# A Framework for Assessing Energy Exporting Countries' Vulnerability and Energy Security: Current Fossil Fuel-Dependent Economy and Future Hydrogen Economy

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# Abstract

As efforts to mitigate anthropogenic climate change increase worldwide, decarbonisation of the global energy system is a high priority. This so-called “energy transition” from $CO_2$ emitting fossil fuels to zero-carbon energy sources will have a major impact on countries that are currently major energy exporters, both on export revenues, and potentially on those countries domestic energy systems.

The global narrative around domestic energy security is dominated by those countries dependent on energy imports, stemming from the emergence of energy security as a discipline and as a core mission of the International Energy Agency in 1974 in response to the first oil shock. Energy security is widely examined from the perspective of energy import vulnerability, but it is less common to evaluate the vulnerability of energy exporters. This work focusses on the conditions unique to energy exporters and develops a comprehensive conceptual framework and a suite of quantitative indictors, complimentary to the existing importer-centric body of knowledge on energy security. The framework includes energy-export related economic vulnerability and exporter-specific domestic energy security blind-spots. This work then considers the conditions for a major energy exporter such as Australia when fossil fuel exports are largely replaced by zero-carbon hydrogen.

The background research of various related conceptual frameworks distils useful insights from energy security, corporate risks, and general economic vulnerability. Carbon risk - exporter exposure to customer climate change action due to the $CO_2$ emissions intensity of exported fuels - is largely missing from related work and is introduced to the study in new factors to evaluate exporter vulnerability to increasing global action on climate change. A holistic view is taken of all energy resource exports as a novel approach, rather than focusing on individual fuels. The developed scorecard is used to provide case studies of 5 major global energy exporters with comparative analysis between countries and over time.

This work further examines two potential blind spots in evaluating the energy security of energy resource exporters (actual primary energy self-sufficiency; and export exposure of the domestic energy system) and explores some case studies to validate the existence of these blind spots. Two novel quantitative indicators for domestic energy security conditions specific to energy exporters are proposed. The overall conclusion is that transition to a zero-carbon energy system based on domestic renewable energy sources allows for the decoupling of energy resource exports from the domestic energy system for the benefit of domestic energy security.

Recently, Australia has articulated aspirations to become a major global exporter of hydrogen as a replacement for fossil fuels and as part of the drive to reduce $CO_2$ emissions. Much of the published literature on this topic concentrates on the details of what being a major hydrogen exporter will look like and what will need to be done to achieve it. This work addresses an apparent gap in the study of the implications of large-scale hydrogen exports for an exporter’s

domestic energy system in terms of energy security and export economic vulnerability, for which a conceptual framework for the implications of becoming a major hydrogen exporter on the exporter's domestic energy system is proposed. The case study of Australia's proposed transformation into a green hydrogen exporting superpower is examined. This work explores the characteristics of the "resource curse" and examine the LNG and aluminium production and export industries for similarities that could instruct the development of the conceptual framework. Finally, an evaluation of a hydrogen export scenarios using various energy security and energy exporter vulnerability tools is presented, to compare with Australia's present-day situation.

The unique and novel contributions of this work include:

- Adapting energy importer energy security conceptual frameworks and indicators to the economic vulnerability of energy exporters, other indicators derived from corporate risk assessments of energy industry participants.
- Introducing two new indicators for exporter carbon risk in the context of the energy transition;
  - Export customer diversity risk subject to customer action on climate change
  - Carbon intensity of the mix of exported energy resources
- Identifying gaps in importer-centric energy security frameworks that leave blind-spots for domestic energy security of exporters.
- Designing indicators for assessing these blind spots in an energy exporter's domestic energy security;
  - Actual primary energy self-sufficiency
  - Export exposure of the domestic energy system
- Developing a conceptual framework for the domestic energy system impacts of large-scale green hydrogen exports, derived from critical review of frameworks for:
  - Resource curse hypothesis
  - Aluminium production for export and impacts on the domestic electricity system.
  - LNG production for export and impacts on the domestic gas and electricity systems.

