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Designing and long-term planning for household hydrogen supply chain in Australia☆

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ABSTRACT

This study presents the development of the long-term Household Hydrogen Supply Chain (HHSC) model, aimed at supporting the decarbonisation of household energy consumption. Structured across three strategic phases: foundation, expansion, and maturation, the model facilitates the systematic phase-out of liquefied petroleum gas (LPG) by 2045 and natural gas (NG) by 2080. Employing demand estimation methodologies grounded in historical data and exponential decay functions, the study forecasts long-term hydrogen adoption trajectories and allocates regional demand to optimise infrastructure placement. A network optimisation model identifies the optimal locations and capacities of national, regional, and local distribution centres (NDCs, RDCs, and LDCs). This staged development ensures operational scalability, geographic equity, and financial viability. A key finding is the substantial increase in profitability from $479 million in 2026 to $88.26 billion by 2090, driven by infrastructure growth and increasing hydrogen demand. Sensitivity analyses indicate that the adoption during the mid years (2040–2060) is particularly vulnerable to cost fluctuations. The model supports net-zero 2050 goals and aligns with several Sustainable Development Goals (SDGs), including SDGs 7, 9, and 13. While the HHSC provides a structured pathway for long-term hydrogen transition, future research should focus on enhancing the resilience of the HHSC by incorporating real-time data integration, assessing vulnerability to supply chain disruptions, and developing risk mitigation strategies to ensure continuity and scalability in hydrogen delivery under uncertain operating conditions.

1. Introduction

The reliance on traditional fossil fuels, such as natural gas (NG), liquefied petroleum gas (LPG), coal, and oil, has long been the cornerstone of energy supply across residential, commercial, and transportation sectors. The International Energy Agency (IEA) projects a 30 % increase in global energy demand by 2040, underscoring the enduring role of these fuels in meeting diverse energy needs (Citaristi, 2022; IEA, 2022). However, the continued dependence on fossil fuels poses significant environmental challenges, primarily due to increased greenhouse gas emissions, contributing to global warming (Godil et al., 2021). According to estimates, fossil fuels may be depleted within about 100 years, and oil, NG, and LPG will run out before coal does (Conti et al., 2014). The global community, including Australia, has recognised the urgent need to transition to sustainable energy alternatives to meet the commitments of the Paris Agreement (Potrč et al., 2021; Rogelj et al., 2016). In this context, hydrogen is emerging as a critical component of a decarbonised energy future, especially in Australia, which boasts abundant renewable energy resources (Ally et al., 2015; Csedő et al., 2024; Li & Jin, 2022).

The motivation for this study stems from the urgent need to transition to sustainable energy solutions that align with Australia's net-zero emissions target. As the reliance on fossil fuels continues to pose environmental threats and challenges to energy security, hydrogen emerges as a viable renewable alternative for household energy consumption. This transition is essential for reducing greenhouse gas emissions, enhancing energy security and diversifying the energy supply. This study's significance lies in its potential to contribute to designing Australia's household hydrogen supply chain (HHSC) network by proposing a long-term and multi-period optimisation model with the identification

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of the optimal locations for national distribution centres (NDCs), regional distribution centres (RDCs), as well as local distribution centres (LDCs).

However, the transition from NG and LPG to hydrogen in the household sector raises concerns about the compatibility of the existing infrastructure. Current systems for NG and LPG may not be suitable for hydrogen, necessitating significant upgrades or new investments. Additionally, the costs associated with producing, transporting, and storing hydrogen could be higher than those for NG and LPG, particularly during the initial stages of the transition, which may impact affordability for households (Giri & Bardhan, 2014). Current research has not adequately addressed the issues of resource stability and distributional impacts in this transition, highlighting a critical research gap. Designing a future HHSC is challenging due to multiple echelons, complex linkages, and fluctuations in demand. Existing research often isolates supply chain components and focuses on cost optimisation, lacking a holistic approach, particularly for the HHSC. Moreover, the literature has limited long-term planning for the Australian context and no multi-period network optimisation modelling has been developed. This study aims to address these gaps through two key research questions (RQs):

RQ1: How will hydrogen replace household consumption of NG and LPG in Australia over the long term?

RQ2: What will be the structure of the long-term Australian HHSC network, and what are the optimal locations for NDCs, RDCs, and LDCs?

To answer these questions, a long-term plan for the Australian HHSC network has been developed (until 2090), considering transportation routes and optimal locations of NDCs, RDCs, and LDCs.

The remainder of this manuscript is organised as follows. Section 2 provides a comprehensive literature review, identifying the key challenges associated with the transition to hydrogen energy. Section 3 details the research methodology. Section 4 presents the results and offers an in-depth discussion of the findings. Section 5 elaborates on the practical implications of the proposed HHSC for the Australian context. Finally, Section 6 concludes the study with recommendations for future research.

2. Literature review

The energy paradigm needs to switch from fossil fuel-based to renewable sources to lower GHG emissions (Midilli et al., 2005). Optimal hydrogen supply chain (HSC) design and management are critical factors in attaining the primary goal of delivering cheaply priced hydrogen to end customers (Farahani et al., 2012; Talebian et al., 2021). The project's complexity calls for a thorough understanding of numerous elements, such as infrastructure configuration, supply chain logistics, and manufacturing efficiency, is required. The locations and varieties of hydrogen sources, order inventories, and means of delivery all impact the HSC optimisation problem (Jauhari et al., 2024; Yoon et al., 2022). Challenges within supply chain optimisation often manifest as intricate covering set problems. In supply chain management research, applying system dynamics to renewable energy production is a significant area of investigation (Delfani et al., 2022). The scholarly discourse has also delved into a spectrum of research issues about HSC design and optimisation. The literature thoroughly explores these research dimensions, emphasising the need for a comprehensive understanding of the complexities inherent in HSC optimisation and design, thereby contributing to the advancement of knowledge in supply chain management. We have classified the literature review into three sections: HSC network design research, impacts of HSC on sustainability, and research gaps.

2.1. HSC network design research

We have classified our literature review into three main states to reflect the scientific evolution of HSC research. The primary state focused on foundational modelling and optimisation using techniques like mixed-integer linear programming (MILP) to establish basic HSC configurations. The secondary state shifted towards sector-specific applications, especially in transportation, exploring integration with existing infrastructure and centralised networks. The recent state emphasises integrated, long-term planning, incorporating sustainability, sectoral integration, and policy considerations. This progression from basic models to comprehensive planning highlights ongoing research gaps, particularly in HHSC and region-specific models like Australia, underscoring the need for holistic, future-oriented approaches.

2.1.1. Primary state: General optimisation framework

The first notable contribution on the topic conceptualised HSC and accompanying transport routes in the United Kingdom as nodes and edges inside an MILP framework (Almansoori & Shah, 2006). Following that, scholars worked on developing an HSC superstructure based on current cost criteria, in which numerous energy sources and spatial nodes representing supply, storage, and transportation techniques were systematically depicted. A series of studies on HSC optimisation used linearised integer programming techniques. Notably, a study conducted in the setting of South Korea pioneered a two-stage probabilistic approach (Kim et al., 2008). This model addressed demand uncertainty within the parameters of the HSC, building on the basic MILP framework. Furthermore, another study developed a multi-objective optimisation model applied to the South Korean context. This line of investigation has aided in developing problem-solving approaches, such as the constraint approach (Kim & Moon, 2008). These research projects highlighted the evolution and variety of approaches used to examine and optimise HSC in various locations.

However, researchers provided a spatially explicit modelling framework based on the scenario of Northern Italy that contributed to the strategic planning of hydrogen-based fuel delivery networks (Zamboni et al., 2009). Furthermore, comparable research endeavours were undertaken within the contextual framework of the Malaysia Peninsular. The analytical focus of this research involved a comprehensive examination of the hydrogen market, culminating in the identification of an optimal truck-based HSC for the Malaysia Peninsular (Kamarudin et al., 2009). Simultaneously, scholars investigated a geographically explicit and temporally evolving HSC model within the Netherlands scenario (Konda et al., 2011). The exploration was underpinned by a meticulous techno-economic analysis, emphasising the intricate interplay of geographical and temporal factors. Evidently, many subsequent studies ensued as a natural progression from the foundational phase of the HSC superstructure. Table 1 offers a succinct overview of the primary stage research within the HSC network, encapsulating the diverse geographic contexts and methodological approaches employed in advancing the understanding of HSC dynamics.

