines, linepack,1 compressor sizing, water availability for electrolysers, and reactive power compensation, all of which play an important role in determining the optimal infrastructure investment decision. The modelling of the linepack is instrumental in quantifying the VRE storage capacity of the H₂ pipeline network, which can in turn influ-

1The linepack is the amount of pressurised gas stored in a pipeline network.
ence the sizing of H₂ pipelines and compressors. In fact, most (if not all) existing works use steady-state gas flow models, which are generally inadequate in gas transmission networks where H₂ injections from the VRE introduce time-varying accumulation rates. More importantly, with the exception of [6, 7], the majority of existing works, including [3, 4, 8, 9], only examine transport options between just two nodes, as opposed to over a network with a general topology (which may include loops and parallel links).

In light of the knowledge gaps identified above, this paper introduces a novel mathematical optimisation model aiming at finding the optimal integrated infrastructure planning for transporting large-scale VRE as either electricity lines and/or H₂ pipelines. Specifically, the model not only considers all relevant infrastructure technologies such as HVDC, HVAC, reactive power plants, and H₂ pipelines and compressors, but also incorporates all the essential nonlinearities that directly influence the optimal infrastructure investment decision, such as voltage drops due to losses in HVAC and HVDC transmission lines, losses in HVDC converter stations, reactive power flow, pressure drops in pipelines, and linepack. Additionally, the model adopts a relatively high temporal resolution to fully capture the variability of RES and its impact on the optimal investment decision. Instead of directly solving the resulting large-scale nonconvex mixed-integer nonlinear programming (MINLP) problem, which is computationally intractable, the paper introduces a tractable alternative in the form of a mixed-integer quadratically constrained programming (MIQCP) relaxation. This novel MIQCP model is demonstrated on a set of studies that rigorously analyse the impact of the two fundamental factors, distance and RES capacity, on the optimal planning decision. The MIQCP model is also demonstrated on a real-world case study involving actual renewable energy zones in Australia.

The paper is organised as follows. Section II introduces the optimal integrated VRE transport infrastructure design model and Section III describes how to derive a strong MIQCP relaxation of the problem. Section IV numerically evaluates the proposed MIQCP model on a canonical 2-node system as well as on a real-world case study involving actual renewable energy zones in Australia. The paper concludes in Section V.

II. MATHEMATICAL MODELLING

A prototype integrated VRE transport infrastructure design model is shown in Figure 1, where electricity transmission line options include both HVDC and HVAC, as well as their associated control equipment such as transformers, reactive power compensation, and converters. The H₂ pipeline options also include compressors and pressure regulators.

A. Electrolyser station model

Electrolysers use electricity to split water into H₂ and oxygen (O₂) in a process called electrolysis. Since the output pressure of a typical proton exchange membrane (PEM) electrolyser is around 3.5 MPa [10], an electrolyser station in this work is assumed to include a gas compressor to boost the pressure to transmission levels (up to 10 MPa), as shown in Figure 2.

The decision to install an electrolyser station at a certain location can be captured by a binary variable \( z_{im}^{ptg} \), which takes a value of 1 if the electrolyser station is installed and 0 otherwise. In constraint form this can be written as

\[
z_{im}^{ptg} \in \{0, 1\}, \quad im \in E,
\]

where \( E \) is the set of all candidate electrolyser stations in the network. The process of converting electrical energy to chemical energy can be mathematically written as

\[
\phi_{mty}^{ptg} = \frac{p_{imy}^{ptg}}{\rho_{mty}^{ptg}}, \quad im \in E, \quad ty \in T \times \mathcal{Y}
\]

where \( \phi_{mty}^{ptg} \) (MW) is the input electrical power to the electrolyser station, \( p_{imy}^{ptg} \) is the aggregated output H₂ volumetric flow rate of the electrolyser modules, and \( \rho_{mty}^{ptg} \) (kg) is the input water consumed by the electrolyser station over a period of \( \Delta t \). In (2), \( \eta_{im}^{ptg} = 70\% \) is the efficiency of each electrolyser module, \( HHV = 12.1948 \text{MJm}^{-3} \) is the higher heating value of H₂, and \( \rho = 0.086 \text{kgm}^{-3} \) is the density of H₂ at standard conditions. The efficiency of the electrolyser station \( \eta_{im}^{ptg} \) includes rectifiers and transformers (including transformer cooling and gas cooling). Constraint (2b) is founded on the fact that producing 1 kg of H₂ requires 10 kg of water. Each candidate electrolyser station location in the network is associated with a predetermined initial amount of water \( \tilde{w}_{iy}^{ptg} \) (at \( t = 0 \) and \( y = 1 \)). The input electrical power is constrained by a maximum predetermined upper limit on the size of the station, \( \tilde{p}_{i}^{ptg} \), through

\[
0 \leq p_{ity}^{ptg} \leq \tilde{p}_{i}^{ptg}, \quad im \in E, \quad ty \in T \times \mathcal{Y}
\]
The size of the compressor can be determined from the required horsepower $P_{mnty}^c$ (MW):

$$P_{mnty}^c = \frac{KTZ_m^p\varphi_{mnty}^{pg}}{(\gamma - 1)\eta_{imp}} \left( \frac{\varphi_{mnty}^o}{\varphi_{mnty}^i} - 1 \right),$$