Conclusions of this research include:

- Import customers decarbonisation is an increasing cause of exporter vulnerability.
- Without deliberate attention, energy exports can have a false sense of their own energy security.
- Transition to renewable energy in the short term is an effective means of reducing the domestic energy system impacts of LNG exports.
- Transition from fossil fuel exports to green hydrogen exports along with global energy system decarbonisation significantly reduces exporters economic vulnerability. Domestic energy self-sufficiency is also improved, however, a reduction in energy security would be experienced as the electricity system becomes export linked.

Through this research, the following opportunities for further work have been identified:

- A deeper study of the application of resource curse hypothesis to large-scale green hydrogen exports, continued from the initial review provided in this work.
- The rate of renewable electricity construction required to support domestic decarbonisation and green hydrogen exports has the potential to be affected by critical minerals supply constraints. Further research on areas of potential supply shortage and alternative materials , specific green to hydrogen production, is proposed.
- The potential opportunities and benefits for reducing import customer energy demand by relocation of energy intensive activities closer to low-cost renewable energy resources, in a similar manner to the relocation of aluminium production from Japan to Australia such as green steel production, rather than transforming renewable electricity into hydrogen, then into a carrier, for shipping to a distant customer.

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# List of Abbreviations

| | |
|---|---|
| AE | Alkaline electrolysis |
| AEMO | Australian Energy Market Operator |
| AESPI | Aggregated Energy Security Performance Indicator |
| AUD | Australian Dollars |
| CEFC | Clean Energy Finance Corporation (Australia) |
| CER | Carbon Emissions Reduction (rating factor) |
| CIF | Carriage, Insurance, Freight (International shipping INCOTERMS designating delivery to destination port) |
| COAG | Coalition of Australian Government (National and State Governments body) |
| CSG | Coal Seam Gas |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation (Australia) |
| EVI | Economic Vulnerability Index |
| GDP | Gross Domestic Product |
| GNI | Gross National Income |
| GWh | Gigawatt-hours (unit of energy) |
| HAI | Human Assets Index |
| HESC | Hydrogen Energy Supply Chain Project (Australia Japan cooperation) |
| HHI | Herfindahl-Hirschmann Index |
| IEA | International Energy Agency |
| IPCC | International Panel on Climate Change |
| kWh | Kilowatt-hours (unit of energy) |
| LH2 | Liquefied Hydrogen |
| LNG | Liquefied Natural Gas |
| MeOH | Methanol |
| METI | Ministry of Economy Trade and Industry, Japan |
| MPa | Megapascals (unit of pressure) |
| MW | Megawatt (unit of electrical power) |
| MWh | Megawatt-hours (unit of energy) |
| NEM | Australia's National Electricity Market |
| NH3 | Ammonia |
| OECD | Organisation for Economic Cooperation and Development |
| OPEC | Organisation of Petroleum Exporting Countries |
| PEM | Polymer Electrolyte Membrane (sometimes also called proton exchange membrane) electrolyser |
| PESS | Primary Energy Self Sufficiency |
| PJ | Petajoules (unit of energy) |
| REED | Risky Energy Exports Demand index |
| SWI | Shannon-Weiner Index |
| TDEP | Total Domestic Energy Production |
| TJ | Terajoules (unit of energy) |

| | |
|---|---|
| TPES | Total Primary Energy Supply |
| TWh | Terawatt-hours (unit of energy) |
| UK | United Kingdom |
| UN | United Nations |
| USD | United States Dollar |
| VoLL | Value of lost load |

# Chapter 1 - Introduction and Background

## 1.1 Background

The global distribution of energy resources is rarely geographically aligned with concentrations of human population and energy consumption, as is demonstrated by the global distribution of oil reserves. For example, eighty percent of the world's total proved reserves of oil is concentrated in only 8 countries [1] (Venezuela, Saudi Arabia, Canada, Iran, Iraq, Russia, Kuwait and the United Arab Emirates), however these countries represent only 5% of global population [2] and 8% of global gross domestic product (GDP) [2]. Hence the need for global trade in energy resources. While the global energy transition from $CO_2$ emitting fossil fuels to renewable energy sources provides some opportunities to increase domestic supply of energy, renewable energy resources are also not evenly distributed worldwide, and not usually co-located with energy demand either. For example, in the case of solar electricity generation, major industrialised countries such as Japan and Germany, ranked 3rd and 4th worldwide by GDP [3], are doubly disadvantaged by limited available space as represented by high population density (346 and 238 people/km$^2$ respectively) and low photovoltaic generation potential (3.4 and 3.0 kWh/kWp respectively), compared to countries such as Australia (3 people/km$^2$, 4.6kWh/kWp) or Morocco (82 people/km$^2$, 5.0kWh/kWp) which have much lower population densities and higher photovoltaic generation potential [4], [5].