2.1.2. Secondary state: Modelling for the transportation sector

In delineating the research landscape of the primary state, a discernible bifurcation emerged between analytical and mathematical approaches. Subsequent investigations within the context of the UK further refined these methodologies, introducing various scenarios to encapsulate potential future manifestations of unknown problem characteristics (Almansoori & Shah, 2012). The iterative process involved various techniques to discern a reliable solution. Upon meticulous analysis, two distinct application scenarios were identified, each illustrating the pragmatic implementation of the developed approaches. Similarly, within the southwestern United States, a study unfolded the hydrogen production and transmission (HyPAT) model (Johnson & Ogden, 2012). Researchers sought to delineate centralised, cost-effective hydrogen production and pipeline infrastructure facilities.

Table 1
Primary state of HSC research.

Reference	Key contributions	Methodology	Geographical location
Almansoori & Shah, 2006	Determined the ideal infrastructure and operating costs to construct the HSC for the transportation sector.	MILP	Great Britain
Kim et al., 2008	Created a stochastic model to account for the influence of the uncertainty in hydrogen activities and analysed the total network costs of several HSC topologies in an uncertain hydrogen demand environment.	A stochastic formulation based on the two-stage programming approach	South Korea
Kim & Moon, 2008	Designed a general multi-threading model to assist in the judgment process for the HSC design.	MILP	South Korea
Zamboni et al., 2009	Provided a modelling framework for the strategic planning of HSC networks that is spatially explicit.	MILP	Northern Italy
Kamarudin et al., 2009	Analysed the hydrogen market and chose the best truck-based HSC.	MILP	Malaysia Peninsular
Konda et al., 2011	Developed a geographically explicit and time-evolving HSC network based on a thorough techno-economic analysis.	Multi-period optimisation framework	Netherlands

Researchers developed a statistical model for an HSC, which demonstrated its efficacy and underscored its potential utility in producing, transporting, and delivering hydrogen to end consumers (Han et al., 2012b).

In a divergent investigative trajectory, researchers delved into a worst-case scenario, envisioning a 25 % market penetration of fuel cell vehicles by 2050 (Murthy Konda et al., 2012). The exploration necessitated the development of a centralised supply network, with production plants situated in the Rotterdam area and the transportation of hydrogen fuel to other regions deemed essential.

Furthermore, a noteworthy study addressed the deployment scenarios of an HSC in France (Almaraz et al., 2014). Additionally, an impactful research initiative scrutinised potential investments in logistics infrastructure, propounding an optimisation plan that significantly contributed to the optimal design of an HSC in South Korea's utility sector (Hwangbo et al., 2017). The cumulative body of research reflects a systematic and diverse exploration of HSC dynamics across varied geographical and contextual domains, enriching the scholarly understanding of HSC intricacies, summarised in Table 2.

Table 2
Secondary state of HSC research.

Reference	Key contributions	Methodology	Geographical location
Almansoori & Shah, 2012	Developed various scenarios to represent the potential future manifestation of unknown problem characteristics and considered the range of techniques while deciding on a reliable solution.	Multi-stage stochastic MILP	UK
Johnson & Ogden, 2012	Created the HyPAT model to determine the cost-effective centralised manufacturing and pipeline infrastructure facilities with genuine geographic regions.	MILP and general algebraic modelling system (GAMS)	Southwestern United States (Arizona, New Mexico, Colorado, and Utah)
Han et al., 2012a	Created a statistical model of an HSC capable of producing, transporting, and delivering hydrogen to end customers and looked at six potential HSC topologies.	The centre of gravity method	South Korea
Murthy Konda et al., 2012	Developed a centralised HSC (with production plants based in the Rotterdam area and trucking hydrogen fuel to other regions), considering the worst-case scenario.	Spatio-temporal techno-economic analysis	Rotterdam, Netherlands
Almaraz et al., 2014	Developed an HSC for deployment scenarios in the French Midi-Pyrénées region.	Multi-objective optimisation	Midi-Pyrénées region, France
Nunes et al., 2015	Analysed potential investments in the logistics infrastructure and put out an optimisation plan.	Sample average approximation	Great Britain
Hwangbo et al., 2017	Developed an optimal design of HSC in the utility sector of South Korea.	Multi-stage stochastic MILP	South Korea

2.1.3. *Recent state: Hydrogen gas distribution network*

The recent state of HSC dynamics has witnessed a recent expansion. An investigation delved into the HSC design within the context of Turkey, intending to meet the anticipated hydrogen demand spanning the years 2021 to 2050 (Güler et al., 2021). In parallel, a study centred on the UK scenario conceived the notion of an HSC, specifically within the gas distribution network, tailored for the transport sector up to 2050 (Wickham et al., 2022).

Concurrently, other studies explored important elements for the HSC network development in different settings, such as integrating hydrogen into the natural gas pipeline in South Korea (Yoon et al., 2022) or identifying optimal locations for refuelling stations in Turkey over the next three decades (Geçici et al., 2022).

Further contributing to the evolving landscape, a comprehensive research review outlined an agenda for future HSC research, encompassing various phases of sustainable adaptation and market development (Dogliani et al., 2024; Sgarbossa et al., 2022). Subsequently, another substantial study, based in Turkey, articulated the conceptualisation of HSC design for the year 2050, optimising considerations of costs, carbon emissions, and safety risks (Erdoğan et al., 2023). Another notable investigation, set in the scenario of Qatar, introduced an optimisation-based model for designing an HSC network (Ibrahim & Al-Mohannadi, 2023). Moreover, researchers proposed a multi-period centralised storage model for France, integrating energy sources, carbon capture, and demand scenarios to minimise costs and emissions (Feng et al., 2024). Their findings demonstrated that centralised storage offers substantial cost benefits compared to decentralised systems. Another study demonstrated that optimising HSC design through a mixed-integer linear programming model, incorporating wind curtailment and centralised biomass-based production, can significantly reduce both daily emissions and network costs (Cutore et al., 2024). Similarly, researchers focused on the environmental and social dimensions, emphasising the need for sustainable practices in labour and emissions management (Degirmenci et al., 2023; Moran et al., 2024). Table 3 presents the recent state of HSC research.

Table 3
Recent state of HSC research.

Reference	Key contributions	Methodology	Geographical location
Güler et al., 2021	Investigated the HSC design in Turkey to satisfy the anticipated hydrogen demand between 2021 and 2050.	MILP	Turkey
Wickham et al., 2022	Designed an HSC (gas distribution network) for the transport sector up to 2050.	Multi-stage stochastic MILP	UK
Yoon et al., 2022	Optimised HSC network blending into the natural gas pipeline with a by-product of hydrogen.	Multi-period MILP	South Korea
Geçici et al., 2022	Analysed the location of the refuelling station in Istanbul for the next 30 years.	Multi-period p-median model	Istanbul, Turkey
Sgarbossa et al., 2022	Outlined an agenda for future HSC research considering various phases of sustainable HSCs adaptation and market development.	PRISMA protocol	–
Erdoğan et al., 2023	Developed HSC design for 2050 by optimising cost, carbon emission, and safety risk.	MILP	Turkey
Ibrahim & Al-Mohannadi, 2023	Developed an optimisation-based model to design HSC.	MILP	Qatar
Feng et al., 2024	Proposed a multi-period centralised storage optimisation model for HSCs, highlighting cost and emissions reduction.	MILP	–
Cutore et al., 2024	Designed an HSC incorporating wind curtailment and centralised biomass-based production.	MILP	Italy

2.2. Impacts of HSC on sustainability

The escalating global population and heightened living standards necessitate substantial energy consumption, profoundly impacting sustainable development's economic, social, and environmental dimensions. To align with the Intergovernmental Panel on Climate Change's (IPCC) imperative of limiting global warming to 1.5 °C, an emission reduction strategy targeting zero-emission resources by 2050 has been delineated (Masson-Delmotte et al., 2018). However, a substantial challenge arises because 80 % of the world's energy requirements are met by carbon-containing resources, perpetuating constant atmospheric emissions (Midilli et al., 2005; Potrč et al., 2021).

The predominant contributors to these emissions emanate from industries and sectors inherently resistant to facile reductions, including pharmaceuticals, metals, aerospace, and transportation (Li & Jin, 2022; Pareek et al., 2020). The rapid expansion of these sectors poses significant hurdles to comprehensive emissions reductions in the short term. Nonetheless, mitigation strategies encompassing increased energy efficiency, sector electrification, biofuel substitution, and implementing carbon capture, utilisation, and storage (CCUS) present avenues for reducing carbon emissions (Ćosić et al., 2012). Within this context, hydrogen emerges as a pivotal element with potential contributions to emissions reduction in the energy system (Sharma, 2019).

