Chapter 9

Renewable Electricity and Energy Transition in Lao PDR: Opportunities for Green Hydrogen and Ammonia

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1. Introduction

The global impetus towards a low-carbon economy has led to the emergence of decarbonised or renewable hydrogen and ammonia as crucial energy carriers that can support the transition of Lao People's Democratic Republic (Lao PDR) towards a net-zero emissions status and sustainable energy system. Redirecting surplus renewable hydropower electricity to decarbonised hydrogen and ammonia production represents a significant but under-evaluated opportunity to diversify Lao PDR's economy across multiple sectors, contribute to sustainable development objectives, and reduce emissions.

Ultimately, the existing and planned hydropower fleet places Lao PDR in a unique position to rapidly adopt renewable hydrogen and ammonia as a new and dynamic industry geared to emerging global trends in decarbonised energy systems and transitions. Redirecting surplus hydroelectricity presents Lao PDR with an opportunity to position itself as an early adopter and regional leader in the hydrogen-ammonia energy system.

The internationally accepted principle to differentiate decarbonised hydrogen and ammonia from fossil fuel derivatives – and the definition used throughout – is the singular reliance on renewable electricity for the entire production, storage, and distribution processes of hydrogen and ammonia. Decarbonised hydrogen and ammonia produce less than 1 kilogram (kg) of carbon dioxide equivalent (CO_2e) per kg of hydrogen. Fossil fuel-based processes produce approximately 10 kg CO_2e/kg of hydrogen.

To capitalise on this opportunities, in 2023, the Government of Lao PDR prioritised developing an integrated and comprehensive national roadmap, strategy, and action plan as a critical first step towards developing a green hydrogen and ammonia industry. Indeed, establishing a robust and integrated planning process is critical to allow policymakers to ensure that sustainable economic and social benefits are shared, while improving community livelihoods and maintaining the integrity of the environment. The strategy will set out the vision and actions to develop a decarbonised hydrogen and ammonia industry in Lao PDR, making important contributions to the renewable energy transition goals set out in the *9th Five-Year National Socio-Economic Development Plan, 2021–2025* (MPI, 2020).

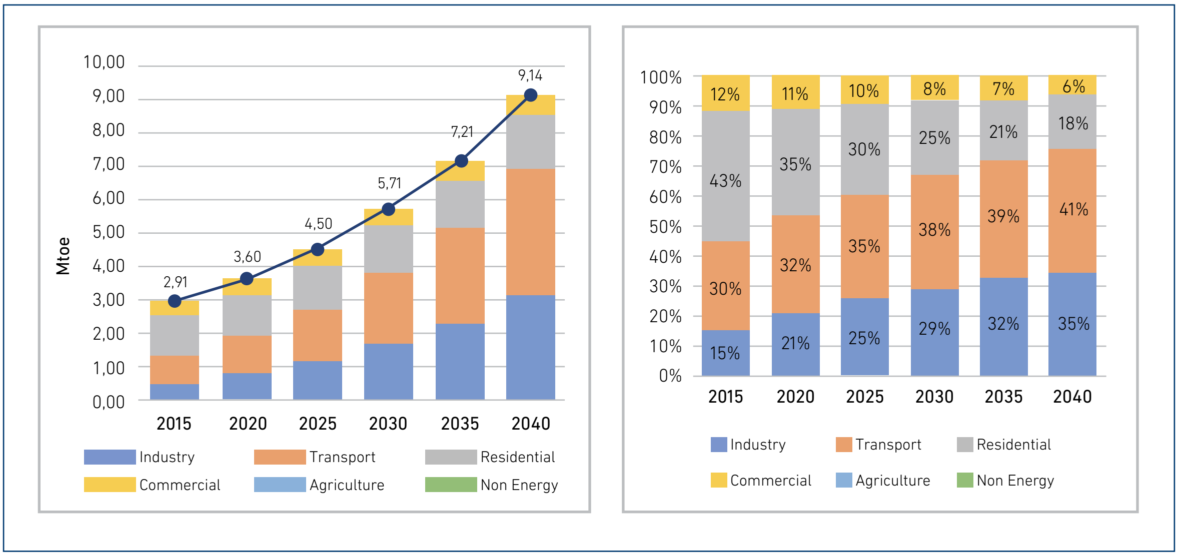
Hydrogen and ammonia are strategically important for countries like Lao PDR that are heavily dependent on the importation of liquid fossil fuels and fossil fuel derivatives, including fertilizers and chemical feedstocks. In transitioning from an emerging technology to viable commercial assets, the policy imperatives woven into hydrogen and ammonia development must focus on integrated decision-making; flexible governance; skills and capabilities; market activation; concession agreements; safety and risk management; and the importance of research, development, and innovation investment.

2. Energy Sources in Lao PDR

Consistent with Lao PDR's riparian neighbours, the majority of energy evaluations, modelling, and analysis – expressed as statutory policy and planning architecture – are concerned with electricity generation, demand, and consumption. A review of the *9th Five-Year National Socio-Economic Development Plan, 2021–2025* and the energy and renewable energy plans reveals a nearly singular focus on electricity (Government of Lao PDR, 2011; MEM, 2021). Other energy sources have received limited attention in energy planning, despite biomass, oil, gas, and petroleum derivatives making up the majority of total energy consumption in Lao PDR (MEM and ERIA, 2020; Kimura, Phoumin, Purwanto, 2023).

Comprehensive and integrated energy planning and policy demand more than a singular focus on electricity. Global energy outlook assessments have addressed this oversight. Electricity represents 20% of the 2021 global total final energy consumption compared to liquid and gaseous fossil fuels, as oil comprises 40% of total final energy consumption and natural gas, 16% (IEA, 2021, 2022).[1] Petroleum imports and derivatives represented 30% of Lao PDR's total energy consumption in 2015 and are estimated to become 37% in 2025, more than twice the proportion of electricity at 13% in 2015 and 20% in 2025 (Figure 9.1). Imported oil, used primarily for road transport and due to the increased demand for passenger vehicles, is estimated to increase to 44% in 2040.

Figure 9.1. Total Lao PDR Final Energy Consumption by Sector, 2015–2040



Mtoe = million tonnes of oil equivalent.

Source: MEM and ERIA, 2020.

[1] IEA, Share of World Final Energy Consumption by Source 2019, https://www.iea.org/data-and-statistics/charts/share-of-world-total-final-consumption-by-source-2019 [accessed March 2023]

2.1. Electricity Generation in Lao PDR

Lao PDR has an estimated 24,000 megawatts (MW)–26,000 MW[2] of potential hydropower capacity of which 18,000 MW are technically exploitable (MEM, 2021; IHA, 2021). In 2023, Lao PDR had an overall installed power generation capacity of 11,652 MW with actual production estimated to be approximately 57,000 gigawatt-hours (GWh) (Bounpha, 2023). About 83% (9,658 MW and 45,050 GWh) was from hydropower, 16% (1,878 MW and 12,200 GWh) from the Hongsa coal-fired power plant, with the remaining from solar (56 MW and 95 GWh) and biomass (43 MW and 228 GWh).

The government continues to rely on the electricity sector as a major driver of growth and development and a source of increased revenue through exports to neighbouring countries. The electricity sector nearly tripled its share of the economy over the past decade, accounting for 21% of exports in 2021 and 25% in 2022,[3] substantial increases compared to 5% in 2010 (BOL, 2021). Electricity led the export sector and power generation in 2021 with 9.7% of real gross domestic product as well (BOL, 2021). Electricity exports are expected to more than triple by 2030 (Bounpha, 2023).

Based on recent memoranda of understanding with neighbouring countries, Lao PDR aims to dedicate 18,000 MW of installed capacity to export by 2030, an increase of about 300% from present export levels. Exports comprise commitments of 10,500 MW of electricity to Thailand[4] and 5,000 MW to Viet Nam (of which less than 1,000 MW has been utilised so far) (MEM, 2021). New agreements with Cambodia will see 6,000 MW exported mostly from the Don Sahong Dam on the Mekong River and two proposed coal-fired plants in southern Lao PDR.[5] Generation from the Monsoon Wind Power Project of 600 MW is destined for Viet Nam. Malaysia has also expanded its agreement to purchase 300 MW of electricity from 100 MW via the Thailand grid, and there are also plans to sell up to 600 MW to Myanmar and 100 MW to Singapore.