Countries dependent on energy imports became much more aware of their vulnerability as a result of the first oil shock in 1973-1974, when a number of major oil producing countries acting together exercised their dominant market position to reduce petroleum production dramatically increasing the price of their petroleum exports to much of the industrialised world [6]. In response to this major economic impact, countries that had become economically dependent on cheap and abundant imported petroleum supplies formed the International Energy Agency (IEA) in 1974, with the mission to ensure security of oil supplies [7]. The study of energy security originates from this time and continues to this day to be an area of significant field academic and policy interest - particularly for countries dependent on energy resource imports. It therefore comes as no surprise that the existing body of knowledge on the topic of energy security primarily originates from and is highly focussed on the concerns of major energy-import-dependent economies such as Japan [8] and the European Union [9].

## 1.2 Knowledge Gap

Through an extensive review of literature on the topic of energy security [8]–[34] , it was found that although international trade in energy resources is a paired relationship between the consumer (importer) and the producer (exporter), the primary focus on the vulnerability of the importer has led to a knowledge gap in understanding the vulnerabilities of energy exporters themselves. Filling this knowledge gap on the side of energy exporters is beneficial for exporting countries themselves, to better understand their own vulnerabilities and development policies and plan development accordingly. It should also be of interest to importing countries, who, after all depend on stable supplies of energy resources and whose own energy security is closely linked with conditions in exporting countries. Indeed, importing countries` focus on their own energy security can create exporter vulnerabilities, as importers attempt to reduce their import dependence, improve their energy efficiency to reduce demand and diversify their energy mix with competition among suppliers. As energy exporting countries see their customers increasingly pursuing decarbonisation of their domestic energy systems, the exporter vulnerability profile is changing rapidly. At the present time it is critical to establish a means to quantify carbon risk – an exporter's vulnerability to loss of export revenue as customers take climate change action and reduce fossil fuel consumption, related to the $CO_2$ emissions intensity of exported fuels - inherent in current energy resource exports. Geopolitical risks and trade disputes can also adversely affect both the supplier and the consumer. Some other exporter vulnerabilities are due to internal factors such as the extent of customer concentration, or the significance of energy resource exports to GDP. The knowledge gap in energy security frameworks for energy exporters extends to the predominant treatment of domestic energy security from a net importer's perspectives with little recognition of the interactions between energy exports and the domestic energy system.

Following the adoption of the 2015 Paris Agreement on climate change action [35], many nations are pursuing a target of net-zero $CO_2$ emissions by 2050 to limit global temperature rise to 1.5$^{o}$C. Although commitment to this target is not universal, from an energy exporter's perspective it becomes necessary to establish an understanding the potential future economic vulnerability profile under these conditions. As a substitute for fossil fuels, some countries such as Japan [36] and Korea [37] are actively pursuing green hydrogen as a zero-carbon energy import, transported in a number of potential carriers including liquefied hydrogen, ammonia, methanol, or other emerging technologies. This opens up a new energy export opportunity to replace reduced fossil fuel exports, however not without its own potential set of specific producer-side vulnerabilities and domestic energy system impacts that will come from participating in the future hydrogen economy as an exporter of green hydrogen.

### 1.3 Aim and Structure of Document

The central aim of this work is to contribute to filling the knowledge gap on energy exporter vulnerability, now and in a net-zero $CO_2$ emissions future. The ultimate contribution is a conceptual framework and its application to exporter case studies. This involved the development of a number of novel approaches, as set out below.