Hydrogen offers a promising avenue through its ability to facilitate deep decarbonisation, particularly in challenging industries with inherent emissions. As these industries inherently produce emissions due to chemical reactions, more than reliance on renewable energy is needed to curtail them. Hydrogen combustion, yielding water vapour as the sole by-product, emerges as an efficacious means to address emissions in these hard-to-regulate sectors (Gurieff et al., 2021). Furthermore, hydrogen's role extends to decarbonising the transportation industry, encompassing aerospace, transit, and long-distance haulage through fuel cell-powered applications (Currie & Phung, 2008). Beyond emissions reduction, hydrogen enhances energy security by enabling the conversion of renewable electricity into hydrogen, facilitating its transport over considerable distances to locations where direct electrification is impractical (Dolci, 2018; Taddei et al., 2024).

Globally, hydrogen has garnered substantial interest and investment, manifesting in over 200 hydrogen initiatives across 30 nations, each delineating roadmaps and ambitious plans for infrastructure development and low-carbon hydrogen generation (Yu et al., 2021). These initiatives show the incredible impetus for hydrogen as a crucial component of the energy future, but there are still big obstacles to overcome (Li et al., 2019). In addition to the government's reluctance to switch to a low-carbon energy economy, the infrastructure of the HSC needs to be strengthened. The HSC, as a critical component of the hydrogen economy, demands meticulous attention to ensure its alignment with sustainability goals, encompassing environmental, economic, and social dimensions (Dwivedi et al., 2022; Jabbour et al., 2020). Addressing these challenges would be imperative for the seamless integration of hydrogen into the global energy landscape.

2.3. Research gaps

The involvement of numerous echelons in the supply chain network, the high level of linkages between supply chain components and subsystems, and uncertainty in hydrogen consumption complicates the design of the future HSC network. Most of the primary state research for future HSCs that attempted to include all these difficulties into a single, general optimisation framework utilising a mathematical modelling method failed to do so (Almansoori & Shah, 2006; Kim et al., 2008; Kim & Moon, 2008; Konda et al., 2011; Zamboni et al., 2009).

The secondary state of the HSC was more focused on the transportation industry. Transportation has almost been included as a prospective market by most optimisation-based models. However, only a very small amount of research has been done on the incorporation of multiple sectors in the HSC. This is because locating the insertion point amongst HSC was becoming increasingly complex and difficult to scale (Almansoori & Shah, 2012; Almaraz et al., 2014; Hwangbo et al., 2017; Johnson & Ogden, 2012; Murthy Konda et al., 2012; Nunes et al., 2015).

Most recent research examined each link in the supply chain separately before combining them to create a particular hydrogen pathway. The "optimal" arrangement predicated on a key indicator of success was then chosen by simulating and comparing each of these well-before paths, with cost as the deciding factor. However, because they depended on various hypotheses about the degree of demand, distribution routes, and geographic locations, most of these assessments had a limited scope for universal application. The analysis also ignored considering the various sizes of manufacturing plants and storage facilities, demand volatility, or the local logistics network for energy sources (Cutore et al., 2024; Degirmenci et al., 2023; Feng et al., 2024; Güler et al., 2021; Moran et al., 2024; Sgarbossa et al., 2022; Talebian et al., 2021; Wickham et al., 2022; Yoon et al., 2022).

The comprehensive scrutiny of existing literature revealed discernible gaps in the understanding and articulation of operational and distributional facets within the HSC. A notable trend in extant research revolved around utilising natural gas pipelines, predominantly focused on blending hydrogen into these pipelines. However, a conspicuous absence persisted in the literature concerning the specific exploration of the HHSC. Furthermore, the reviewed studies offer limited insights into how the HSC can systematically phase out conventional fossil fuel consumption across significant sectors. Moreover, a long-term planning framework for the HSC within the Australian context is non-existent in the literature. More specifically, a multi-period network optimisation model for HSC had yet to be developed. This study aspires to contribute meaningfully to the discourse by addressing the identified research gaps and recognising the significant challenges inherent in the HSC domain. The primary objective is to develop a comprehensive long-term planning framework for the HHSC within the Australian context from 2026 to 2090. Additionally, the study seeks to make substantive contributions to the discourse on phasing out the consumption of NG and LPG in Australian households over the same temporal horizon. By undertaking this ambitious research agenda, the study aspires to enhance the understanding of the operational intricacies of HHSC, offer insights into sectoral fossil fuel phase-out strategies, and contribute to establishing a sustainable hydrogen landscape in Australia.

3. Research methodology

This study employs multi-period network optimisation methodology to design the HHSC for Australia. It begins with estimating household hydrogen demand, which involves collecting historical data on household NG and LPG consumption, projecting future hydrogen demand, and estimating regional hydrogen demand density. This information is used to develop a hydrogen demand map to determine potential locations of LDCs. Next, the mathematical model aims to maximise total profit by determining the optimal number and locations of NDCs, RDCs, and LDCs. The model includes sets, variables, parameters, an objective function, and constraints and is optimised using AnyLogistix software to provide key outputs such as total profit, different costs, and optimal distribution centre configurations.

3.1. Problem statement

Like any other supply chain network, an HHSC has various unique components. NDCs, RDCs and LDCs act as nodes in the HHSC, and arcs in the networks serve as links between nodes and ways of distribution. This study suggests a multi-period network optimisation approach to develop an HHSC plan with the locations of NDCs, RDCs and LDCs and the distribution of liquid hydrogen for Australian households. The model optimises the total profit considering total revenue and total household hydrogen distribution cost from NDCs to RDCs, total household hydrogen distribution cost from RDCs to LDCs, and total production cost of hydrogen. The choices relate to the size and placement of the NDCs, RDCs and LDCs, the total demand of the households, the volume of hydrogen that is distributed between each node, and the number of NDCs, RDCs and LDCs required over the period. Several hydrogen activities are chosen to examine the suggested model thoroughly. As per the design of the Australian HHSC structure, NDCs will distribute hydrogen gas in a tanker to the RDCs, and RDCs will distribute LHG compressed into various sizes of cylinders to LDCs by the retailer's truck.

The following assumptions are made in this study.

(1) The HHSC is assumed to be demand-driven even though supply and demand are connected in this model. The projected household hydrogen demand has been driven by the data on the projected growth of NG and LPG over the coming years.

(2) The study considers the distribution cost of liquid hydrogen from NDCs to RDCs and from RDCs to LDCs.

(3) This study's hydrogen network only offers an overview of the HHSC and ignores a possible migration route away from the current carbon infrastructure.

3.2. Estimating the demand of household hydrogen

This section outlines the modelling framework used to estimate future household hydrogen demand in Australia. The steps to estimate the demand are as presented in Fig. 1.

3.2.1. Phase-out modeling of LPG and NG

The forecasted demands for LPG and NG over the planning horizon are modelled using exponential decay functions with variable annual reduction rates. Equations (1) and (2) incorporate the expected decline in fossil fuel usage as national and regional energy policies push for cleaner household energy sources. Specifically, the projected demands in year t, relative to a baseline year t_0, are presented as follows.