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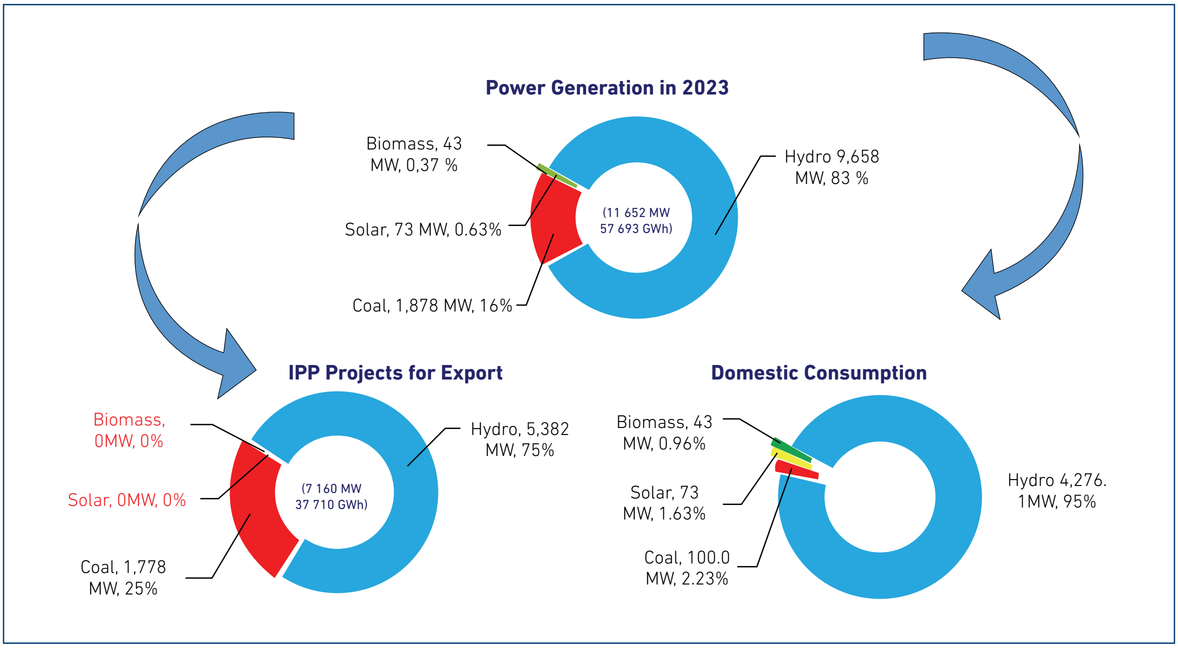
2 The International Hydropower Association assumes that the more exploitable and profitable projects are usually developed first, with subsequent projects costing more and having less projected production efficiencies (IHA, 2021).

3 Electricity contributed 21.2% to export revenues in 2021 and 25.0% in 2022. See OEC, Laos, https://oec.world/en/profile/country/lao [accessed 1 June 2024]

4 About 6,000 MW was exported to Thailand in 2020.

5 At the time of this writing, discussions with Ministry of Energy and Mines officials indicate that the two coal-fired plants may not proceed due to uncertainties around the kilocalorie content of local lignite and the rising costs of Indonesian imports.

Figure 9.2. Lao PDR Electricity Generation by Source, 2023



GWh = gigawatt-hour, IPP = independent power producer, MW = megawatt.

Source: Bounpha (2023).

In Lao PDR, total domestic electricity demand in 2023 was 11,583 GWh, which is expected to increase to 13,700 GWh in 2024 (Kyophilavong, 2024). Industry consumption was the largest user (39%), followed by cryptocurrency production (24%), and the residential (22%) and commercial/government (13%) sectors.

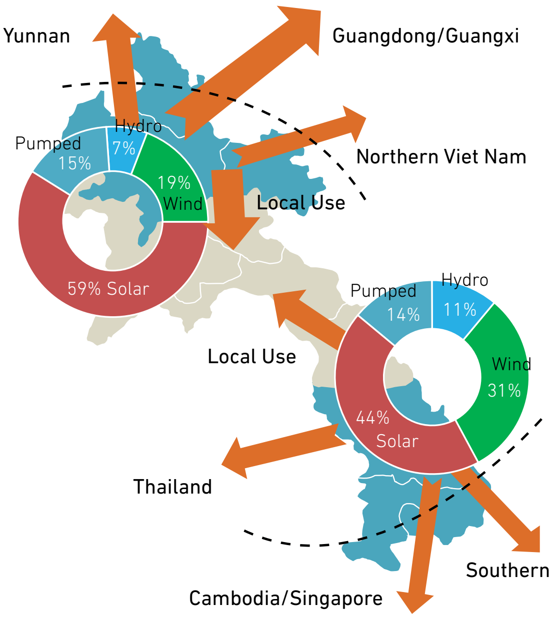
The proposed development of future renewable electricity in Lao PDR is illustrated in Figure 9.3. Hydropower generation is planned to rise from 9.6 gigawatts (GW) to 28.0 GW – a 290% increase – assuming all planned, under construction, and memoranda of understanding developments are realised. Solar will increase by 15.6 GW and wind by 13.7 GW. Currently, only projects under development can proceed, and over 300 projects are categorised as 'to be developed after 2030' (The Asia Foundation, 2021). The total renewable energy generation planned by 2030 is 5.7 GW, excluding the 1.0 GW of planned coal generation (Phongsavath, 2024).

Figure 9.3. Renewable Electricity Development Plan

Hydropower	No	MW
Existing	81	9615.14
Under-Construction	21	1259.3
CA	18	2466.2
PDA	109	6431.95
MOU	245	8143.43
Total	**474**	**27916.02**

Solar	No	MW
Existing	8	56
Under-Construction	0	0
CA	4	2688
PDA	13	873
MOU	25	12147
Total	**50**	**15672**

Wind	No	MW
Existing	0	0
Under-Construction	0	0
CA	1	600
PDA	1	187.2
MOU	17	13.000
Total	**19**	**13.787**



CA = concession agreement, MW = megawatt, MOU = memorandum of understanding, PDA = project development agreement.
Source: Bounpha (2023).

Estimates of domestic electricity demand across scenarios –which include industry expansion and more electric vehicles – range from 2.1 GW to 2.6 GW in 2024 and 2.9 GW to 3.8 GW in 2030 (MEM, 2021). An estimated surplus of approximately 2.0 GW to 2.5 GW is therefore available from the 4.5 GW assigned to meet domestic demand.

Redeploying seasonal renewable electricity that is surplus to domestic demand to decarbonised hydrogen and ammonia production is a central pillar of the rapid development of the industry in Lao PDR. Seasonal generation refers to total generation during the wet season months of typically May through October and dry season generation during the remainder of the calendar year. Surplus generation refers to additional supply in excess of domestic electricity demand and export obligations. Redeployment of existing surplus renewable electricity helps Lao PDR avoid the capital expenditures of renewable electricity infrastructure and confers a significant advantage in developing a national hydrogen-ammonia industry. This advantage translates as reduced construction times and up to a 60% reduction in capital expenditure and investment (IRENA, 2022; Hosseini et al., 2023).

3. Hydrogen and Ammonia Production Chain

Flagship reports by The Royal Society, International Energy Agency, Commonwealth Scientific and Industrial Research Organization (CSIRO), and International Renewable Energy Agency identify hydrogen and ammonia (and their derivatives) as having a significant role in meeting global climate change objectives and national net-zero emissions goals.[6]

Hydrogen, as a component of ammonia, can be produced by the gasification of coal or biomass, steam reforming of methane, water electrolysis, or methane pyrolysis, with each pathway characterised by high levels of energy intensity and a process dependent on levels of technical and commercial maturity. Over 95% of global hydrogen is produced by steam methane reforming, associated with 9.3 kg of CO_2e for every 1 kg of hydrogen produced.[7] In 2022, hydrogen production resulted in more than 900 million tonnes of emissions – only 2% of total global emissions.

General convention designates hydrogen produced via methane reforming without carbon capture and storage (CCS) as grey hydrogen, as blue hydrogen when CCS is included in the production process, and as green hydrogen when only renewable electricity is deployed to produce electrolytic hydrogen. These qualitative classifications are also applied to ammonia (Figure 9.4). Grey hydrogen accounts for 96% of global production, responsible for 10 kg of CO_2e for every 1 kg of hydrogen, CCS reduces this to 1–3 kg of CO_2e/kg of hydrogen in blue hydrogen production, and less than 1 kg of CO_2e/kg of hydrogen for green hydrogen.

[6] See reviews by IEA (2021), The Royal Society (2018), IRENA (2021), and CSIRO, HyResource, https://research.csiro.au/hyresource/

[7] Not including the carbon footprint of compression and transport.

Figure 9.4. Classification of Hydrogen Production According to Carbon Intensity

Color	Primary Feedstock	Primary energy Source	Primary Production Process	Carbon Intensity $kgCO_{2}e/kgH_{2}$
Brown	Coal or Lignite	Chemical Energy in Feedstock	Gasification & Reformation	
Gray	Natural Gas	Chemical Energy in Feedstock	Gasification & Reformation	
Blue	Coal, Lignite, or Natural Gas	Chemical Energy in Feedstock	Gasification with Carbon Capture and Sequestration	
Pink	Water	Nuclear Power	Electrolysis	
Green	Water	Renewable Electricity	Electrolysis	
	Biomass or Biogas	Chemical Energy in Feedstock	Gasification, Reformation, & Thermal Conversion	

kg = kilogramme.