where $\gamma = 1.296$ is the isentropic exponent (dimensionless), $K = 0.351121 \times 10^{-3}$ (MJ K$^{-1}$ m$^{-3}$), and $\eta_{imp}$ (dimensionless) is the overall efficiency of the compressor. The maximum output pressure of the compressor can be set to the maximum operating pressure of the H$_2$ network $\varphi_m = 10$ MPa, which, combined with a fixed output pressure of the electrolyser modules $\varphi_{mnty}^{pg} = 3.5$ MPa, makes (4) linear in $P_{mnty}^c$ and $\varphi_{mnty}^{pg}$. Note that at the demand point a compressor is not needed and therefore $P_{mnty}^c = 0$. Finally, the compressibility factor in (4) is obtained from the Soave-Redlich-Kwong (SRK) equation of state [11] with $T = 288.15K$ as the H$_2$ gas temperature at standard conditions.

The investment cost of electrolyser stations is given by

$$I^{pg} = \sum_{im \in E} \left( c_{i,0}^{pg} \varphi_{im}^o + c_{l,1}^{pg} \varphi_{mnty}^o \right) + c_{m}^{pg} \varphi_{mnty}^o,$$

where $c_{i,0}^{pg}$ (MS) is the base installation cost of an electrolyser station, $c_{l,1}^{pg}$ (MS/MW) is the unit cost of an electrolyser station, $c_{m}^{pg}$ (MS/MW) is the unit cost of the compressor. The unit cost of an electrolyser station $c_{l,1}^{pg}$ includes the cost of the step-down transformer and rectifier.

**B. H$_2$ pipeline model**

Each gas transmission corridor $mn \in P$ between junctions $m$ and $n$ is associated with a pre-determined set of candidate H$_2$ pipeline link options $O^{p}$. A model of an H$_2$ pipeline link over gas transmission corridor $mn$ is shown in Figure 3.

Different pipeline link options are distinguished by different pipeline diameters including 0.5 m, 0.9 m, and 1.2 m. The gas transmission capacity $\varphi_{mnty}^o$ (m$^3$s$^{-1}$) of a pipeline increases with the diameter $D_m^o$ (m). The decision of choosing a certain pipeline option can be captured by a binary variable $z_{mn}^p$, which takes a value of 1 if option $o$ is installed and 0 otherwise. In constraint form this can be written as

$$z_{mn}^p \in \{0, 1\}, \quad mn \in P, \ o \in O^{p}$$

where $P$ is the set of all tentative pipeline corridors where H$_2$ gas is flowing from junction $m$ towards junction $n$. In this work, the direction of gas flow is known in advance owing to the predetermined locations of RES and H$_2$ demand (off-take) locations. The average gas volume flow rate $\varphi_{mnty}^o$ (m$^3$s$^{-1}$) across pipeline option $o$ over transmission corridor $mn$ can be obtained from the discretised equation of motion along the full length of the pipe [12]

$$\left( \varphi_{mnty}^o \right)^2 = \Phi_{mn}^o \left( \left( \varphi_{mnty}^o \right)^2 - \left( \varphi_{mnty}^o \right)^2 \right), \quad mn \in P,$$

for all $o \in O^{p}$, $ty \in T \times Y$, where

$$\Phi_{mn}^o = \frac{\eta_{mn}^o \pi^2 (D_{mn}^o)^5}{16 \rho^2 Z_{mn}^{o} \tau L_{mn}^{o} f_{mn}^{o}},$$

and $f_{mn}^{o} = 4 \left( 20.621 (D_{mn}^o)^{1/6} \right)^{-2}$ defines the Weymouth friction factor [13], and $\eta_{mn}^o$ is the pipe efficiency. The compressibility factor $Z_{mn}^{o}$ is computed from the SRK equation of state [11]. In (6), the pressures $\varphi_{mnty}^o$ (Pa) are related to the junction pressures $\varphi_{mnty}^o$ (Pa) through

$$\varphi_{mnty}^o \leq \varphi_{mnty}^o \leq \varphi_{mnty}^o,$$

and

$$\varphi_{mnty}^o \leq \varphi_{mnty}^o \leq \varphi_{mnty}^o,$$

for all $mn \in P$, $o \in O^{p}$, $ty \in T \times Y$ and

$$\varphi_{mnty}^o \leq \varphi_{mnty}^o$$

where $J$ is the set of all gas junctions in the network. The volumetric gas flows entering and leaving the pipe are related to the average volumetric flow rate across the pipe through

$$\varphi_{mnty}^o = 0.5 \left( \varphi_{mnty}^o + \varphi_{mnty}^o \right), \quad mn \in P$$

for all $o \in O^{p}$, $ty \in T \times Y$, and the average pressure across a pipe is defined as

$$\varphi_{mnty}^o = \frac{2}{3} \left( \varphi_{mnty}^o + \varphi_{mnty}^o - \varphi_{mnty}^o \varphi_{mnty}^o \right), \quad mn \in P$$

for all $o \in O^{p}$, $ty \in T \times Y$. The linepack in the pipeline can now be captured by

$$L_{mnty}^o = L_{mnty}^o + \Delta t \left( \varphi_{mnty}^o - \varphi_{mnty}^o \right), \quad mn \in P, \ o \in O^{p},$$