The hydrogen demand for city c in year t, denoted as $D_{c,t}$ is given by,

$$D_t^{LPG} = D_{t_0}^{LPG} \cdot \prod_{T=t_0+1}^{t} \left(1 - r_T^{LPG}\right) \tag{1}$$

$$D_t^{NG} = D_{t_0}^{NG} \cdot \prod_{T=t_0+1}^{t} \left(1 - r_T^{NG}\right) \tag{2}$$

Where,

D_t^{LPG} = The forecasted LPG demand in year t.
D_t^{NG} = The forecasted NG demand in year t.
$D_{t_0}^{LPG}$ = Baseline demands of LPG in base years.
$D_{t_0}^{NG}$ = Baseline demands of NG in base years.
r_T^{LPG} = Annual phase-out rate of LPG in year T, where $.T \in (t_0, t)$
r_T^{NG} = Annual phase-out rate of NG in year T, where $.T \in (t_0, t)$

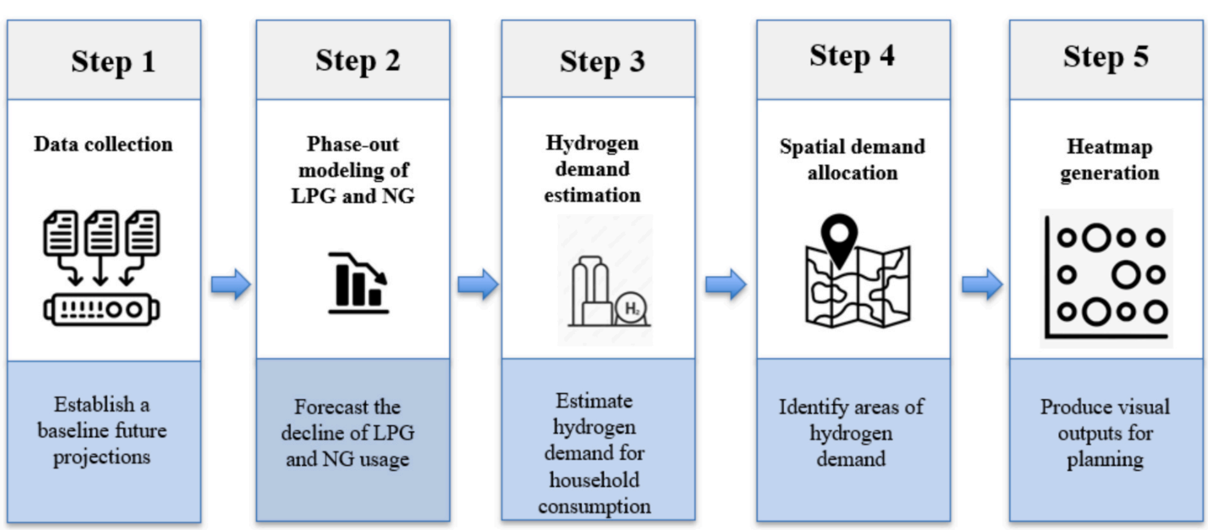

Fig. 1. Steps to estimate hydrogen demand over the years.

t_0 = base year.
t = Any future year such that $.t_0 < t$

3.2.2. Hydrogen demand estimation

Equation (3) estimates the total national hydrogen demand in year t resulting from the displacement of LPG and NG consumption. The differences between $\left(D_{t_0}^{LPG} - D_t^{LPG}\right)$ and $\left(D_{t_0}^{NG} - D_t^{NG}\right)$ quantify the fossil energy displaced up to time t, and the adoption coefficients α^{LPG} and α^{NG} represent the proportion of this displaced demand that is substituted with hydrogen. This formulation assumes that hydrogen is delivered for direct end-use (e.g., household cylinders), and, therefore, no efficiency loss is incurred in the substitution, enabling a direct one-to-one energy equivalence.

$$D_t^{H_2} = \alpha^{LPG}.\left(D_{t_0}^{LPG} - D_t^{LPG}\right) + \alpha^{NG}.\left(D_{t_0}^{NG} - D_t^{NG}\right) \quad (3)$$

Where,
α^{LPG} = The fraction of displaced LPG.
α^{NG} = Represent the fraction of displaced NG.
$D_t^{H_2}$= National hydrogen demand in the time period t.

3.2.3. Regional demand allocation

The hydrogen demand for city c in year t, denoted as $D_{c,t}$ in Equation (4), disaggregates hydrogen demand across cities or regions. This spatial allocation is critical for informing network-level infrastructure decisions, such as locating NDCs, RDCs and LDCs and optimising transport flows in subsequent stages of the supply chain model.

$$D_{c,t} = D_t^{H_2}.\left(\frac{Pop_c}{\sum_{k\in c} Pop_i}\right) \quad (4)$$

3.3. Mathematical model for network optimisation

The primary objective of the mathematical model for network optimisation is to maximise total profit by estimating the locations and number of NDCs, RDCs, and LDCs needed over the planning period. The profit function, detailed in equation (1), accounts for dynamic cost factors, assuming an annual 5 % variable increase in production cost, transportation costs over the years due to inflation and other influencing variables. The mathematical model is structured into five key components: sets, variables, parameters, the main objective function, and constraints. This model optimises the locations of NDCs, RDCs, and LDCs to determine the optimal number of distribution centres (DCs) required over time to meet the projected household demand for hydrogen. The mathematical model comprises five fundamental components, such as sets, variables, parameters, the main objective function, and constraints. These elements collectively define the mathematical structure required to optimise the HHSC network. The sets specify the potential locations for NDCs and RDCs, while the variables represent hydrogen production quantities and flow across the network. The parameters include capacity limits, projected demand, cost values, and transportation characteristics. The objective function aims to maximise total profit. Finally, the constraints ensure that the solution adheres to physical, economic, and logistical limitations, enabling a dynamic design of the HHSC.

3.3.1. Sets

Sets of potential locations of DCs are helpful in determining the number of DCs required over the period to satisfy the household demand for hydrogen. Sets are described as follows:
I: Set of potential locations of NDCs indexed on $.i = 1, \cdots., I$
J: Set of locations of RDCs indexed on $.j = 1, \cdots\cdots, J$
K: Set of locations of LDCs indexed on $k = 1, \ldots \ldots, K$.

3.3.2. Variables

Variables are essential for determining the production quantity of hydrogen at the production facility (NDC), as well as for modelling the flow of hydrogen from the NDC to the RDC and from the RDC to the LDC. They also specify the transport mode, such as vehicles, and the quantity of hydrogen received at designated distribution centres, including RDCs and LDCs. The variables are as follows.
P_i= Hydrogen production quantity at NDC $.i$
X_{ij}= Hydrogen amount in m^3 distributed from NDC i to RDC $.j$
R_j= Hydrogen received at RDC $.j$
L_k= Hydrogen received at LDC $.k$
Y_{jk}= Hydrogen amount in m^3 distributed from RDC j to LDC k.

3.3.3. Parameters

The parameters are as follows.
c_i = capacity of NDC $.i$
c_j = capacity of RDC j.
d_k = annual projected demand from LDC k.
S = The selling price of hydrogen is determined using a 60 % markup applied to the production cost (Almansoori & Shah, 2009; Reuß et al., 2021).
M = Production cost of hydrogen, assumed to be variable per m^3.
T_1 = Transportation cost of hydrogen from NDC i to RDC j is assumed to be variable per km per m^3, with a maximum vehicle capacity of 50 m^3, average speed 80 km/hour (Ng et al., 2024; Smit et al., 2024).
T_2 = Transportation cost of hydrogen from RDC j to LDC k is assumed to be variable per km per m^3, with a maximum vehicle capacity of 50 m^3, average speed 80 km/hour (Ng et al., 2024; Smit et al., 2024).

3.3.4. Main objective function

The objective function is to maximise the total profit as stated in equation (5).

$$Max\pi = s\sum_{k=1}^{K} l_k - M\sum_{i=1}^{I} P_i - \left(T_1\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij} + T_2\sum_{j=1}^{J}\sum_{k=1}^{K} Y_{jk}\right) \quad (5)$$

The objective function presented in Equation (5) determines total profit, which equals total revenue minus production and transportation costs. Total revenue is calculated by multiplying the quantity of hydrogen delivered to the LDCs by the selling price. Production cost is similarly determined by multiplying the quantity of hydrogen produced at the NDCs by the indexed production cost. Transportation costs consist of two components: the cost of transporting hydrogen from NDCs to RDCs and from RDCs to LDCs.

3.3.5. Constraints

The objective function, presented in equation (5), is subject to the following constraints.

$$P_i \le C_i; \forall i \quad (6)$$

$$R_j = \sum_{i=1}^{I} X_{ij}; \forall j \quad (7)$$

$$L_k = \sum_{j=1}^{J} Y_{jk}; \forall k \quad (8)$$

$$L_k = d_k; \forall k \quad (9)$$

$$P_i \ge \sum_{j=1}^{J} X_{ij}; \forall i \quad (10)$$

$$R_j \ge \sum_{k=1}^{K} Y_{jk}; \forall j \quad (11)$$

$$P_i, X_{ij}, Y_{jk} \ge 0; \forall i, \forall j, \forall k \quad (12)$$

Equation (6) represents that the quantity of hydrogen produced at NDC i must be less than or equal to the capacity of NDC i. Equation (7) represents that the quantity of hydrogen received by RDC j must equal the quantity of hydrogen transported from NDC i to RDC j. Similarly, Equation (8) represents that the quantity of hydrogen received by LDC k must equal the quantity transported from RDC j to LDC k. Equation (9) represents that the quantity of hydrogen received at LDC k must be equal to the demand of LDC k. Equation (10) represents that the production at NDC i must be greater than or equal to the quantity of hydrogen transported from NDC i to RDC j. Similarly, Equation (11) represents that the quantity of hydrogen received at RDC j must be greater than or equal to the quantity of hydrogen transported from NDC i to RDC j. Equation (12) represents that production at NDC i, the quantity of hydrogen transported from NDC i to RDC j and the quantity of hydrogen transported from RDC j to LDC k must be greater than or equal to 0.