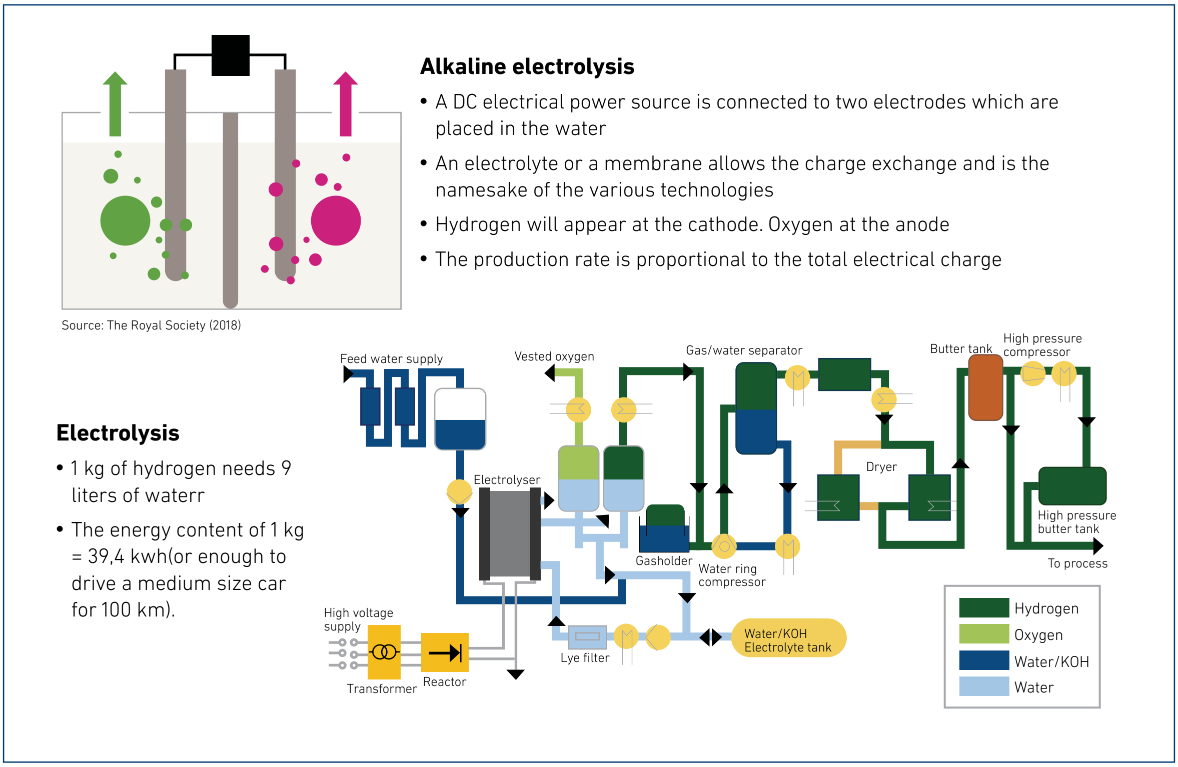
Source: Connell et al. (2022).

3.1. Hydrogen Production

Electrolytic hydrogen production, also known as electrolysis, splits water into hydrogen and oxygen using electricity in an electrolysis cell (Figure 9.5). The electrolysis produces pure hydrogen, which is ideal for low-temperature fuel cells (e.g. in electric vehicles currently in production by BMW, Hyundai, and Toyota).

There are four main electrolyser technologies: alkaline, proton exchange membrane (PEM), anion exchange membrane (AEM), and solid oxide electrolyser cell (SOEC). The most mature electrolysis technology is the alkaline electrolyser, which has been in commercial use since the mid-20th century. An alkaline electrolyser uses a cell with a cathode, anode, and electrolyte based on a solution of caustic salts (e.g. sodium hydroxide). Alkaline technology has a relatively low capital cost compared to other types of electrolysers. Other advantages include virtually instant operation and resistance to humidity and salt air. Alkaline fuel cells are mostly used in backup generators or long-duration uninterruptible power supplies as well as for powering telecommunications towers.

Figure 9.5. Production of Hydrogen and Oxygen via Alkaline Electrolysis

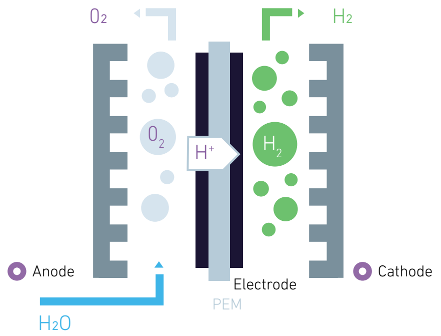


kg = kilogram, km = kilometre, kWh = kilowatt-hour.

Source: The Royal Society (2018) and IRENA (2021a).

PEM electrolysers utilise an ionically conductive solid polymer rather than a liquid to drive hydrogen production (Figure 9.6). PEM electrolysers can react quickly to the fluctuations in power generation typical of renewable power and produce higher-purity hydrogen gas. PEM electrolysers can be used for renewable power-to-gas applications.

Figure 9.6. PEM Electrolyser for Green Hydrogen Production



- Electrodes are attached on both sides of the proton exchange membrane
- The proton exchange membrane is the electrolyte
- The proton exchange membrane acts as separator to prevent mixing of hydrogen and oxygen gases

- High power density
- Well suited to intermittent renewable electricity supply
- Extended dynamic range and direct connection to PV and wind renewables as well as hydropower
- High efficiency
- High purity of gases
- Relatively low maintenance

PEM = proton exchange membrane.

Source: Connell et al. (2022).

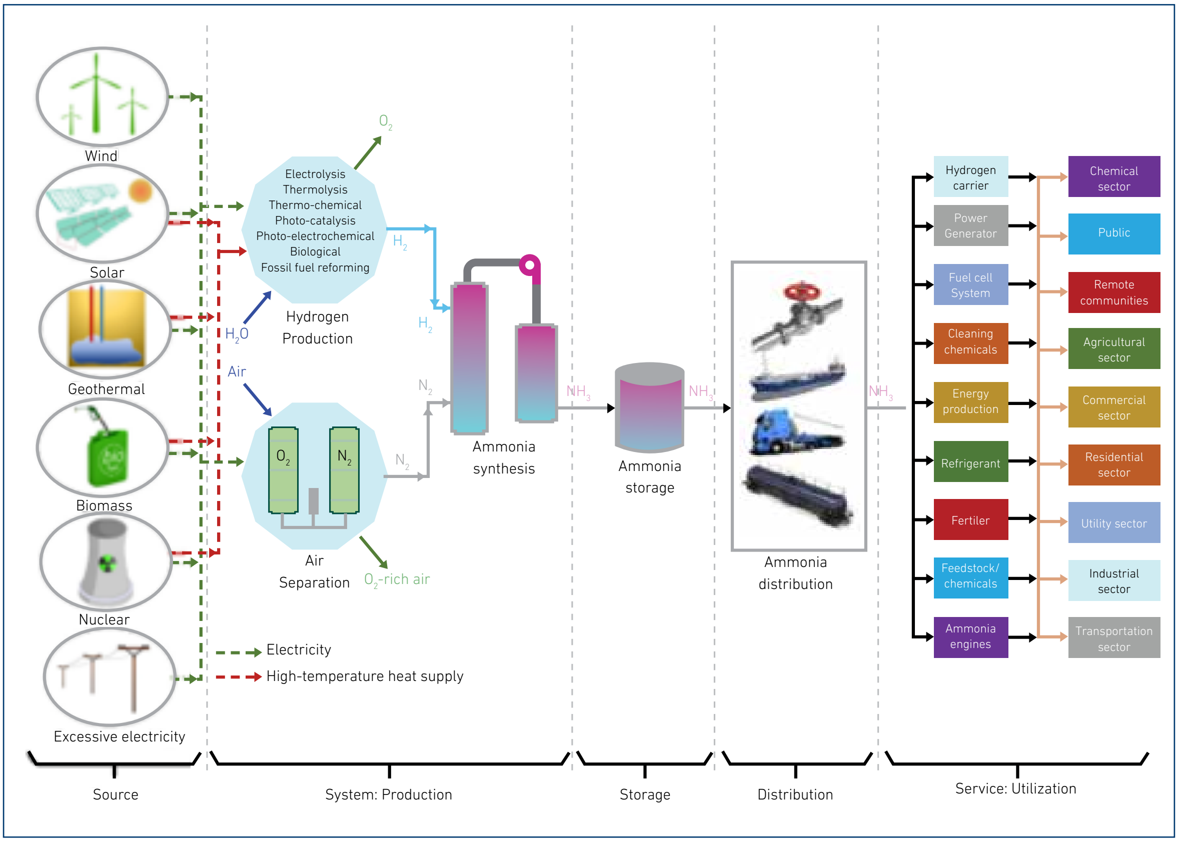
High-temperature SOEC utilises ceramic membranes that conduct ions at very high temperatures and pressures to separate superheated steam into oxygen and hydrogen. The efficiency offered by a SOEC electrolyser is much higher than other technologies, but this technology is in an early commercialisation stage.

Increasing the size of an alkaline electrolyser facility has the largest cost reduction effect; however, facility size is also a function of the intended application. Smaller units are best aligned to residential, agricultural, or transport use where higher investment costs can be offset by onsite reductions in transport costs. Alkaline electrolyser investment costs vary according to plant size – US$1,000 per kilowatt (kW) as a median estimate for a 1-MW unit, US$620/kW for a 10-MW unit, and US$450/kW for a 100-MW unit (Böhm et al., 2020; IRENA, 2021). PEM electrolysers range from US$700 to US$1,400/kW.

3.2. Ammonia Production

Ammonia is an essential global commodity. Around 85% of all ammonia is used to produce synthetic nitrogen fertilizer, and the balance is deployed in a wide range of other applications such as refrigeration, mining, pharmaceuticals, water treatment, plastics and fibres, and abatement of nitrogen oxides (Figure 9.7). The relatively inefficient application of nitrogen-based fertilizers (i.e. approximately 14% reaches plant roots) has a substantial impact on global nitrogen, potential eutrophication of waterways, and biodiversity (IRENA, 2022). Ammonia is also a highly efficient and relatively safe hydrogen carrier (Giddey et al., 2017; The Royal Society, 2020).

Figure 9.7. Economic Cycle of Ammonia from Production to Utilisation



Source: Erdemir and Dincer (2021).