and

$$\Psi_{mnty}^o = \pi (D_{mn}^o)^2 L_{mn}^o$$

To ensure fairness, the initial value of the linepack (at $t = 0$ and $y = 1$) for all the pipeline options is set to its minimum value, i.e.,

$$L_{mnty}^o = \Psi_{mnty}^o \varphi_{mnty}^o.$$
for all $mn \in \mathcal{P}$, $o \in \mathcal{O}^p$, $ty \in \mathcal{T} \times \mathcal{Y}$. Finally, the gas balance equations at each junction of the gas network can now be written as
\begin{equation}
\left( \phi_{mty}^{\text{in}} - \phi_{mty}^{\text{out}} \right) = \sum_{o \in \mathcal{O}^p} \left( \sum_{mn \in \mathcal{P}} \phi_{mnty}^{\text{in},o} - \sum_{mn \in \mathcal{P}} \phi_{mnty}^{\text{out},o} \right) + \phi_{mty}^{H_2},
\end{equation}
for all $m \in \mathcal{M}$, $ty \in \mathcal{T} \times \mathcal{Y}$, where $\phi_{mty}^{H_2}$ is the H$_2$ volumetric flow rate demand at each junction and $\mu = 0.2624 \text{m}^3 \text{MJ}^{-1}$ is the gas turbine fuel rate coefficient of a centrifugal H$_2$ compressor. The product $\mu \phi_{mty}$ delineates the amount of gas consumed by the compressor in the electrolyser station (see Figure 2) during the pressure boosting process.

The investment cost of the pipeline link is given by
\begin{equation}
I_{\text{pipe}} = \sum_{mn \in \mathcal{P}} \sum_{o \in \mathcal{O}^p} c_{mn}^{\text{p},o} \phi_{mnty}^{\text{in},o},
\end{equation}
where $c_{mn}^{\text{p},o}$ (M$\$$) is the installation cost of a pipeline link of option $o$ over corridor $mn$.

C. HVDC link model

An HVDC link over transmission corridor $ij$ consists of an HVDC transmission line connecting two converter stations, one at the sending end (rectifier) and one at the receiving end (inverter) of the link as shown in Figure 4. Each HVDC transmission corridor $ij \in \mathcal{L}^{dc}$ between buses $i$ and $j$ is associated with a predetermined set of candidate HVDC link options $\mathcal{O}^{dc}$ and a maximum number of parallel links $c \in \mathcal{C}^{dc,o}$ for each option $o \in \mathcal{O}^{dc}$.