3.4. Solving the mathematical model

We solved the mathematical model using AnyLogistix software, employing the optimisation tool on a periodic basis, with each period representing one year (365 days) to determine the multi-period Australian HHSC. The model outputs include the total profit, production costs, transportation costs, the number of DCs required, optimal locations of these DCs, and their required capacities.

4. Results and discussions

The results highlight the optimal locations and capacities of NDCs and RDCs required to meet projected household hydrogen demand, the strategic evolution of the HHSC network over time, and the financial implications of this transition. The findings provide a comprehensive roadmap for integrating hydrogen into Australia's household energy mix, supporting the country's sustainability and emissions reduction goals.

4.1. Phasing out LPG and NG from the household sector

The proposed long-term Australian HHSC network is designed to enable the phased elimination of LPG and NG in the Australian household sector. The model outlines a timeline for this transition, targeting complete LPG phase-out by 2045, a significant reduction in NG consumption by 2050, and full NG elimination by 2080.

An important component of the model is the introduction of liquid hydrogen gas as a sustainable household energy source. The model anticipates a progressive scale-up in hydrogen supply from 2026 to 2090, enabling hydrogen to fully replace LPG by 2050 and NG by 2080. While these projections are aligned with national decarbonisation goals, their realisation depends on multiple interrelated factors, including infrastructure readiness, technological advancement, economic viability, and public acceptance.

Although Fig. 2 showcases the transition framework, the assumptions underpinning the model must be critically assessed. Sensitivities to policy changes, economic disruptions, or behavioural resistance may significantly impact timelines. Additionally, the inclusion of liquid hydrogen requires careful evaluation of production methods, distribution logistics, and environmental implications, particularly regarding the carbon intensity of hydrogen sources, which is not within the specific scope of this manuscript.

In summary, the HHSC network presents a credible long-term vision, but achieving its objectives will require coordinated planning, robust modelling, and responsiveness to uncertainty across technical, regulatory, and social dimensions.

4.2. Estimating the demand of hydrogen for households

The results of the demand estimation model indicate a progressive and regionally varied transition from traditional gas fuels to hydrogen across Australian households between 2026 and 2090. Based on historical consumption data and forward projections, the model assumes a 5 % annual reduction in household consumption of NG and LPG, alongside a 10 % annual increase in hydrogen adoption.

Under these assumptions, LPG is fully phased out by 2045, reflecting its limited scope and ease of substitution, while NG sees a massive reduction by 2050 and complete elimination by 2080. Hydrogen, introduced at low levels in the early years, rises steadily to replace both fuels, becoming the primary household energy source in the second half of the century. This substitution occurs across heating, hot water, and cooking applications.

Spatial analysis of hydrogen demand density reveals significant regional variation. Densely populated areas such as Greater Melbourne,

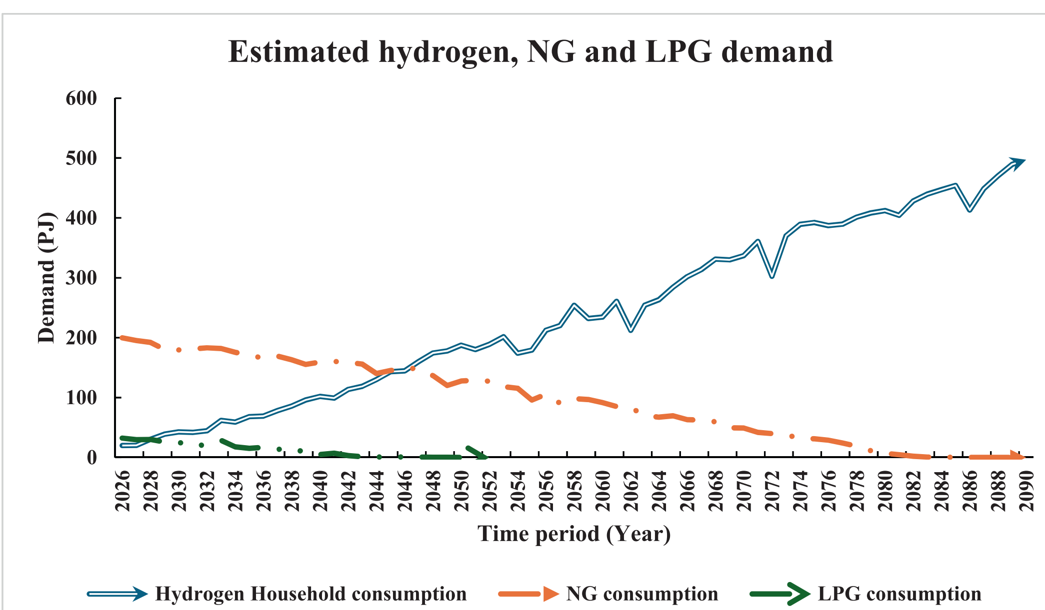

Fig. 2. Estimated household energy demand trends for hydrogen, NG, and LPG between 2026 and 2090.

Sydney, and Brisbane are identified as high-priority zones for hydrogen infrastructure, particularly LDCs. The development of a national hydrogen demand map supports infrastructure planning, identifying optimal locations for HHSC. Fig. 2 visually illustrates these projections and transitions.

While the findings align with national sustainability goals, they also highlight the need for careful planning around infrastructure readiness, policy support, and consumer uptake to ensure the practical realisation of the projected hydrogen transition.

4.3. Australian HHSC network from 2026 to 2090

The Australian HHSC represents a national strategy to deliver clean hydrogen energy directly to household users through a multi-tiered distribution network. Spanning the years 2026 to 2090, the HHSc evolves in three structured phases: foundation, expansion, and maturation, developing from a single-point regional model into a fully integrated national system (refer to Figs. 3, 4 and 5). The foundation phase (2026–2045) is defined as the period during which LPG is phased out, and a single NDC supplies hydrogen to pilot households along key urban corridors. The expansion phase (2045–2070) is defined as the period of rapid infrastructure growth, with the addition of a second NDC, multiple RDCs and LDCs, and accelerated network coverage. The maturation phase (2070–2090) is defined by a gradual increase in population coverage, with a third NDC enabling national access and full redundancy.

4.3.1. Foundation phase (2026–2045)

This phase represents the initial and strategic establishment of national infrastructure to deliver hydrogen directly to Australian households. As illustrated in Fig. 3, this phase embodies a staged roll-out, concentrated in high-demand and urbanised corridors, to validate early feasibility and develop operational experience. In 2026, the system is anchored by a single NDC located in Portland, Victoria (refer to Appendix 2). This primary hub distributes hydrogen to one RDC in Melbourne, which supplies 26 LDCs across Victoria and New South Wales (refer to Appendix 3). This configuration mirrors international best practices in pilot-phase hydrogen deployments, such as Japan's early regional hubs (Nagashima, 2018), which prioritise high-density areas to optimise early infrastructure returns. By 2030, a second RDC is added in Perth, reflecting both rising Western demand and the adaptive expansion of the network based on geographical equity and projected household uptake (refer to Appendix 1). LDCs expand to 38, increasing coverage across metropolitan regions. Despite growing demand, the Portland NDC sustains the national supply until 2045 due to its strategic coastal location and sufficient capacity, echoing literature which supports centralised supply in early-phase energy networks to reduce complexity and capital exposure (Citaristi, 2022; IEA, 2022). By 2045, the HHSC expands to four RDCs, adding Brisbane and 47 LDCs, signalling a transition from pilot infrastructure to semi-scaled operations.