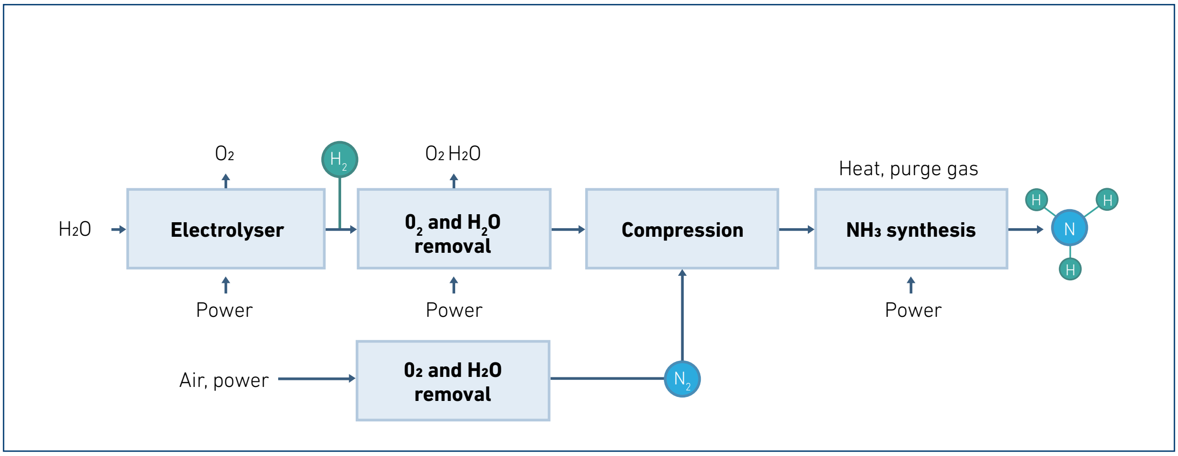
Global production of up to 176 million tonnes of ammonia per year only accounts for around 2% of overall global emissions (The Royal Society, 2020). However, to meet net-zero emissions targets, an urgent plan to decarbonise ammonia production needs to be developed and implemented, which in turn would open opportunities for ammonia to replace fossil fuels in other applications.

The electrolysis of water to produce hydrogen offers a pathway to zero-carbon ammonia production but relies on low-cost renewable electricity and continuing reductions in electrolyser costs. Renewable energy electricity costs are already close to a tipping point for the cost-competitive production of zero-carbon ammonia (IRENA, 2022). An ammonia market would strengthen the economic opportunities to extend renewable energy penetration into Lao PDR.[8]

[8] Developing and enforcing a safety regulatory framework to include the production, storage, and distribution of ammonia is key as identified by decision-makers (Ward and Smajgl, 2023). International standards have been developed over the 100 years of ammonia production and can be readily adapted for Lao PDR ammonia production.

To produce renewable ammonia, water is split into hydrogen and oxygen via electrolysis using a renewable electricity source. Various electrolysis technologies can be used, which vary in temperature and energy consumption (The Royal Society, 2020; IRENA, 2021, 2022).[9] Nitrogen is purified from the air using an air separation unit. Hydrogen plus nitrogen are converted to ammonia in a Haber-Bosch synthesis loop (Figure 9.8).

Figure 9.8. Ammonia Synthesis Using Water, Air, and Renewable Electricity



Source: Rouwenhorst, Travis, Lefferts (2022).

The Haber-Bosch process requires high temperatures (400°C–500°C), high pressure (100 bar–200 bar), and purified nitrogen and hydrogen. The high plant costs associated with these high temperatures and pressures and reliance on fossil fuels (i.e. natural gas) translate as industrial-scale operations producing thousands of tonnes per day and generally accepted production boundaries of ammonia.

Developing new small-scale plant designs that couple electrolysis with ammonia production are also under development, including smaller-scale Haber-Bosch units (The Royal Society, 2020; Suryanto et al., 2021). The opportunity to combine smaller-scale ammonia production with remote renewable generation is attractive if lower capital costs can be realised. To enable ammonia to be produced at this scale, adaptation must operate at a sub-MW scale. The downscaling of the Haber-Bosch process (i.e. 30 kW–500 kW) presents intermittency challenges for solar and wind sources, but not for hydropower.

For small renewable ammonia plants, capital expenditure is critical. The operational cost is not as important as for larger plants, as reflected in the process design that minimises equipment and applies standardised plant components and design modules where possible to decrease construction work, time on site, and cost-effective expansion.

[9] See CSIRO, HyResource, https://research.csiro.au/hyresource/ for more information.

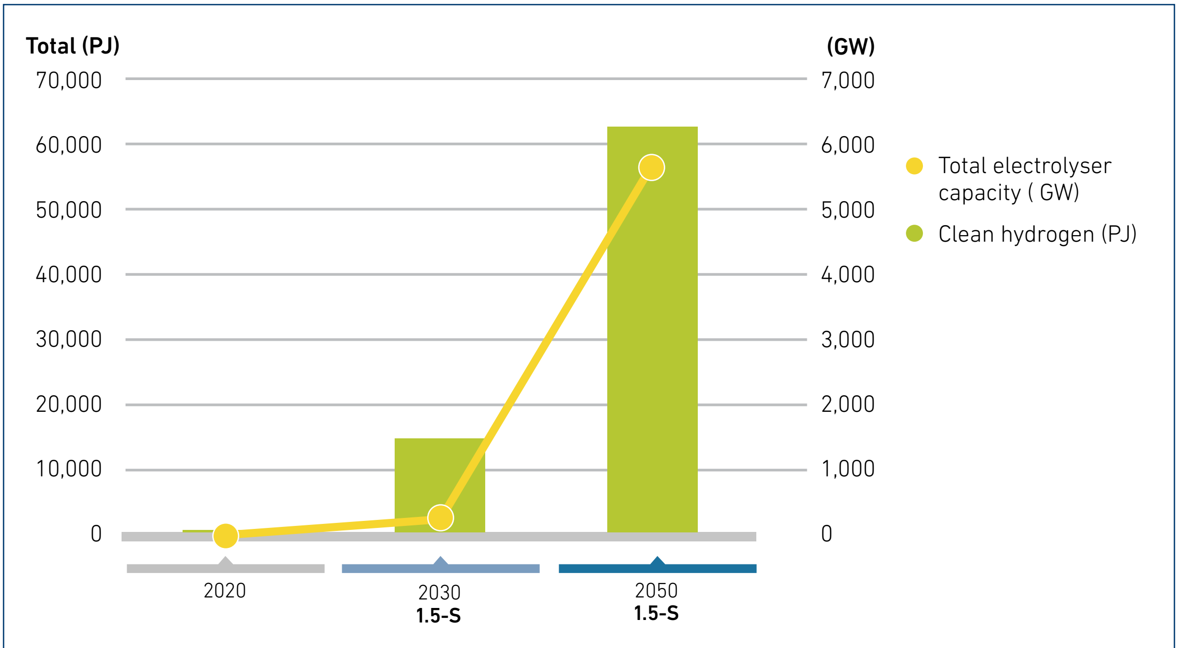
Hydrogen produced from renewable electricity-based water electrolysis is the basis of both large- and small-scale ammonia production. Alternative ammonia catalytic reactors to the Haber-Bosch process are being rapidly developed and tested and may play a substantial role in future ammonia production in Lao PDR (MacFarlane et al., 2020; The Royal Society, 2020; Chehade and Dincer, 2021; Suryanto et al., 2021).

4. Hydrogen Outlook

In 2022, approximately 95 million tonnes of predominately natural gas-based grey hydrogen were produced globally. Grey hydrogen is produced through steam reforming during the methane production process. It is primarily used in industrial applications such as crude oil refining, ammonia production, and methanol synthesis, which collectively account for nearly 93% of total hydrogen consumption (IEA, 2023).

Green hydrogen is expected to play a significant role in the energy transition towards the 1.5°C climate goal by 2050 (IRENA, 2023; UNIDO, IRENA, IDOS, 2024). Indeed, a substantial increase in global green hydrogen production is predicted, reaching approximately 492.0 million tonnes by 2050. Residual blue hydrogen production will total around 31.5 million tonnes (IRENA, 2023).

Figure 9.9. Global Green Hydrogen Supply in 2020, 202.3 and 2050 under a 1.5 °C Scenario



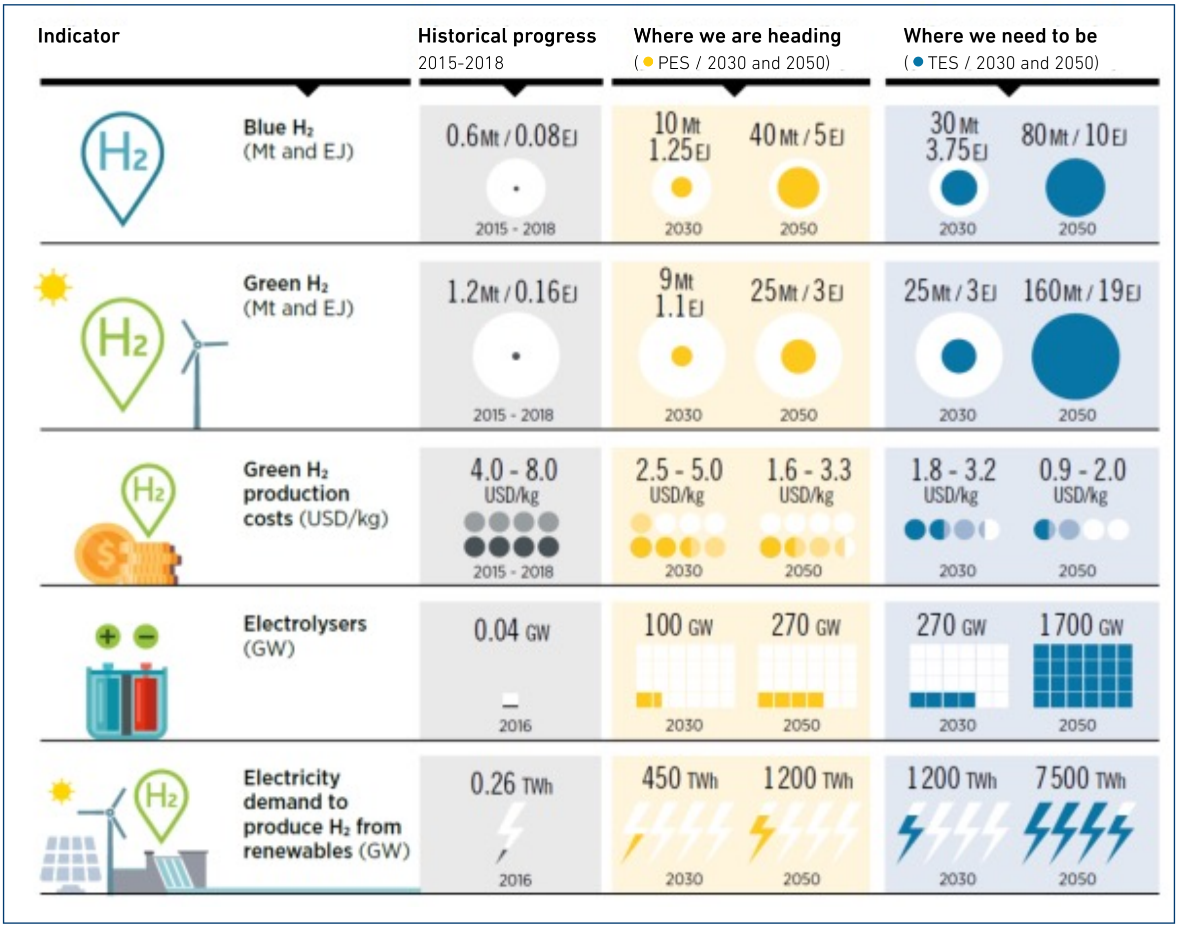
GW = gigawatt, PJ = petajoule.