Examples of an HVDC transmission link option include a 500 kV bipole at 1, 2, or 3 GW rated capacity. The decision to install a certain option and number of parallel links can be captured by a binary variable $z_{ij}^{dc,o}$ which takes a value of 1 if option $o$ and $c$th link are installed and 0 otherwise. It therefore follows that
\begin{align}
z_{ij}^{dc,o} & \in \{0, 1\}, \quad i j \in \mathcal{L}^{dc}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o} \quad (18) \\
\sum_{c \in \mathcal{C}^{dc,o}} z_{ij}^{dc,o} & = \zeta_{ij}^{dc}, \quad i j \in \mathcal{L}^{dc}, \quad o \in \mathcal{O}^{dc} \quad (19) \\
z_{ij}^{dc,o} & \leq z_{ij}^{dc,o(c-1)}, \quad i j \in \mathcal{L}^{dc}, \quad c \in \mathcal{C}^{dc,o} \setminus \{1\} \quad (20)
\end{align}
where constraints (19) and (20) enforce the sequential installation of links in each option and transmission corridor. In this work, HVDC converter stations are assumed to be of the voltage-source (VSC) type, which can control active and reactive power independently. The main reason for this assumption is that, unlike other converter types such as line commutated converters (LCC), VSC HVDC incorporates self-commutating switching elements that can control active and reactive power independently without additional compensation equipment [14]. This therefore makes VSC HVDC more suitable for transporting renewable energy over long distances, as is the case in this paper. The active, reactive, and apparent power of a VSC are bounded by its ratings and MVA capacity ($S^{\text{v},o}$) as follows
\begin{align}
\sum_{ij} p_{ijty}^{\text{v},oc} & \leq P_{ijty}^{\text{v},oc} \leq \mathcal{P}^{\text{v},oc}_{ijty}, \quad (21a) \\
\sum_{ij} q_{ijty}^{\text{v},oc} & \leq Q_{ijty}^{\text{v},oc} \leq \mathcal{Q}^{\text{v},oc}_{ijty}, \quad (21b) \\
\sqrt{(p_{ijty}^{\text{v},oc})^2 + (q_{ijty}^{\text{v},oc})^2} & \leq S^{\text{v},oc}_{ijty}, \quad (21c)
\end{align}
for all $i j \in \mathcal{L}^{dc} \cup \mathcal{L}^{ac}^{\text{o}}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o}, \quad ty \in \mathcal{T} \times \mathcal{Y}$, where $\mathcal{L}^{ac}$ is the set of HVDC corridors such that $j$ is the sending-end bus and $i$ is the receiving-end bus. A power electronic converter is an active device whose losses can be obtained from the following parametric equation
\begin{equation}
p_{ijty}^{\text{loss},oc} = \alpha_{ijty}^{dc,o} z_{ijty}^{dc,o} + \beta_{ijty}^{dc,o} i_{ijty}^{\text{v},oc} + \gamma_{ijty}^{dc,o} (i_{ijty}^{\text{v},oc})^2,
\end{equation}
for all $i j \in \mathcal{L}^{dc} \cup \mathcal{L}^{ac}^{\text{o}}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o}, \quad ty \in \mathcal{T} \times \mathcal{Y}$, where $\alpha_{ijty}^{dc,o}$ is the magnitude of the AC-side current, $\beta_{ijty}^{dc,o}$ captures the no-load losses of transformers and averaged auxiliary equipment losses, $\gamma_{ijty}^{dc,o}$ captures the switching losses of valves and freewheeling diodes as well as some conduction losses due to the series voltage drop, and $\gamma_{ijty}^{dc,o}$ captures the conduction losses of transformers, switches, and inductors in the VSC. Typical values for the loss parameters are $\alpha_{ijty}^{dc,o} = 6.62 \text{MW}$, $\beta_{ijty}^{dc,o} = 1800 \text{V}$, and $\gamma_{ijty}^{dc,o} = 1.98 \Omega$ [15]. The converter current $i_{ijty}^{\text{v},oc}$ is in turn bounded by
\begin{equation}
0 \leq i_{ijty}^{\text{v},oc} \leq \zeta_{ijty}^{\text{v},oc},
\end{equation}
for all $i j \in \mathcal{L}^{dc} \cup \mathcal{L}^{ac}^{\text{o}}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o}, \quad ty \in \mathcal{T} \times \mathcal{Y}$. The AC and DC sides of the converter are related through
\begin{equation}
p_{ijty}^{\text{v},oc} + p_{ijty}^{\text{c},oc} = p_{ijty}^{\text{loss},oc},
\end{equation}
for all $i j \in \mathcal{L}^{dc} \cup \mathcal{L}^{ac}^{\text{o}}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o}, \quad ty \in \mathcal{T} \times \mathcal{Y}$, and the DC-side power of the converter is linked to the power flowing through the HVDC transmission line, $p_{ijty}^{\text{dc},oc}$, through
\begin{equation}
p_{ijty}^{\text{dc},oc} + p_{ijty}^{\text{dc},oc} = 0,
\end{equation}
for all $i j \in \mathcal{L}^{dc} \cup \mathcal{L}^{ac}^{\text{o}}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o}, \quad ty \in \mathcal{T} \times \mathcal{Y}$. Additionally, the AC-side current and voltage are related to the active and reactive power injections of the converter through
\begin{equation}
(p_{ijty}^{\text{c},oc})^2 + (q_{ijty}^{\text{c},oc})^2 = (v_{ijty}^{\text{c},oc})^2 \left(i_{ijty}^{\text{c},oc}\right)^2,
\end{equation}
for all $i j \in \mathcal{L}^{dc} \cup \mathcal{L}^{ac}^{\text{o}}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o}, \quad ty \in \mathcal{T} \times \mathcal{Y}$. Finally, the power flowing through the HVDC transmission line, $p_{ijty}^{\text{dc},oc}$, is defined by
\begin{equation}
p_{ijty}^{\text{dc},oc} = \frac{(v_{ijty}^{\text{dc},oc})^2 - v_{ijty}^{\text{dc},oc} v_{ijty}^{\text{dc},oc}}{\rho_{ijty}^{\text{dc},oc}},
\end{equation}
for all $i j \in \mathcal{L}^{dc} \cup \mathcal{L}^{ac}^{\text{o}}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o}, \quad ty \in \mathcal{T} \times \mathcal{Y}$, where $\rho_{ijty}^{\text{dc},oc}$ is the equivalent resistance of the HVDC bipolar transmission line and the DC voltage $v_{ijty}^{\text{dc},oc}$ is bounded by
\begin{equation}
v_{ijty}^{\text{dc},oc} \leq v_{ijty}^{\text{dc},oc} \leq v_{ijty}^{\text{dc},oc},
\end{equation}
for all $i j \in \mathcal{L}^{dc} \cup \mathcal{L}^{ac}^{\text{o}}, \quad o \in \mathcal{O}^{dc}, \quad c \in \mathcal{C}^{dc,o}, \quad ty \in \mathcal{T} \times \mathcal{Y}$.
D. HVAC link model

An HVAC link over transmission corridor $ij$ consists of an HVAC transmission line connecting two ideal transformers, one at the sending end and one at the receiving end of the link as shown in Figure 5. Each HVAC transmission corridor $ij \in \mathcal{L}^a_i$ between buses $i$ and $j$ is associated with a predetermined set of candidate HVAC line options $\mathcal{O}^a$ and a maximum number of parallel links $c \in \mathcal{O}^{a,c} = \{1, \ldots, \tilde{c}_{ij}^a\}$ for each option $o \in \mathcal{O}^c$.