4.3.2. Expansion phase (2045–2070)

This phase builds strategically upon the foundational infrastructure by shifting from a concentrated southeast corridor to nationwide coverage. While the foundation phase (2026–2045) established a single NDC in Portland and supported urban clusters via a limited number of RDCs and LDCs, the expansion phase introduces decentralisation to meet growing demand and broaden geographical inclusivity. As shown in Fig. 4, although the network in 2050 still relies on Portland's NDC, by 2055, a second NDC is introduced in Bowen, Queensland (refer to Appendix 2). This step decentralises supply and reduces network fragility, an approach validated by European hydrogen corridor models (Kountouris et al., 2024; Trincone & Ronconi, 2024). By 2065, the HHSC includes two NDCs, six RDCs, and 67 LDCs (refer to Appendix 3), reflecting increasing demand and spatial expansion. RDCs in cities like Townsville, Adelaide, and Darwin (refer to Appendix 1) provide proximity-based distribution to key urban and regional centres. This mirrors successful hydrogen rollouts such as Germany's H_2 project and Japan's hydrogen society initiative, which demonstrate how decentralised distribution enhances resilience and adoption (Chen et al., 2022; Quitzow et al., 2024). The growth of LDCs from 47 to 67 over two decades underpins market penetration and supports the national phase-out of NG and LPG. This phase also addresses Australia's hydrogen infrastructure roadmap (COAG, 2019), aligning with energy equity, net-zero commitments, and SDG targets by providing regional energy access and supply redundancy.

4.3.3. Maturation phase (2070–2090)

This phase reflects the transition from a growing national network into a fully integrated, operationally mature logistics system. This phase completes the staged development initiated in earlier phases, marking the final expansion of NDCs, RDCs, and LDCs across the country.

As seen in Fig. 5, the network enters its final structure by 2070, with the introduction of the third NDC in Port Hedland, Western Australia, which joins the existing Portland and Bowen NDCs (refer to Appendix 2). This tri-nodal structure reduces spatial dependency and balances supply flows between eastern, northern, and western corridors, key to maintaining efficiency across long transport distances. By 2090, the

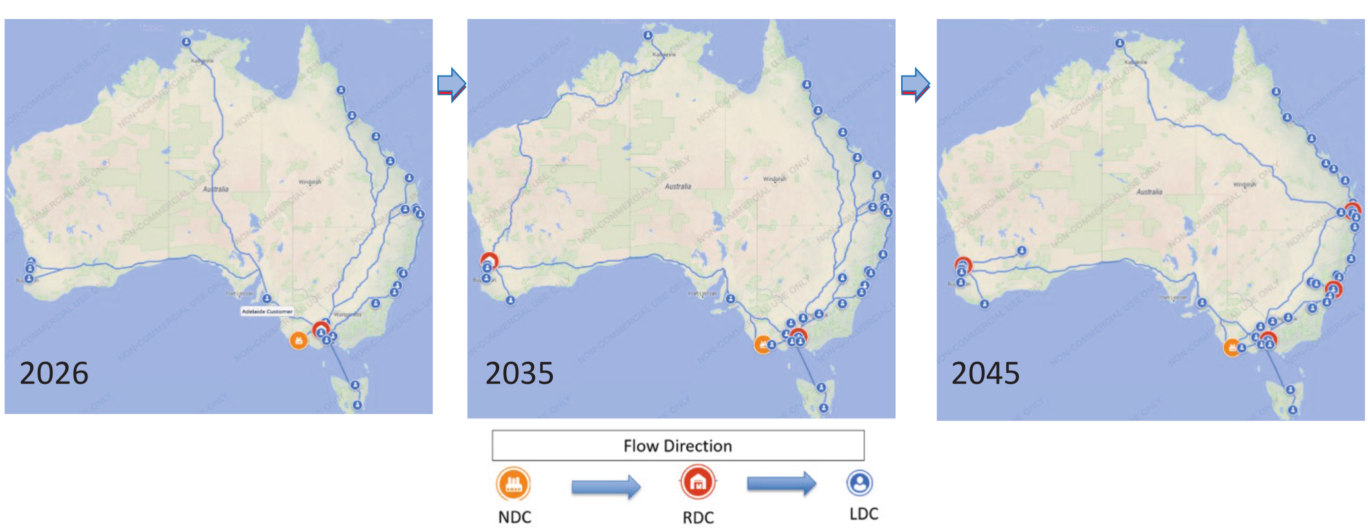

Fig. 3. Foundation phase of the HHSC (2026–2045).

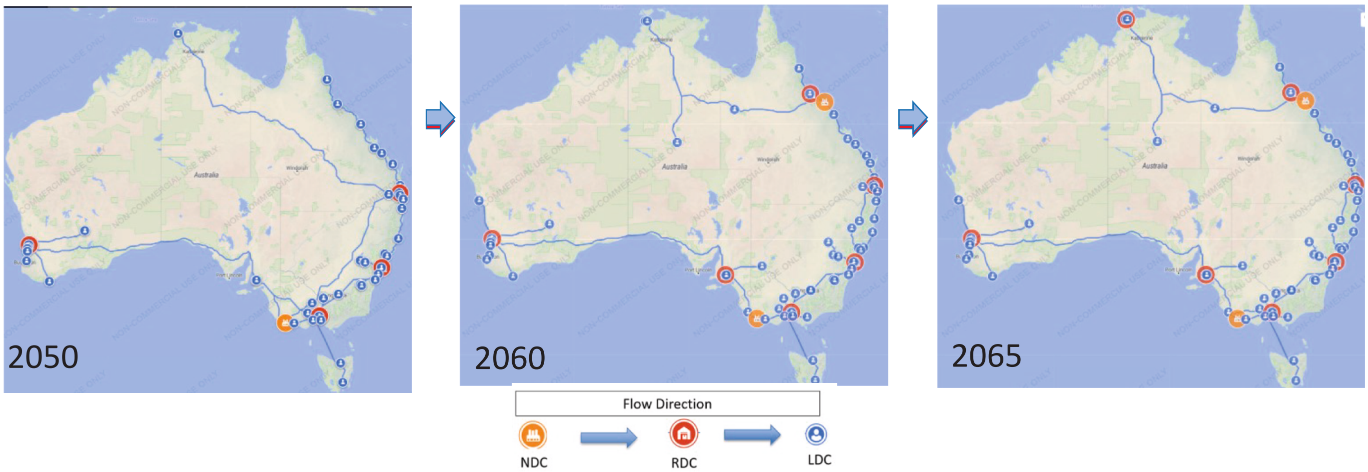

Fig. 4. Expansion phase of the HHSC (2045–2070).

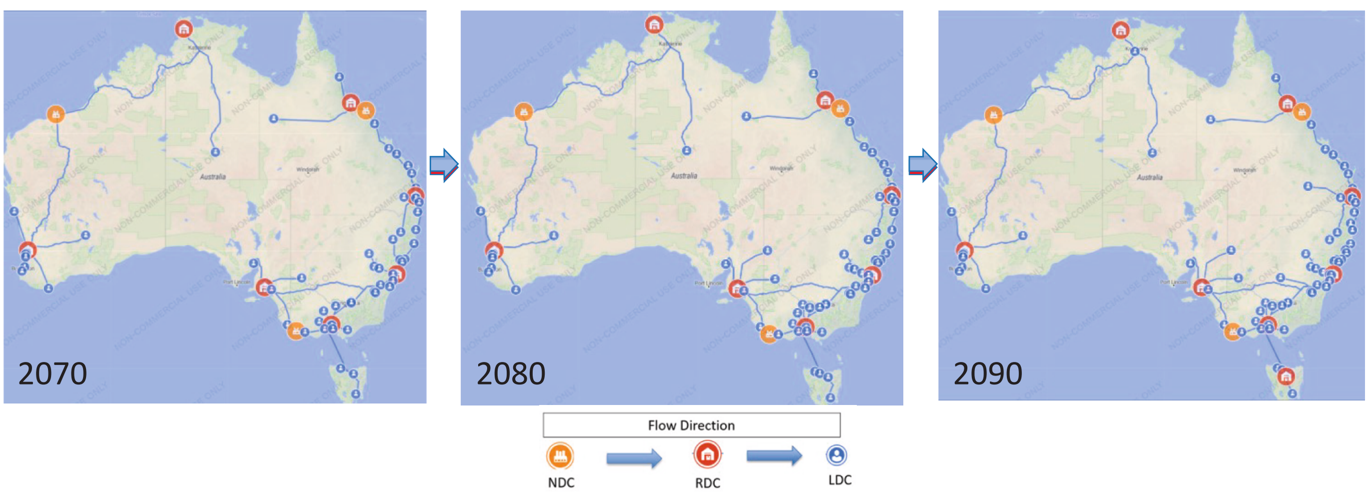

Fig. 5. Maturation phase of the HHSC (2070–2090).