Source: Ruf and Weichenhain (2024).

Figure 9.9 estimates that the capacity of green hydrogen projects will grow to 119 GW by 2030, less than half of the 260 GW that governments have committed to globally and only around one-fifth of the 590 GW required to achieve the 1.5°C target (Ruf and Weichenhain, 2023). For this reason, experts consider the 2030s a critical decade for the hydrogen industry, including that of Lao PDR. About 2,400 GW of installed electrolyser capacity is also forecasted by 2040 (Ruf and Weichenhain, 2023).

The relative capacities for green hydrogen production (especially for hard-to-electrify solutions) across three emissions scenarios were also estimated – a baseline of 43.0 gigatonnes (Gt) in 2025, a planned energy scenario (PES) with an emissions target of 33.0 Gt in 2050, and a targeted energy scenario (TES) with an emissions target of 9.5 Gt in 2050 (IRENA, 2023). In the TES, green hydrogen production costs would decrease to US$0.90–US$2.00/kg of hydrogen, and electrolyser capacity would increase to 1,700 GW requiring 7.5 petawatt-hours of renewable electricity (Figure 9.10). Total emissions abatement from green hydrogen production is estimated at 80 Gt by 2050 (Hydrogen Council and McKinsey & Co., 2022).

Figure 9.10. Historical Progress and Targets for Hydrogen Production



EJ = exajoule, GW = gigawatt, kg = kilogram, Mt = million tonnes, PES = planned energy scenario, TES = targeted energy scenario, TWh = terawatt-hour.

Source: IRENA (2023).

Green hydrogen can be produced at competitive costs with blue hydrogen in the best-case scenario, where low-cost renewable electricity is around US$20/megawatt-hour (MWh) coupled with trading in high-value carbon offsets (IRENA, 2021). Indeed, trading in carbon offsets from green hydrogen and ammonia will be a crucial source of revenue for Lao PDR. Capital expenditure reductions of up to 60% can be achieved, depending on a combination of electrolyser costs, manufacturing scale, technological improvements, and increased stack module size and deployment levels.

The costs for alternate production pathways for hydrogen were compared against a benchmark target of US$2.00/kg of hydrogen. Depending on electricity costs, capital expenditures, and the capacity factor (i.e. approximately 60%–70% in the case of Lao PDR seasonal hydropower surpluses), Lao PDR can potentially produce hydrogen at an estimated median price of US$1.86/kg (Baldwin et al., 2021).

4.1. Outlook for Developing Countries

The hydrogen and ammonia economy is a major opportunity for sustainable development and shared prosperity amongst low-income and developing countries (Gielen, Lathwal, Lopez Rocha, 2024; UNIDO, IRENA, IDOS, 2024). To date, there are five green hydrogen projects outside of China of more than 10 MW and three in the final investment decision phase that will be operational by 2030 (i.e. Neom in Saudi Arabia and proposed green ammonia plants in Ba Tri, Viet Nam and India).

The world's energy transition requires a global roll-out of green hydrogen production to obtain the necessary volumes by 2030. Organisation for Economic Co-operation and Development (OECD) countries alone do not have the renewable resources necessary to sustain a global renewable hydrogen industry. About 25%–30% of all clean hydrogen will be traded internationally, mainly in the form of hydrogen derivatives; by 2050, developing countries will account for 35% of that trade (Hydrogen Council and McKinsey & Co., 2022). Therefore, active support in developing countries is crucial to accelerate hydrogen production.

For Lao PDR, it is important to remember the following.

(i) **Green hydrogen projects are capital-intensive**. They are comparable to hydropower and large mining projects, where typically large private sector institutions have been able to assume risk.

(ii) **Utilising the existing surplus from Lao PDR hydropower fleet avoids capital expenditure of new renewable energy**. Renewable energy represents up to 66% of total project capital expenditures, and the remaining investment is related to domestic manufacturing and installation. Electrolyser investments follow a similar pattern; stacks, gas-processing equipment, and inverters are likely to be purchased overseas, and local value-added to the economy may be limited.

(iii) **Demand certainty in terms of volume and price remains as important as perceived risk**. Government mechanisms to mitigate risks related to users are being developed by OECD countries but not in developing countries, compromising reliable social and economic impact analysis from hydrogen and ammonia production.

(iv) **Green hydrogen projects create many jobs during the initial construction phases of the project but are limited in the later stages**. Initial assessments suggest that job creation during the operation stage is less than one-tenth of the early years during project construction.

Lao PDR is well placed to address the first two points, as it has a long history of successful large-scale hydropower plants characterised by multi-billion-dollar capital expenditures. Lao PDR can avoid the infrastructure costs and demands of new renewable electricity at least in the formative years of green hydrogen and ammonia production development. Initial Lao PDR demand for green hydrogen and ammonia is focussed on domestic use, primarily green ammonia fertilizer to replace imports, stabilise supply, add value to renewable electricity, and minimise global price volatility. Predictable domestic demand enables reliable social and economic analysis, addressing the last two points. Export opportunities are more likely to be realised during 2030–2040.

4.2. Green Ammonia Outlook

Ammonia production accounted for around 45%–50% of global hydrogen consumption or around 33 million tonnes of hydrogen in 2020. Replacing conventional ammonia with renewable ammonia produced from renewable hydrogen presents an early opportunity for action in decarbonising the chemical, energy, transport, maritime, and refining sectors. Ammonia is also proposed as one of the most cost-effective hydrogen carriers for long-range transport (MacFarlane et al., 2020; Erdemir and Dincer, 2021).

By 2050, in a scenario aligned with the Paris Agreement goal of keeping global temperature rise within 1.5°C, this transition would lead to a 688-million-tonne green ammonia market, nearly four times larger than in 2022 when 566 million tonnes of ammonia were estimated to have been decarbonised, produced from renewable hydrogen and renewable electricity (IRENA, 2022).

A global manufacturing and distribution system is in place, with over 100 years of infrastructure development and operation. While the safe transport and use of ammonia are well-established, new applications will require careful risk assessment. Additional control measures are required to reduce risks to health and the environment (The Royal Society, 2018, 2020; IRENA and ACE, 2022). Moreover, the rate at which renewable ammonia plants are being announced is correlated with the speed at which the cost of renewable electricity is decreasing. As of 2022, renewable ammonia production costs for new plants are estimated to be US$720–US$1,400/tonne, falling to US$310–US$610/tonne by 2050 (IRENA, 2022).

There are five major issues to be considered when evaluating the route towards ammonia production: capital expenditures, availability and cost of renewably sourced electric power, restrictions and cost of ammonia transport, restrictions of emissions to meet national and global targets, and carbon-related taxes and offsets (Chehade and Dincer, 2021).

Green ammonia production will cost US$450–US$500/tonne in Lao PDR by 2030 and can be competitive with non-renewable ammonia relatively quickly. Applying a carbon-trading price of US$50/tonnes (t) of CO_2e, offsetting the 2.6 tCO_2e/tonne of ammonia associated with grey ammonia would bridge the price gap between renewable and grey ammonia (IRENA, 2022). Significant funding and financial resources, directed at developing countries, are required to meet the 10%–15% green hydrogen targets set for 2050 (Lopez Rocha, Gielen, de Calonje, 2024).

Six sub-categories of risks, that if mitigated, would enable developing countries (including Lao PDR) access to finance are: (i) existing buyers, (ii) political and regulatory, (iii) infrastructure, (iv) technology, (v) permitting and compliance, and (vi) macroeconomic (ESMAP et al., 2023). De-risking instruments such as concessional credit lines and carbon offset pricing can be supplemented by well-established Multilateral Investment Guarantee Agency (MIGA) mechanisms focussed on tackling macroeconomic and political risks as well as equity and debt financing from the International Finance Corporation (IFC) and risk mitigation instruments issued by MIGA.