Examples of an HVAC transmission link option include 345 kV at 0.75 GW rated capacity, 500 kV at 1.5 GW rated capacity, and 765 kV at 1.5 GW rated capacity in both single and double circuit arrangements. The decision of choosing a certain option and number of parallel links (single or double circuits) can be captured by a binary variable $z_{ij}^{a,c}$ which takes a value of 1 if option $o$ and $c$th link are installed and 0 otherwise. It therefore follows that

$$z_{ij}^{a,c} \in \{0,1\}, \quad \forall \ ij \in \mathcal{L}_i^a, \ o \in \mathcal{O}^a, \ c \in \mathcal{O}^{a,c}$$

$$\sum_{c \in \mathcal{O}^{a,c}} z_{ij}^{a,c} \leq \tilde{c}_{ij}^a, \quad \forall \ ij \in \mathcal{L}_i^a, \ o \in \mathcal{O}^a$$

$$z_{ij}^{a,c} \leq z_{ij}^{a,c,(c-1)}, \quad \forall \ ij \in \mathcal{L}_i^a, \ c \in \mathcal{O}^{a,c} \setminus \{1\}$$

where constraints (30) and (31) enforce the sequential installation of links in each option and transmission corridor.

The complex voltage $\vec{v}_i$ (pu) at bus $i$ can be expressed as $\vec{v}_i = v_i e^{j\theta_i} = v_i \cos(\theta_i) + j v_i \sin(\theta_i)$ in polar form, where $\theta_i = \sqrt{-1}T$. HVAC transmission lines and phase-shifting transformers are represented by their $\pi$-model equivalents, in which the admittance is defined as $y_{ij} = 1/(r_{ij} + j r_{ij}) = g_{ij} + j b_{ij}$, where $g_{ij}$ and $b_{ij}$ are the conductance (pu) and susceptance (pu), respectively. Additionally, the charging susceptance in the $\pi$-model of branch $ij$ is denoted by $b_{ij}^a$ (pu). By defining

$$w^a_{ij} = |\vec{v}_i|^2 = v_i^2, \quad i \in \mathcal{B}$$

the active and reactive power flows over link $c$ of option $o$ in corridor $ij$ can be written as

$$p_{ij}^{a,o} = g_{ij} w_{ijy}^{a,o} - g_{ij} w_{ijy}^{r,o} + b_{ij}^{a} w_{ijy}^{r,o}, \quad q_{ijy}^{a,o} = b_{ij} w_{ijy}^{a,o} - b_{ij} w_{ijy}^{r,o} - g_{ij} w_{ijy}^{r,o},$$

for all $ij \in \mathcal{L}_i^a \cup \mathcal{L}_j^a$, $o \in \mathcal{O}^a \cup \mathcal{O}^{a,o}$, $ty \in \mathcal{T} \times \mathcal{Y}$. The investment cost of the HVDC transmission line is given by

$$I^{HVDC} = \sum_{ij \in \mathcal{L}_i^d} \sum_{o \in \mathcal{O}^{d,c}} \sum_{c \in \mathcal{O}^{d,c,o}} \left( c_{ij}^{d,o} z_{ij}^{d,o} \right),$$

where $c_{ij}^{d,o}$ (M$)$ is the investment cost of HVDC link option $o$ over corridor $ij$. The investment cost $c_{ij}^{d,o}$ includes the cost of HVDC transmission lines as well as the cost of the two converter stations at the sending-end and receiving-end of the line.

Fig. 4: Model of an HVDC link consisting of two converter stations and a transmission line.

Constraints (33)–(35) ensure that $p_{ijy}^{a,o}$ and $q_{ijy}^{a,o}$ in (32) are set to zero when the $c$th link of option $o$ in corridor $ij$ is not installed, by setting the corresponding $z_{ij}^{a,c} = 0$ and therefore $w_{ijy}^{a,o}$, $w_{ijy}^{r,o}$, and $w_{ijy}^{i,o}$ all to zero.

Additionally, links installed in parallel in option $o$ along corridor $ij$ should have their $w_{ijy}^{r,o}$ and $w_{ijy}^{i,o}$ equal to $w_{ijy}^{r,o}$ and $w_{ijy}^{i,o}$, respectively, as follows

$$0 \leq w_{ijy}^{r,o} - \bar{w}_{ijy}^{r,o} \leq \bar{w}_{ijy}^{r,o} \left( 1 - z_{ij}^{a,c} \right),$$

$$w_{ijy}^{r,o} - \bar{w}_{ijy}^{r,o} \leq \bar{w}_{ijy}^{r,o} \left( 1 - z_{ij}^{a,c} \right),$$

$$w_{ijy}^{r,o} - \bar{w}_{ijy}^{r,o} \leq \bar{w}_{ijy}^{r,o} \left( 1 - z_{ij}^{a,c} \right),$$

$$Q \leq w_{ijy}^{i,o} \leq Q, \quad i \in \mathcal{B}, \ ty \in \mathcal{T} \times \mathcal{Y}$$