HHSC includes 8 RDCs strategically located in major cities such as Sydney, Melbourne, Perth, Brisbane, Adelaide, Darwin, Townsville, and Launceston (refer to Appendix 1). The number of LDCs rises to 87 by 2090 (refer to Appendix 3), enabling last-mile delivery even in remote areas. The layout evolves into a multi-directional network, where hydrogen flows are no longer linear but meshed across multiple nodes. This structure is consistent with supply chain resilience theory, which suggests decentralisation and interconnectivity improve adaptability and reduce bottlenecks (Giannoccaro, 2018).

4.4. Financial implications for the Australian HHSC network

This section presents the outcomes of the proposed HHSC model in Australia. It explores the phased transition from NG and LPG to hydrogen, the evolution of the network infrastructure, and the financial, operational, and strategic implications towards national sustainability and net-zero targets.

4.4.1. Profit maximisation

The profit maximisation trajectory of the Australian HHSC reflects the compound effect of phased infrastructure expansion and rising demand for clean household energy. As evidenced in the financial implications (2026–2090), profit grows steadily from $479 million in 2026 to $88.26 billion by 2090, under a variable pricing strategy with a 60 % mark-up over production costs and an annual variable 5 % increase in both production and transportation costs, reflecting market volatility and inflation.

The foundation phase (2026–2045) yields modest profits, averaging under $2 billion annually due to limited infrastructure and low household penetration. During this phase, the system is anchored by a single NDC (refer to Fig. 6). The expansion phase (2045–2070) marks a turning point. The commissioning of additional NDCs in Bowen and later Port Hedland, coupled with the deployment of new RDCs and LDCs, significantly boosts hydrogen accessibility and network coverage. Revenues increase due to both higher consumption volumes and operational efficiencies achieved through scale, with profits exceeding $26.6 billion by 2070.

In the maturation phase (2070–2090), the network reaches national saturation. As demand for hydrogen continues to grow and the distribution network becomes fully developed and efficient, overall profitability reaches its highest point of $88.26 billion by 2090. This profit maximisation pathway underscores the strategic importance of a phased rollout and well-calibrated cost management, both of which align with literature on sustainable hydrogen infrastructure economics.

4.4.2. Sensitivity analysis

The sensitivity analysis conducted for the HHSC reveals that the period between 2040 and 2060 represents the most financially vulnerable stage of the system's development. This timeframe aligns with the expansion phase, during which the supply chain experiences a rapid

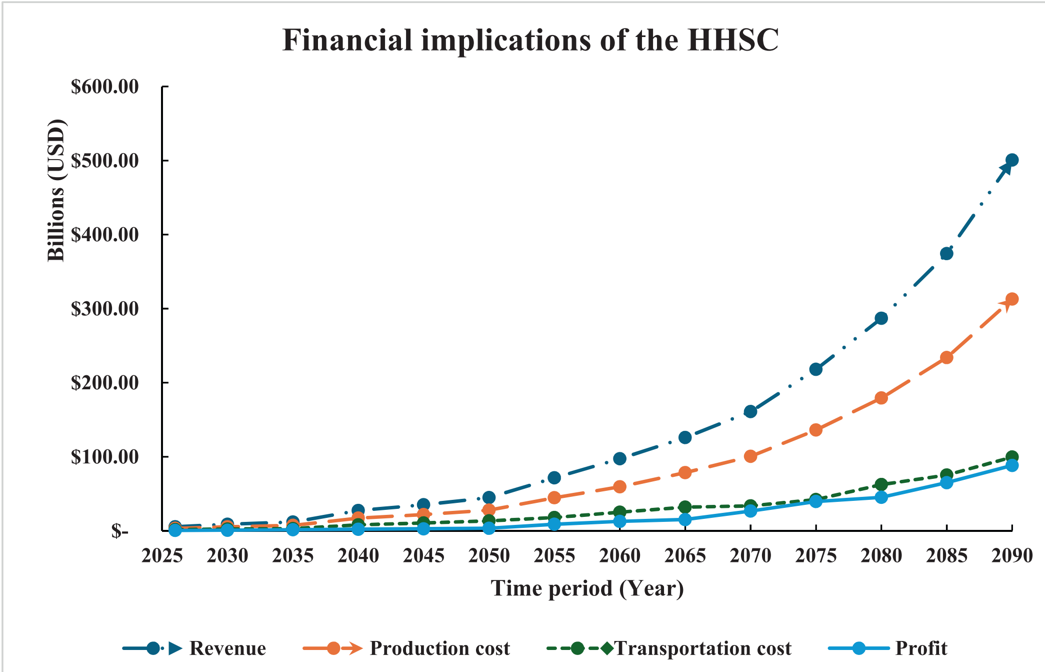

Fig. 6. Financial implications of the HHSC over time.

scale-up in infrastructure and geographic outreach. With the introduction of new RDCs in areas such as Townsville, Adelaide, and Darwin, and the commissioning of the second NDC in Bowen by 2055, the network incurs significantly increased production and transportation demands.

When transportation costs rise by 15 % to 20 %, profitability in these years declines sharply. For example, profits fall from $2.1 billion to just $464 million in 2040, and from $8.8 billion to around $5.2 billion by 2055 under the 20 % scenario (refer to Fig. 7). These reductions stem from escalating transportation costs due to network decentralisation and increased last-mile distribution complexities, supporting the findings by researchers, who emphasised the vulnerability of hydrogen infrastructure to transport cost volatility in its growth stages (Agnolucci, 2007; Galimova et al., 2023).

Similarly, rising production costs have a profound impact, especially in 2040 and earlier years when the system's revenue generation is still ramping up (refer to Fig. 8). A 20 % increase in production costs leads to operational losses in 2026 and 2030, highlighting a critical need for controlled cost structures during the early rollout phase. While the HHSC becomes increasingly adaptive to cost fluctuations in the maturation phase (post-2070), owing to improved scale efficiencies and decentralised redundancy that buffer financial volatility, the earlier years remain highly sensitive to external cost pressures.

4.5. Implications to net-zero targets

The proposed HHSC in Australia can significantly contribute to achieving net-zero emissions by enabling a clean, renewable energy alternative to fossil fuels. Hydrogen, particularly green hydrogen

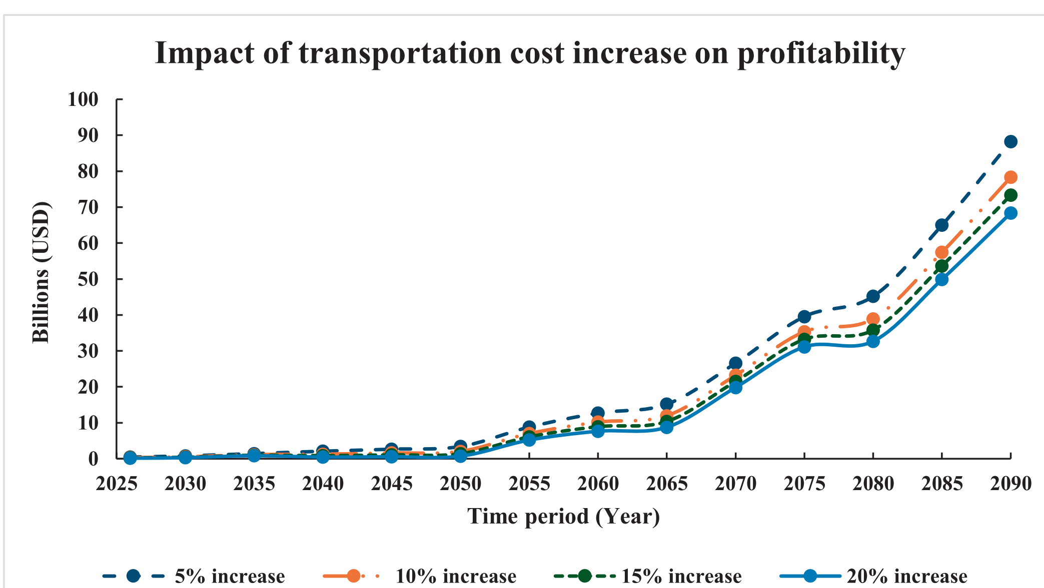

Fig. 7. Impact of transportation cost increase on profitability by 5%, 10%, 15% and 20%.