Firstly, the exporter's side of importer's energy security – economic vulnerability as it relates to energy resource exports (the potential for loss of export revenue and domestic economic activity generated from export facing energy resource production and related activities) – is explored. Inputs are drawn from various related frameworks including general economic vulnerability, oil producer vulnerability, energy producing company risks, and importer energy security. In considering importer energy security factors, the applicability of each factor as either a shared vulnerability, or an inverse relationship (a gain for the importer causes a loss for the exporter), or simply not applicable. From these inputs, a scorecard of 6 novel indicators for quantitatively evaluating energy exporter vulnerability is developed; 3 focussed on external factors and 3 focussed on internal factors. The formation of these 6 indicators contains a number of novel approaches, as follows:

- While some methods for oil exporter vulnerability exist, in this work the full energy export basket is considered as interrelated resources with a common demand, and as such an energy value weighting of exports is applied rather than revenue earned, so as to overcome the influence of short-term price variations.
- Exporter vulnerability to loss of revenue as a result of customers switching to lower $CO_2$-emitting energy sources is included in both the external (customer diversity and climate change polices) and internal (weighted $CO_2$ emissions intensity of the exported mix of fuels) indicators.
- The usual reserves to production ratio method is adapted to instead be based on all proven resources not just economically recoverable reserves, in consideration of historical developments in extraction technology such as unconventional gas production render more resources economically recoverable over the decades of production activity.

Secondly, the exporter's own domestic energy security is examined as it is impacted specifically export activities, which is an entirely novel approach. Common energy security indicators that are typically applied to import-dependent countries are filtered for their relevance to the conditions of energy exporters. The extent to which export activity of energy resources has a return impact on the exporter's domestic energy system is explored using a systems approach to consider possible exporter-specific blind spots in existing energy security frameworks. Two unique new quantitative indicators specifically adapted to evaluate aspects of energy exporters domestic energy security are presented:

- A redefined indicator for primary energy self-sufficiency that looks deeper than basic energy resource production and considers self-sufficiency in all steps of the energy supply chain from resource production to end use and excludes export-destined production.
- A new indicator for exposure of the domestic energy system to external impacts due to linkages with export activities.

Thirdly, a future scenario set in 2050 where Australia shifts from fossil fuel exports to large scale exports of green hydrogen is applied as the context to assess domestic energy system impacts. Although numerous articles, reports and papers have examined the technology options, potential costs, and implementation pathway to establish a large-scale hydrogen export industry in Australia and other countries, the domestic energy system impacts are unaddressed. This research establishes a novel conceptual framework of the implications for the domestic energy system of the hydrogen export superpower scenario, including:

- An overview of main features of the resource curse hypothesis that is often applied to natural resources such as coal and gas, and whether they would apply to green hydrogen exports, being an energy export, but renewable.
- Analysis of comparative resource exports aluminium and LNG, and consideration of relevant factors that might be applied to the domestic energy system impacts of hydrogen exports.

- Application of the quantitative indications developed in chapter 2 and 3 of this work to compare Australia's current energy exporter vulnerability and domestic energy security situation with the 2050 hydrogen export superpower scenario.

Finally, conclusions from each chapter are drawn together to complete the narrative of this work in establishing a novel and comprehensive framework with a suite of new quantitative tools to fill the gap in understanding of energy exporters economic vulnerability and domestic energy security, now and in a zero-carbon future where hydrogen exports have replaced fossil fuels.

The overall structure of the study and this thesis is shown in Figure 1-1.