Note that $w_{ijy}^{r,o} = w_{ijy}^{i,o}$. 
for all \( ij \in \mathcal{L}^\text{ac}_t, \ o \in \mathcal{O}^\text{ac}_t, c \in \mathcal{C}^\text{ac,o}_t \setminus \{1\}, \ ty \in \mathcal{T} \times \mathcal{Y} \). Since all installed parallel links are constrained by (35) and (37) to all have the same values for \( w_{ijty}^{\text{ac,oc}}, w_{ijty}^{\var}, \) and \( w_{ijty}^{\text{ch,oc}} \) as \( w_{ity}^{\text{ac,oc}}, w_{ity}^{\var}, \) and \( w_{ity}^{\text{ch,oc}} \), respectively, it suffices to enforce the (nonconvex) rotated second-order cone constraints

\[
w_{ijty}^{\text{al}} w_{ijty}^{\var} = \left( w_{ijty}^{\text{al}} \right)^2 + \left( w_{ijty}^{\var} \right)^2,
\]

for all \( ij \in \mathcal{L}^\text{ac}_t, \ o \in \mathcal{O}^\text{ac}_t, \ ty \in \mathcal{T} \times \mathcal{Y} \), the angle difference constraints

\[
\tan(\theta_{ij}) w_{ijty}^{\text{al}} \leq w_{ijty}^{\var} \leq \tan(\theta_{ij}) w_{ijty}^{\text{al}},
\]

for all \( ij \in \mathcal{L}^\text{ac}_t, \ o \in \mathcal{O}^\text{ac}_t, \ ty \in \mathcal{T} \times \mathcal{Y} \), and the apparent power limit constraints

\[
\sqrt{\left( w_{ijty}^{\text{al}} \right)^2 + \left( w_{ijty}^{\var} \right)^2} \leq S_{ijty}^{\text{ac,oc}}, \quad \forall \ ij, \ ty.
\]

where the nodal active power balance constraints can now be written as

\[
P_{ity}^{\text{res}} = \sum_{ij \in \mathcal{B}_i} \left( \sum_{o \in \mathcal{O}_c} P_{ijty}^{\text{ac,oc}} + \sum_{c \in \mathcal{C}_c} P_{ijty}^{\text{ac,o}} \right) + P_{ity}^{\text{plg}}, \quad i \in \mathcal{B}, \ ty \in \mathcal{T} \times \mathcal{Y}
\]

where \( P_{ity}^{\text{res}} \) is the total generated VRE (wind and solar) at bus \( i \) during time slot \( t \).

The HVAC planning options typically include reactive power compensation at some HVAC buses, which can improve line loadability by maintaining voltages near rated values and angular displacement below 45°. A shunt reactor, or more generally a static VAr compensator (SVC), at bus \( i \) can be modelled as

\[
q_{ity}^{\text{var}} \leq q_{ity}^{\var} \leq q_{ity}^{\text{var},\text{max}}, \quad i \in \mathcal{B}, \ ty \in \mathcal{T} \times \mathcal{Y}
\]

where \( q_{ity}^{\text{var}} \) denotes the reactive power output of a VAr plant at bus \( i \) at time \( ty \). The nodal reactive power balance constraints can now be written as

\[
-q_{ity}^{\text{var}} = \sum_{ij \in \mathcal{B}_i} \left( \sum_{o \in \mathcal{O}_c} q_{ijty}^{\text{ac,oc}} + \sum_{c \in \mathcal{C}_c} q_{ijty}^{\text{ac,o}} \right) + \sum_{c \in \mathcal{C}_c} q_{ijty}^{\text{cv,oc}}, \quad i \in \mathcal{B}, \ ty \in \mathcal{T} \times \mathcal{Y}
\]

where \( q_{ijty}^{\text{var}} \) (MVAR) is the investment cost of HVAC link option \( o \) over corridor \( ij \), \( e_{ij}^{\text{var}} \) (MVAR) is the installation cost of the VAR device (SVC) at bus \( i \), and \( c_{ij}^{\text{var}} \) (MVAR/MVAR) is the unit cost of reactive power output from the VAr device at bus \( i \). The investment cost \( e_{ij}^{\text{var}} \) includes the cost of HVAC transmission lines as well as the cost of step-up and step-down transformer substations \( tx_i \) and \( tx_j \) at the sending-end and receiving-end of the line.

\[E. \text{ Optimal integrated infrastructure planning}\]

Mathematically, the objective of the integrated infrastructure planning problem is to simultaneously minimise the total investment cost and maximise the H2 sale over the whole planning horizon \( \mathcal{Y} = \{1, \ldots, Y\} \) as

\[
\min_{z} \quad I^{\text{plg}} + I^{\text{pipe}} + I^{\text{HVDC}} + I^{\text{HVAC}}
\]
\[
\sum_{y \in Y, t \in T, m, \mathcal{J}} \frac{H_2^m \phi_{mty} \Delta t}{(1 + i)^y} \tag{45a}
\]

subject to (1)–(44),
\[
\sum_{y \in Y, t \in T, m, \mathcal{J}} \frac{H_2^m \phi_{mty} \Delta t}{(1 + i)^y} \tag{45b}
\]

where \(c_m^H \, (\$/m^3)\) is the selling price (profit) of \(H_2\), \(i\) is the discount rate, and \(x\) is a vector that concatenates all the variables of the problem.3

III. MIXED-INTEGER CONVEX RELAXATION

Due to the nonconvex nonlinear constraints in (6), (14), (22), (26), (27) and (38), Problem 45 belongs to the class of mixed-integer nonlinear programming (MINLP) problems that have a nonconvex continuous relaxation, thus making it extremely difficult to solve to global, or even local, optimality. To make matters worse, Problem 45 requires disjunctive constraints to (encode “or” statements) associated with different design variables that correspond to the optimal choice of transport option. These disjunctive constraints require a Big-M reformulation to transform them into MILP constraints such as the ones in (7)–(10), (33), (35), and (37). Unfortunately, Big-M reformulations are notorious for having weak root node relaxations in general. As a result, this class of MINLPs in particular is intractable even for small scale problems.