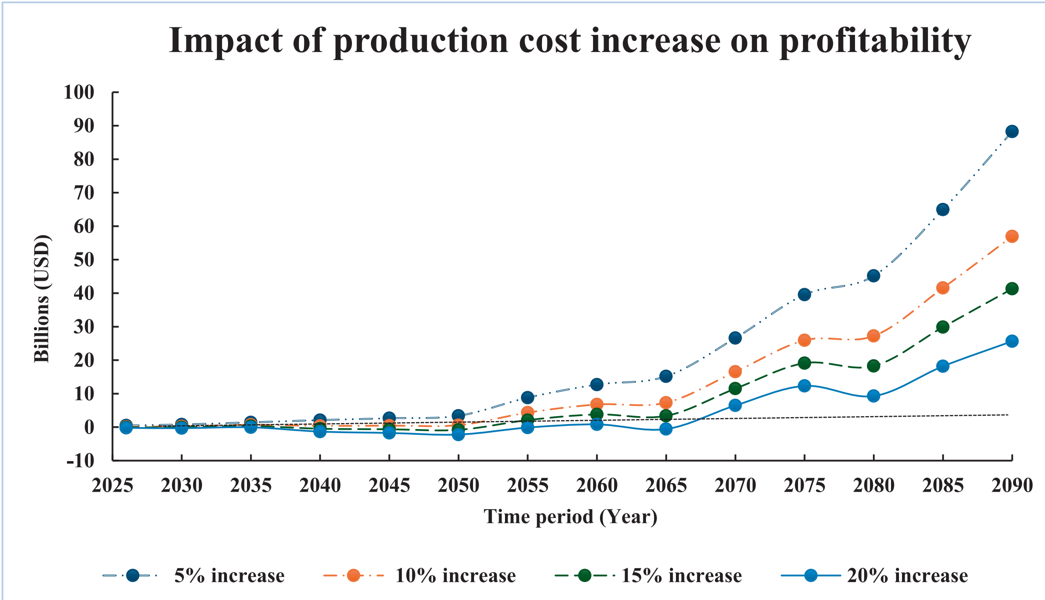

Fig. 8. Impact of production cost increase on profitability by 5%, 10%, 15% and 20%.

produced using renewable energy sources like wind and solar, emits no greenhouse gases during use, making it a critical component in reducing carbon emissions across residential sectors. By replacing NG and LPG with hydrogen for household heating, cooking, and power generation, the HHSC will help to decarbonise energy consumption at the household level. Furthermore, the development of an efficient HHSC network will reduce reliance on fossil fuel-based infrastructure. The proposed Australian HHSC will play a crucial role in transitioning to a low-carbon economy and achieving the country's 2050 net-zero targets. Its long-term viability of HHSC planning from 2026 to 2090 ensures that it will continue to evolve alongside advancements in renewable energy, making a lasting contribution to climate goals.

5. Practical implications

The development and analysis of the long-term Australian HHSC offer substantial practical and managerial implications. Strategically structured in three phases, such as foundation, expansion, and maturation in the HHSC, enables a staggered yet scalable transition away from fossil-based household fuels like LPG and NG. Each phase offers critical decision-making insights. In the foundation phase, managers and policymakers can prioritise urban corridor deployment, targeting high-density regions for early adoption, thereby reducing risk and building stakeholder confidence. The expansion phase supports broader regional integration, necessitating logistical coordination across decentralised nodes and strengthening resilience through system redundancy. The maturation phase achieves national saturation and redundancy, allowing policymakers to institutionalise long-term climate strategies aligned with the "Net Zero 2050" pathway. In addition to SDG 7 (*Affordable and Clean Energy*), the HHSC aligns with multiple Sustainable Development Goals (IEA, 2022). It directly supports SDG 9 *(Industry, Innovation, and Infrastructure)* by fostering clean energy innovation and constructing resilient hydrogen infrastructure. It contributes to SDG 11 *(Sustainable Cities and Communities)* by providing decentralised clean energy access, enhancing urban sustainability, and reducing air pollution (Vaidya & Chatterji, 2020). The transition to hydrogen also mitigates emissions, aligning with SDG 13 *(Climate Action)* through the decarbonisation of household energy use. Further, by promoting equitable access to clean energy and reducing health risks associated with indoor LPG and NG combustion, the model supports SDG 3 *(Good Health and Well-being)* and SDG 10 *(Reduced Inequalities)* (Allen et al., 2018). Altogether, the HHSC embodies an integrated sustainability framework, enabling environmental, economic, and social transformation within Australia's energy landscape (Brandon & Kurban, 2017; Hosseini & Wahid, 2016). From a managerial perspective, the HHSC model highlights the importance of infrastructure phasing, population-based demand mapping, and supply chain optimisation, allowing decision-makers to allocate capital efficiently and respond adaptively to demand surges (Akbari et al., 2022; Almansoori & Shah, 2012). By establishing strategic NDCs in Portland, Bowen, and Port Hedland, the network ensures geographic equity.

The cost sensitivity analysis reveals that an increase in transportation and production costs significantly influences profitability, especially during the infrastructure-intensive expansion phase. This insight mandates cost-containment measures, such as co-locating production with NDCs (Almaraz et al., 2022). Policymakers must also anticipate energy justice concerns, ensuring that rural and disadvantaged areas are not priced out during this transition. The phased HHSC approach provides a comprehensive planning template. It empowers managers to stage investments, adapt to regional demand while giving policymakers the tools to align energy systems with broader decarbonisation goals, international climate commitments, and socio-economic equity mandates.

6. Conclusions and future research directions

This study examined the design and planning of a long-term HHSC network in Australia, with a focus on optimising distribution centres to accommodate future energy demands and facilitate the country's sustainability transition by phasing out both NG and LPG. By modelling the supply chain from 2026 to 2090, the research highlights the crucial role that hydrogen can play in Australia's journey towards clean energy and its net-zero emissions target. The strategic location of distribution centres and the flexibility of the supply chain were central considerations. The findings suggest that optimising the long-term HHSC network could deliver substantial economic, environmental, and societal benefits, positioning hydrogen as a sustainable energy source for households and reducing reliance on fossil fuels such as NG and LPG. However, the research is not without its limitations. The study is based on several assumptions regarding future technological advancements, market adoption rates, and regulatory developments, all of which may evolve over time. Furthermore, the model does not fully account for geopolitical risks or unforeseen disruptions, such as supply shortages or shifts in energy markets, that could affect the efficiency of the HSC. Additionally, the research assumes a steady increase in hydrogen demand without fully considering potential deviations in consumer behaviour or the emergence of alternative energy technologies, which could influence the pace at which NG and LPG are phased out.

Future research could build on this study by incorporating real-time data and advanced simulation techniques to better predict the impact of unexpected events, such as supply chain disruptions, technological innovations, or policy changes. Further integration of renewable energy sources into the HSC could enhance system optimisation and help achieve cost reductions, aligning with Australia's net-zero targets. Expanding the scope to explore decentralised energy production, such as microgrids, could offer insights into localised energy supply models. Additionally, investigating policy frameworks and market incentives that promote the transition from NG and LPG to hydrogen would complement the technical optimisations presented, providing a more comprehensive approach to developing a sustainable hydrogen economy and supporting Australia's decarbonisation efforts. Finally, while this study provides a preliminary exploration of the design and planning of a long-term HHSC network in Australia, key considerations regarding the resilience of the network remain untested. This represents a valuable opportunity for research to investigate further and discuss.

CRediT authorship contribution statement

Pranto Chakrabarty: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Sanjoy Kumar Paul:** Writing – review & editing, Supervision, Conceptualization. **Andrea Trianni:** Writing – review & editing, Supervision. **Suvash C. Saha:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1:. Capacity of RDCs

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Location of RDCs	Capacity, Cubic Meter
Melbourne	5.9 bn
Perth	4.3 bn
Sydney	4.9 bn
Brisbane	3.7 bn
Adelaide	2.8 bn
Townsville	2.3 bn
Darwin	2.7 bn
Launceston	1.4bn

Appendix 2:. Capacity of NDCs

.

Locations of NDCs	Capacity, Cubic Meter
Portland, VIC	15.7 bn
Bowen, QLD	8.2 bn
Port Headland, WA	7.1 bn

Appendix 3:. Number of NDCs, RDCs, and LDCs required over the years

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Year	Total number of NDCs required	Total number of RDCs required	Total number of LDCs required
2026	1	1	26
2030	1	2	35
2035	1	2	38
2040	1	3	43
2045	1	4	47
2050	1	4	49
2055	2	5	55
2060	2	5	60
2065	2	6	67
2070	3	7	71
2075	3	7	74

(*continued on next page*)

(*continued*)

Year	Total number of NDCs required	Total number of RDCs required	Total number of LDCs required
2080	3	7	79
2085	3	8	84
2090	3	8	87

Data availability

Data will be made available on request.

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