5. South-East Asia Hydrogen and Ammonia Initiatives

In 2020, hydrogen had not formally entered the policy agenda as an alternative fuel (ERIA, 2019). By 2024, Malaysia and Viet Nam had developed hydrogen roadmaps, indicating the rapid change and importance of hydrogen production and use in the region. In addition, in February 2024, Viet Nam approved *Vietnam's Hydrogen Energy Development Strategy to 2030 and Vision to 2050* (MOIT, 2024), which sets out a range of development targets for the hydrogen industry. The strategy details production of hydrogen from renewable energy utilisation and other processes with carbon capture to reach around 100,000–500,000 tonnes/year by 2030 and around 10 million–20 million tonnes/year by 2050. Similarly, Malaysia's Ministry of Science, Technology and Innovation published the Hydrogen Economy and Technology Roadmap, setting out the country's strategies and action plan for hydrogen production, including green hydrogen (MOSTI, 2023).

The *Association of Southeast Asian Nations (ASEAN) Plan of Action for Energy Cooperation Phase II (2021–2025)* (ACE, 2020), which was endorsed at the 38th ASEAN Ministers on Energy Meeting in November 2020, provides policy measures to address emerging and alternative technologies, such as hydrogen storage and entry, into the national energy mix to accelerate the region's energy transition and to strengthen energy resilience through innovation and cooperation.

In a 1.5°C-targeted energy scenario for green hydrogen, demand is expected to grow significantly to 1.5 exajoules or 11 million tonnes by 2050 (IRENA and ACE, 2021). The majority of demand would come from Indonesia, Malaysia, Thailand, and Viet Nam, where there will be a stronger base for hydrogen production. The expectation is that two-thirds of the hydrogen demand will be for green hydrogen from 2030 onwards. The ASEAN region has the technical potential to become a hydrogen hub. A proportion of low-cost green hydrogen (i.e. less than US$2/kg) can be produced in the region (IRENA, 2022).

In Phase III of the ASEAN Centre for Energy green hydrogen trajectory, the expected decreases in capital expenditures for hydrogen production and transport, levelised cost of renewables over the coming decade, and formation of overseas hydrogen energy markets would make green hydrogen competitive compared to fossil fuels (ACE, 2021). Surplus hydropower electricity redeployed to green hydrogen and ammonia production would allow Lao PDR to meet Phase III ACE criteria and have the potential to be at the vanguard of the ASEAN hydrogen and ammonia economy.

5.1. Potential of Green Hydrogen and Ammonia in Lao PDR

Participatory system mapping (PSM) is a practice-oriented network/system analysis tool developed to investigate cross-sectoral energy planning and natural resources governance (Barbook-Johnson and Penn, 2022; Smajgl and Ward, 2013). PSM is a structured tool that can assist key decision-makers in understanding, discussing, and improving complex multi-faceted energy transitions in which multiple, diverse actors either influence green hydrogen and ammonia energy transition outcomes or are affected by those energy decisions (Ward and Smajgl, 2023).

Through a series of interacting casual relationships amongst impacts, representatives from 15 Lao PDR ministries, institutes, and the private sector identified 8 opportunities and 4 risks associated with the development of green hydrogen and ammonia in Lao PDR. The participants prioritised the domestic production of fertilizer from green ammonia, potential for cement kiln co-firing, and applications in mining processing as immediate applications, with export, fuel cells, and substitute fuels for transport as future applications (Ward and Smajgl, 2023).

Risk 1 notes the potential trade-offs between green hydrogen and ammonia production and the environment, affecting the quantity and quality of water and indirectly agricultural production and food security. Risk 2 references the lack of market demand, which connects to the mandates of the Ministry of Industry and Commerce, Ministry of Public Works and Transport, and Ministry of Agriculture and Forestry. Co-development of a strategy with these ministries was recommended to raise community awareness and to prepare for a likely increase in market demand and the associated increased uptake of green hydrogen and ammonia production industry. Risk 3 refers to the required investment for setting up a green hydrogen and ammonia production industry, or Dutch disease, which means that the rapid development of one sector can cause the decline of other sectors, particularly access to capital, labour, and natural resources. The negative consequences of Dutch disease can be avoided by macroeconomic planning and involving sustainable foreign aid strategies.

The eight opportunities noted were as follows.

(i) **Improved policy and governance**. Develop a comprehensive policy framework for hydrogen and ammonia production, establish a dedicated government agency to oversee the development and implementation of these policies, and mobilise international financing institutions to provide financial support.

(ii) **Improved macroeconomy and public debt**. Create new export revenue streams, and reduce dependence on imported fossil fuels, supporting macroeconomic growth and debt reduction.

(iii) **Improved energy security**. Reduce dependence on imported fossil fuels, enhance the reliability and resilience of the energy system, and promote the development of renewable energy sources.

(iv) **Improved economic growth and household incomes**. Generate new skilled employment opportunities, and increase incomes for households and businesses through developing the hydrogen and ammonia production sectors.

(v) **Improved human resources**. Develop a capacity-building and training programme for hydrogen and ammonia production, including technical vocational skills, safety procedures, and environmental regulations; promote innovation through collaboration between the private sector and research and development institutions; implement pilot demonstrations; and encourage regional technology transfers and raise public awareness.

(vi) **A more sustainable and resilient energy market**. Increase the share of renewable energy sources in the energy mix, reduce emissions, and promote sustainable development of the energy market.

(vii) **Improved food and nutritional security**. Increase domestic ammonia production for use as a fertilizer, promoting food security and reducing dependence on imported fertilizers.

(viii) **Emissions mitigation**. Promote climate-change mitigation by reducing emissions through the displacement of fossil fuels with hydrogen and ammonia.

5.2. Techno-economics of Green Hydrogen and Ammonia Production in Lao PDR

Techno-economic evaluation estimates the flow sheet, mass and energy balance, equipment sizing and list, capital and operating costs, cash-flow analysis, net present value, internal rate of return, pay-back period, and risk and sensitivity analysis of green hydrogen and ammonia production and distribution technologies (Hosseini et al., 2023).

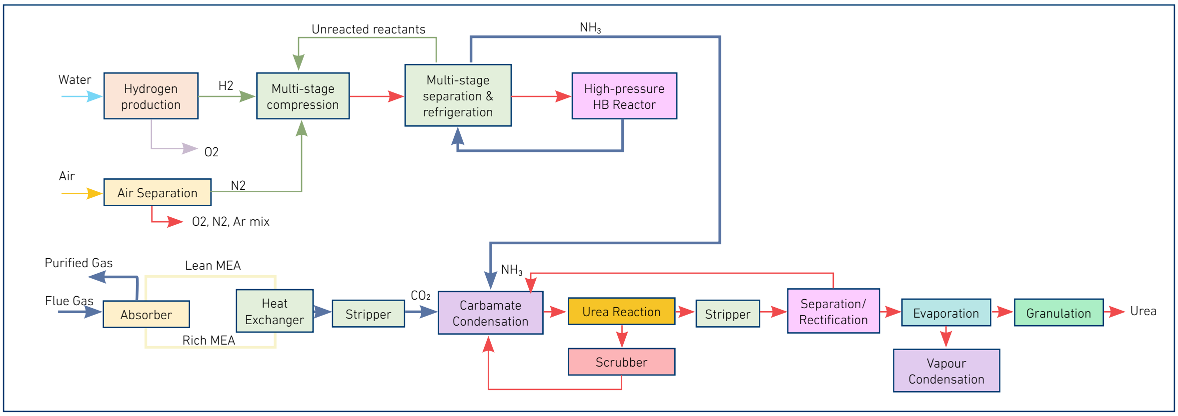
CSIRO modelling was informed by the main findings from the PSM process – domestic production and use of 200,000 tonnes of green urea per year. The capital cost estimation for green hydrogen and ammonia production was based on correlations from publicly available references and proprietary CSIRO databases. Estimated and calculated raw material inputs, labour, utilities, consumables, maintenance, insurance, and the cost of capital were imputed for operating cost estimates. A sensitivity analysis was undertaken by varying the key inputs of the operating cost, including electricity tariffs, taxes, and labour. Lao PDR modelling relied on a package of background tools and research on hydrogen and ammonia production technologies based on previous and current CSIRO research studies (Hosseini et al., 2023).

Evaluating production comprised a comparative analysis of alternative hydrogen and ammonia production and distribution technologies identified during participatory processes. The intended outcome is improved capacity of the Ministry of Energy and Mines and the Research Institute for Energy and Mines to negotiate for such production and distribution technologies as an alternative to fossil fuel generation and independently undertake robust social, ecological, and economic assessments of private sector and government proposals.

Urea is a compound of ammonia and carbon; bioethanol is the main carbon source. Urea importation prices in Thailand in 2022–2023 fluctuated between US$357/tonne and US$1,050/tonne (with an average of US$722/tonne). The average exportation price was US$670 (IndexBox, 2024). Lao PDR imports from Thailand commanded a 40% price increase. The May 2023 retail price of urea in Lao PDR was US$700/tonne.

The primary raw materials to produce urea are ammonia and carbon dioxide. For urea to be designated as green, carbon via carbon dioxide needs to be produced from bio-ethanol production (e.g. sugar cane or cassava). The urea production sequence is illustrated in Figure 9.11.

Figure 9.11. Urea Production



HB = Haber-Bosch, MEA = monoethanolamide.

Source: Musa et al. (2023)..

CSIRO modelled production variables to produce green hydrogen (20 kilotonnes per year [ktpa]), ammonia (113 ktpa) and urea (200 ktpa), which are depicted in Table 9.1. The total estimated investment cost is US$258 million, and the levelised costs over 30 years are US$488/tonne of urea, US$710/tonne of ammonia, and US$2,963/tonne of hydrogen. Levelised costs represent the unit cost a green urea plant would need to break even over a 30-year plant life at an electricity price of US$50/MWh. Sensitivity analysis of variable tax rates, electricity prices, and capital expenditure indicated the critical role that electricity tariffs would play in the annual operating costs and potential to produce price-competitive ammonia and urea.