Luckily, there exists a tractable alternative to Problem 45 in the form of a strong mixed-integer quadratically constrained programming (MIQCP) problem. It is straightforward to check that the nonconvex second-order cone (SOC) constraint in (6) becomes convex when it is relaxed into an inequality constraint of the form
\[
\left(\phi_{mnty}^{\alpha}\right)^2 \leq \Phi_{mny}^\alpha \left(\psi_{mnty}^{\alpha} - \psi_{mnty}^{\alpha}\right)^2, \quad mn \in \mathcal{P} \tag{46}
\]

for all \(o \in \mathcal{O}^p, ty \in T \times Y\). Moreover, because the nodal pressures are nonnegative, constraint (14) becomes convex because it is relaxed into an inequality constraint of the form
\[
\psi_{mnty}^{\alpha} \geq \frac{2}{3} \left(\psi_{mnty}^{\alpha} + \psi_{mnty}^{\alpha} - \frac{\psi_{mnty}^{\alpha} \psi_{mnty}^{\alpha}}{\psi_{mnty}^{\alpha} + \psi_{mnty}^{\alpha}}\right), \quad mn \in \mathcal{P} \tag{47}
\]

for all \(o \in \mathcal{O}^p, ty \in T \times Y\). However, although convex, constraint (47) cannot be directly handled by state-of-the-art MIQCP solvers such as Gurobi [19]. For this reason, constraint (47) can instead be replaced by a tight polyhedral envelope
\[
\psi_{mnty}^{\alpha} \geq \frac{2}{3} \left(\psi_{mnty}^{\alpha} + \psi_{mnty}^{\alpha} + \text{conv} \left(- \frac{\psi_{mnty}^{\alpha} \psi_{mnty}^{\alpha}}{\psi_{mnty}^{\alpha} + \psi_{mnty}^{\alpha}}\right)\right) \tag{48}
\]

for all \(mn \in \mathcal{P}, o \in \mathcal{O}^p, ty \in T \times Y\).

The first step towards conferring a strong convex relaxation property to constraints (22), (26), and (27) is to define new variables to substitute the square of the voltage and the square of the current terms, i.e., \(w := u^2\) and \(l := i^2\), respectively. Constraints (22), (26), and (27) can now be equivalently rewritten as
\[
P_{ijty}^{\text{loss,oc}} = \alpha^{dc,o} v_{ijty} + \beta^{dc,o} c_{ijty} + \gamma^{dc,o} v_{ijty}, \tag{49}
\]

3The original selling price is typically in $/kg but is then converted to $/m³ for consistency of dimensions.

4The proof can be found in [18].
Since the base installation costs of electrolyser stations and SVCs are negligible compared to total station cost, both $a_{i0}^{ptg}$ and $c_{i0}^{ptg}$ are assumed to be zero, which obviates the need for binary variables, i.e., $z_{int}^{ptg}$ and $z_{var}^{ptg}$ are no longer needed. It should be emphasised that the cost and parameter assumptions in Tables I-IV are for the sole purpose of demonstrating the novel integrated modelling in Problem 58. Therefore, in the context of these specific costs and parameter assumptions, the findings in this paper should be considered solely for illustration and demonstration purposes rather than real guidelines for energy infrastructure planners and stakeholders, for which specific studies based on agreed input data and assumptions should be performed.

In this implementation setup, JULIA v1.7.2 [29] is used as a programming language along with JUMP v0.22.3 [30] as a mathematical modelling layer for all the optimisation problems. All simulations are conducted on a computing platform with an Intel Core i7-6820HK CPU at 2.7GHz, 64-bit operating system, and 32GB RAM. The MIQCP problem in (58) is solved using GUROBI v9.5.0 [19] with the branch-and-bound algorithm which solves continuous QCP relaxations at each node. In contrast, the linearised outer-approximation approach performed poorly on this problem.

The proposed MIQCP formulation in Problem 58 is demonstrated on two case studies, one consisting of a canonical two-node system, and one involving actual renewable energy zones (REZ) in Queensland, Australia. In both case studies the profiles of RES forecasts are obtained from AEMO’s Integrated System Plan (ISP) “Central” scenario [20].

### A. Case study 1: Canonical 2-node system

This case study is intended to thoroughly analyse the two fundamental drivers, namely distance and RES capacity, affecting the investment decision between two nodes. In particular, the RES capacity is varied from 1 GW and 10 GW and the distance is varied from 200 km to 1000 km, and the

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6At the time of writing this paper, the largest commissioned 500 kV VSC HVDC project has a capacity of 700 MW. However, 1 GW, 2 GW, and 3 GW 500 kV VSC HVDC technology is assumed to be available in the near future. The costs for those are assumed to be the same as existing LCC HVDC technology of the same capacity.
results are shown in Figure 6. The RES capacity is shared equally between wind and solar and a single solar profile and a single wind profile are used, with capacity factors of 0.2731 and 0.4041, respectively. The immediate inference that can be drawn from Figure 6 is that H\textsubscript{2} pipelines tend to be preferred for higher RES capacities (7500 MW and above) transmitted over medium to long distances (400 km and above), whereas lower capacities (5000 MW and below) are dominated by electricity options. In particular, HVAC systems are the preferred option for short distances (200 km and below) across all RES capacities and HVDC systems are the preferred option for medium to long distances (600 km and above) and medium RES capacities (2500 MW and 5000 MW).

Despite lower losses in HVDC systems, the high cost of converter stations places them at a disadvantage compared to HVAC systems for short to medium distances and an RES capacity of 2500 MW to 5000 MW. However, the larger cost of overhead conductors of HVAC tips the scale in favour of HVDC systems for medium to long distances. Additionally, angle displacement constraints on HVAC systems require SVCs to absorb the large reactive power induced by inductive and capacitive effects of long distance AC transmission, which further increases the cost of HVAC links. These results are congruent with HVAC vs HVDC comparisons in existing literature, which identify a break-even distance of around 600 km, beyond which HVDC becomes more competitive [9].

At smaller RES capacities (1000 MW), where the capacity factors of 0.2731 and 0.4041 for solar and wind, respectively, translate to an average available RES power of 338 MW, a 345 kV 750 MW HVAC with an SVC at node 1 is more cost-effective than a 1 GW 500 kV VSC HVDC system for transmission distances below 800 km.

On the other hand, the high operating pressure range (3.5 MPa to 10 MPa) of H\textsubscript{2} pipelines translates to much smaller transmission losses and large linepack capacities that together give H\textsubscript{2} pipelines an edge over electricity options for higher RES capacities (7500 MW and above) transmitted over medium to long distances (400 km and above). The linepack can be thought of as a large storage element that can smooth out the variability of RES.

Each one of the MIQCP problems in Figure 6 has more than 400,000 continuous variables, 28 binary variables, and more than 900,000 constraints including more than 69,000 (convex) quadratic constraints. It takes Gurobi between 1 and 3 hours to solve each one.

B. Case study 2: REZ in Queensland, Australia

AEMO’s ISP identifies potential renewable energy zones (REZ) across the national electricity market (NEM) [31]. In more detail, this case study considers four REZ in Queensland and one H\textsubscript{2} demand point (off-take), as shown in Figure 7. Figure 7 also shows the RES capacity forecast for 2040. The solution to this integrated planning problem, shown in Figure 8, is a hybrid system consisting of a 2 GW VSC HVDC link between REZ Q1 and Q4 (570 km), a 3 GW 500 kV double circuit HVAC link between REZ Q8 and the demand point.
point (200 km), and a 0.5 m diameter H\(_2\) pipeline between REZ Q4 and Q6 (300 km) and Q6 and the demand point (500 km). No VAr plants (SVCs) were needed in this case as the HVAC link is installed over the relatively short distance of 200 km where both the voltage drop and angle difference (and also power losses) are small. These results are in congruence with the 2-node results in the previous section.

Finally, the profiles of available (forecast) VRE, accommodated VRE (\(p_{\text{resity}}^{\text{H}}\)) and demand (\(\phi_{\text{mty}} HHV\)) at the optimal solution of Problem 58 are shown in Figure 9. It can be seen from Figure 9 that the demand profile varies over a smaller range compared to the profile of available (forecast) VRE input and this is due to the effect of the linepack in the two H\(_2\) pipelines installed between REZ Q4 and Q6 (300 km) and Q6 and the demand point (500 km). This linepack profile is shown in Figure 10. Figure 9 also shows that the optimal infrastructure investment planning in Figure 8 has an energy transmission factor of 0.9901, which means that 99.01% of the total generated VRE is accommodated by the installed infrastructure. Recall that the energy transmission factor is defined as

\[
TF = \frac{\sum_{t \in T} \sum_{y \in Y} \sum_{i \in B} p_{\text{resity}}^{\text{H}}}{\sum_{t \in T} \sum_{y \in Y} \sum_{i \in B} p_{\text{resity}}^{\text{H}}}. \tag{59}
\]

The MIQCP problem in this case study has around than 560,000 continuous variables, 44 binary variables, and more than 1,160,000 constraints including more than 107,000 (convex) quadratic constraints. It takes Gurobi around 4 days to solve it.

V. CONCLUSION

To address the challenging question of whether to transport large-scale VRE as molecules in H\(_2\) pipelines or as electrons in electricity transmission lines, this paper introduced a first-of-its-kind mathematical framework for finding the optimal integrated planning of electricity and H\(_2\) infrastructure. The model fills the gap in existing state-of-the-art literature by (i) considering all relevant infrastructure technologies such as HVDC, HVAC, SVCs, and H\(_2\) pipelines and compressors, and by (ii) incorporating essential nonlinearities such as voltage drops due to losses in HVAC and HVDC transmission lines, losses in HVDC converter stations, reactive power flow, pressure drops in pipelines, and linepack, all of which play an important role in determining the optimal infrastructure investment decision. The high temporal resolution of the RES forecasts makes this model a large-scale nonconvex MINLP problem that is intractable if solved directly using MINLP solvers. The paper therefore proposes a tractable alternative in the form of an MIQCP relaxation that is demonstrated on a canonical two-node system as well as on a real-world case study involving actual renewable energy zones in Australia.

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