Table 9.1. Production Variables for the Green Urea Base Case, 2022

Parameter	Urea Production	Ammonia Production	Hydrogen Production
Plant capacity (tpa)	200,000	113,000	20,000
Plant life (years)	30	30	30
Total Investment Cost (US$ million)	258	184	104
Variable OPEX	69	62	50
Fixed OPEX	12	9	5
Total OPEX	81	71	55
Operator labour cost (US$/hour)			3.5
Supervisor labour cost (US$/hour)			8.0
Electricity cost (US$/MWh)			50
Discount rate (%)			8.5
Levelised cost (US$/tonne)	488	710	2,963

MWh = megawatt-hour, OPEX = operating expenses, tpa = tonnes per year.

Source: Musa et al. (2023).

The levelised production costs of US$488/tonne of urea compete with 2023 importation prices. The inclusion of a carbon offset value of US$60/$tCO_2e$ would mean that Lao PDR-produced green urea competes with the costs of Thai imports of brown urea from the Middle East.[10] A reduction in the electricity tariff to US$10/MWh translates to a levelised cost of urea at US$296/tonne or a 40% reduction. The levelised cost of ammonia at US$10/MWh is US$376/tonne, and hydrogen US$1.20/tonne.

Lao PDR green urea production thus translates to an annual importation replacement value of approximately US$120 million/year at 2023 market prices – coupled with the development of new industries, new vocational skills, and a less volatile urea price. The critical role of electricity tariffs introduces three important discussion themes for Lao PDR:

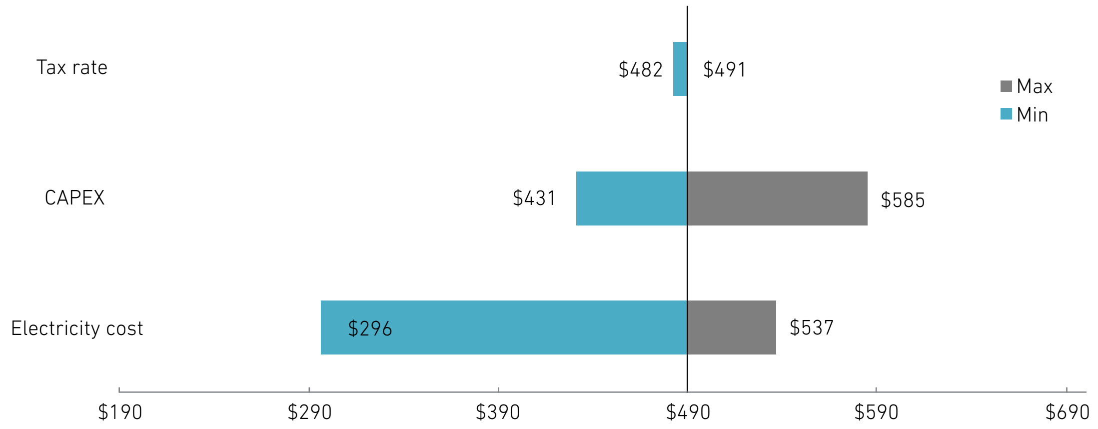
(i) **Alternate public–private partnership business model for the Government of Lao PDR and Électricité du Laos (EDL)**. EDL would be compensated for supplying a reduced electricity tariff due to shareholding in the green ammonia-urea plant, carbon offset revenues, and attendant profit sharing.

(ii) **Short-term power purchase agreements**. These would focus on EDL agreements on the above. Medium-term contracts would focus on a power purchase agreement with individual hydropower plants and operators and be located close to sites suited to urea production and markets. Long-term electricity purchases could involve direct contracts and shareholding with the government as build–operate–transfer hydropower dams reverting to full government ownership.

[10] 1.0 tonne of brown ammonia produces 2.6 tCO_2e or a US$156 offset (2.6 x US$60).

(iii) **Trading of carbon offsets**. These would have direct and indirect impacts on the financial viability and performance of the urea plant operator, government, and potentially communities. Establishing international carbon trading arrangements, especially in high-value markets, such as the European Union Emissions Trading Scheme, would directly affect the profitability and marketing potential of Lao PDR green urea.

Figure 9.12. Sensitivity Analyses of the Levelised Costs of Green Urea Production in Lao PDR
(US$)



Parameter	Minimum	Base	Maximum
Tax rate (%)	0	0 for 10 years	10
CAPEX (%)	–30	100	+50
Electricity cost	Hydropower	20.0	124.0
($/MWh)	10	50	60

CAPEX = capital expenditure, MWh = megawatt-hour.
Source: Musa et al. (2023).

6. Applications of Green Hydrogen and Ammonia

6.1. Mining Sector

There are substantial opportunities for green hydrogen and ammonia in the mining sector as a replacement for grey ammonium leachates and fossil fuel in co-firing and heavy machinery. Mining concessions (i.e. combined exploration and extraction) in Lao PDR have been approved for 11.12 million hectares (ha) (Ingalls et al., 2019). In 2018, the area of active mining concessions in Lao PDR was estimated at 0.42 million ha, whilst the area of exploration concessions was 10.70 million ha. The number of artisanal miners is increasing, especially those focussed on rare earth and critical minerals, and are estimated to number more than 10,000 in Lao PDR (Hatcher, 2020).

Up to 10 tonnes of ammonium sulphate per tonne of rare earth mineral is used as a leachate the initial processing phase, all based on grey ammonia production (Zapp et al., 2022; Andrews-Speed and Hove, 2023). That equates to 26 tCO_2e per tonne of rare earth production. There are an estimated 600,000 tonnes of rare earth deposits in Lao PDR, mainly in Xiangkhouang and Houaphanh provinces, with exploration contracts signed with 18 companies (Liang et al., 2022). The processing of rare earth minerals is currently under a Prime Minister's decree to explore a pilot project and represents an important potential market for green ammonia production in Lao PDR.

The production of silicon metal in Lao PDR uses energy-intensive heating, primarily from coal and biomass. Co-firing with green ammonia is an additional potential market. The substitution of liquid fuels in heavy trucks and mining equipment with hydrogen fuel cells or ammonia has been recommended and is another potential application of green ammonia (The Royal Society, 2020; IRENA, 2022). All substitutions of decarbonised ammonia in mining operations represent substantial carbon offset trading opportunities and revenues.

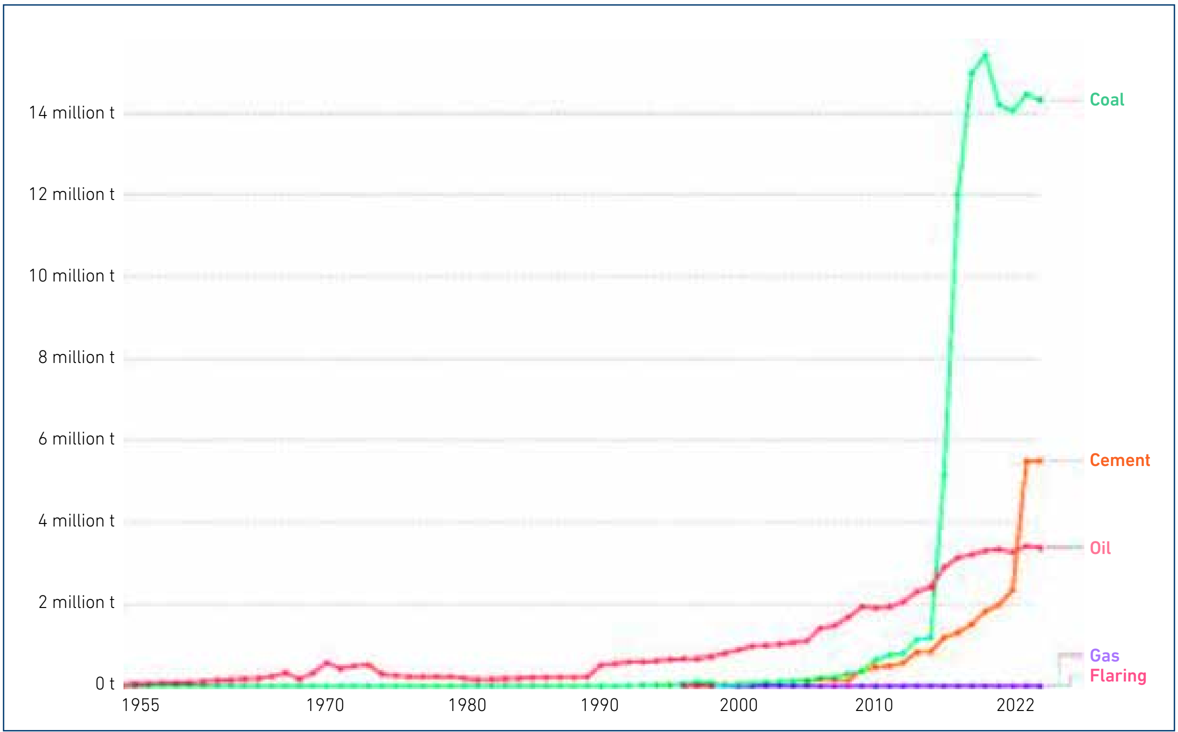
6.2. Cement Production and Co-firing

Lao PDR has 15 integrated cement plants. Because most are fairly small, they only have a total combined capacity of 10.7 million tonnes/year (Edwards, 2020). The largest producer by installed capacity is Lao Cement Public Company, which produces 3.4 million tonnes/year of capacity across four plants – three in Vientiane and one in Khammouane Province. The company is jointly operated by and obtains funding from China. The company's major products are Kating Thong Portland cement clinker and Kating Thong high-grade Portland cement. This cement is supplied mainly to Vientiane, as well as the provinces of Vientiane, Xiangkhouang, and Luang Prabang.

The second-largest cement producer by installed capacity is Khammouane Cement, a 100% subsidiary of Thailand's Siam Cement Group. Its 1.8 million tonnes/year plant at Khammouane was built in 2017. The third-largest producer is Luang Prabang Cement, a joint venture by Anhui Conch Cement and local investors. It operates three cement plants, all in Luang Prabang, with capacities of 0.1, 0.2, and 1.0 million tonnes/year. The third and largest plant is the most recent, first firing its kiln in December 2019.

Lao PDR cement kilns used 744,000 tonnes of anthracite in 2022.[11] Green ammonia, via an autothermal process to release the hydrogen fuel, can substitute for lignite and immediately fire site furnaces to manufacture cement (Cranfield University, 2024). This could offset the 2022 total emissions from Lao PDR cement production, estimated at 5.5 million tCO_2e (Figure 9.13).

Figure 9.13. Emissions by Fuel Type or Industry, 1955–2022
(million tonnes)



t = tonne.

Source: Ritchie et al., 2024

[11] According to the Government of Lao PDR, Ministry of Mines and Energy, Department of Mines Management.

6.3. Transport and Imported Liquid Fossil Fuels

Lao PDR is entirely dependent on imported liquid fossil fuels, primarily from Thailand. Petroleum imports and derivatives represented 30% of 2015 Lao PDR total energy consumption and are estimated to rise to 37% in 2025, more than twice the proportion of electricity at 13% in 2015 and 20% in 2025, respectively. Imported oil, primarily for road transport and passenger vehicles, is estimated to increase to 44% of total energy consumption by 2040 in the business-as-usual scenario (MEM and ERIA, 2020).

The number of pick-up trucks, sedans, minivans, jeeps, and trucks in Lao PDR in 2021 (764,612) increased by 26% compared to 2020 (567,373).[12] Assuming five motorcycles represent one pick-up truck (i.e. 2.2 million motorcycles in 2021), the total number of vehicles in 2021 equals 1,135,244. Total liquid fossil fuels were estimated to be 1.6 billion litres in 2023.[13] Emissions in 2022 from vehicles were estimated at 3.4 million tCO_2e (Figure 9.13). Fuel imports cost Lao PDR US$1.25 billion in 2022 or 16% of total imports.

Applications of both hydrogen and ammonia as a complement to electric vehicles and as a replacement/transitional fuel for liquid fossil fuels is a key focus of global research and applications, particularly for heavy trucks, mining machinery, and river transport (Giddey et al., 2017; The Royal Society, 2020; Chehade and Dincer, 2021; IRENA, 2022). Ammonia as a transport fuel has been used since the 1940s; although Toyota, Hyundai, Cummins, and MAN Truck & Bus are developing both ammonia and hydrogen internal combustion engines, this technology is still in an immature phase. Yet hydrogen fuel cells are rapidly being developed and deployed for long-distance trucking applications, passenger vehicles, and public train and bus transport (MacFarlane et al., 2020; The Royal Society, 2020; Erdemir and Dincer, 2021; IRENA, 2022; IRENA and ACE, 2022; Kimura, Phoumin, Purwanto, 2022). The *Renewable Energy Development Strategy for Lao PDR* forecasted approximately 50% of new vehicles will be electric vehicles by 2031 based on a medium scenario of uptake (i.e. 3%–6% increase per year) (Castalia Advisory Group, 2020).

[12] Lao Statistics Bureau, Type of Car for the Whole Country, Statistics Database, https://laosis.lsb.gov.la/statHtml/statHtml.do?orgId=856&tblId=DT_YEARBOOK_Q003&language=en&conn_path=I3 [accessed 1 June 2024]

[13] Personal communication from the Department of Customs, Ministry of Industry and Commerce, 2024, and World Bank, World Development Indicators, https://databank.worldbank.org/source/world-development-indicators [accessed 1 June 2024]

7. Conclusion and Policy Implications

The PSM described the opportunities and risks identified as a consequence of green hydrogen and ammonia in Lao PDR. Its third-order system map illustrated the direct and indirect downstream causality or impacts of green hydrogen and ammonia production, storage distribution, and utilisation.

Upstream enabling factors and constraints represent the precursors and conditions necessary for green hydrogen and ammonia production to commence in Lao PDR. There are two critical enabling factors. The first is the allocation of an agreed, secure, and reliable proportion of hydropower generation deployed to hydrogen and ammonia production, including likely infrastructure locations and based on generation surplus (MEM, 2021). The second critical enabling factor is the drafting and ratification of a national hydrogen and ammonia roadmap and strategy. The Ministry of Energy and Mines is coordinating a cross-sectoral drafting of the roadmap with multiple ministries aligned with the Prime Minister's Hydrogen Decree.[14] A collaborative process to draft and to agree on a national hydrogen and ammonia production roadmap, strategy, and action plan is the foundation of effective energy system planning and policy that meets the needs of all sectors.

In transitioning from an emerging technology to a commercial asset, the policy imperatives woven into the national hydrogen and ammonia roadmap and strategy must focus on market activation and the importance of investment in research and innovation while reducing costs and other barriers to technology deployment. CSIRO noted that the hydrogen transition parallels the recent experience in the solar photovoltaic industry, especially in developing clean hydrogen technology solutions across the value chain capable of large-scale deployment by 2030.[15]

There is no one one-size-fits-all solution; hydrogen-ammonia roadmaps require extensive consultation and collaboration with all affected stakeholders across all sectors. Each will always base its policies and actions on its social and political priorities and constraints, as well as resource availability and existing infrastructure. An adaptive management approach to policy design and implementation is recommended, with established review periods to evaluate agreed on performance indicators and metrics. If Lao PDR acts as an early adopter, there may be opportunities to draw upon energy resources that are underutilised or used in lower-value applications. A summary of recommended approaches to drafting a national hydrogen and ammonia roadmap and strategy as well as examples from ASEAN Member States can be found in Ward and Smajgl (2023).

To identify additional enabling factors, a group of experts familiar with Lao PDR energy systems were invited to review the hydrogen and ammonia production maps developed by Lao PDR officials during a series of participatory systems mapping workshops (Ward and Smajgl, 2023). The process employs the Delphi method[16] to further enrich the PSM and to identify additional consequences and potential intervention points, likely to be important in the design of the National Hydrogen and Ammonia Roadmap and Strategy.

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[14] The Prime Minister's hydrogen decree is currently in draft format and expected to be ratified in late 2023.

[15] CSIRO, HyResource, https://research.csiro.au/hyresource/

[16] Delphi techniques help structure a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem. The Delphi technique relies on the collectivisation of individual opinions and evaluations, because discovering solutions can benefit from subjective judgments on a collective basis (Linstone and Turoff, 2002).

Expert opinions and discussions held during the 2023 participatory systems mapping workshops identified additional enabling factors that warrant consideration by the government:

(i) **Form a national task force responsible for coordinating the development of the green hydrogen and ammonia production industry**. The task force should include government agencies, industry associations, and experts to monitor and help implement the national strategy and action plan for green hydrogen and ammonia production. The task force would facilitate policy and regulatory discussions, evaluate infrastructure development, and promote public–private partnerships.

(ii) **Establish a centre of excellence as a trusted source of data and analysis**. Research institutes and the National University of Laos should be integrated into this, with a focus on hydrogen and ammonia production research and development and selection of a site for a pilot plant.

(iii) **Establish a green hydrogen and ammonia industry association**. This will represent the interests of industry stakeholders, enabling collaboration between the public and private sectors and development partners.

(iv) **Negotiate and formalise participation in international carbon credit trading networks**. A legal property rights framework for hydrogen and ammonia carbon offsets and tradable renewable energy certificates based on green hydrogen and ammonia production should be created in Lao PDR. The distribution of revenue from carbon trading will need to be specified in contractual arrangements with foreign entities investing in hydrogen and ammonia production and distribution. The proposed hydrogen and ammonia industry association could also play an active role in negotiations.

(v) **Create incentives for developing a green hydrogen and ammonia industry.** These should include adapting existing special economic zone tax breaks, subsidies, and import duty exemptions for hydrogen and ammonia capital goods.

(vi) **Foster strong collaborative frameworks**. These will help accelerate the uptake of emerging hydrogen and ammonia technologies by fostering knowledge transfer, promoting economies of scale, and identifying failures. Weak cooperation mechanisms can slow down the deployment of technologies in the demonstration phase by up to 10 years or more (IRENA, 2020).

(vii) **Access Australian and other international expertise and training programmes to support sound energy and financial analysis of hydrogen and ammonia investments and trends**.

(viii) **Actively collaborate with regional neighbours to expand information sharing and to build relationships on hydrogen and ammonia production safety, transport, and utilisation**.

Additional constraints were identified during the second and third 2023 participatory system mapping workshops: (i) absence of university curricula and vocational training programmes geared towards green hydrogen and ammonia production, creating a lack of skilled engineering and tradespeople; (ii) limited access to low-interest funding and investment, exacerbated by the current national and EDL debt and downgrading of Lao PDR's credit rating by Moody's and Fitch Ratings; (iii) inertia of EDL to expand the electricity exportation strategy; (iv) uncertainty that ammonia and hydrogen infrastructure will not become stranded assets; (v) green hydrogen and hydrogen production not specified in the power development plan; (vi) volatility in global demand and price premiums for green hydrogen and ammonia; and (vii) poorly specified incentives to decarbonise through green hydrogen and ammonia.

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