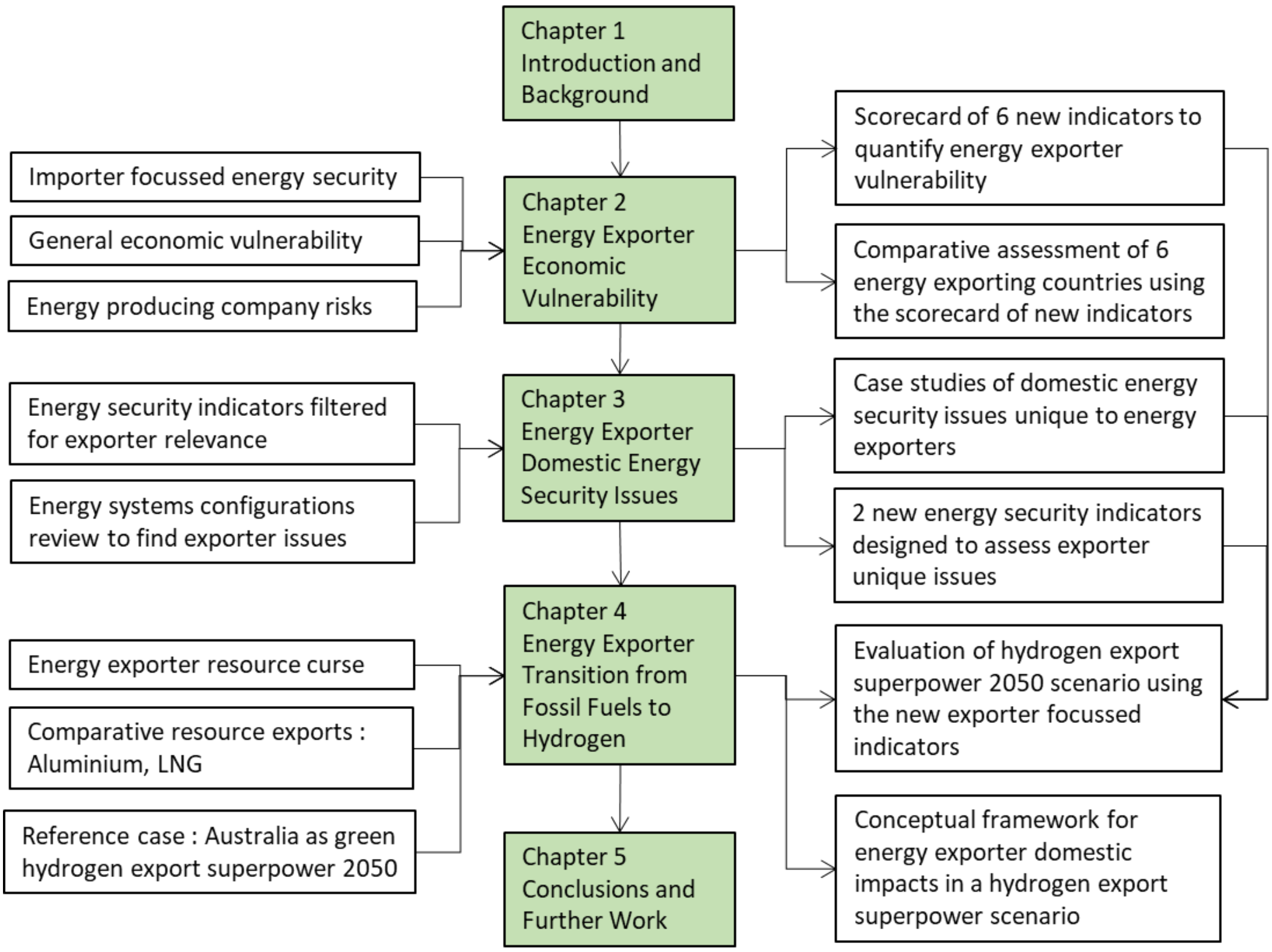



*Figure 1-1 - Methodological Structure of this Document*

# Chapter 2 - Framework for Assessing the Economic Vulnerability of Energy Resource Exporters

## 2.1 Chapter Introduction

Domestic energy self-sufficiency is widely considered to be desirable [8] to protect the local population and domestic economy from external supply disruptions or price hikes. However, the energy demand of many countries significantly outweighs their domestic energy production potential, due to either a high energy demand in the case of a large population and industrial development, a lack of domestic energy resources, or a combination of both. In such cases, affected countries are dependent on imports of energy resources to support economic activity, and the study of domestic energy security of import-dependent countries (notably Japan [10], South Korea [38], the European Union [9] ) is well developed. In response to increasing demand from energy import-dependant countries, many countries with an abundance of local energy resources have expanded their energy production capacity through major capital investment well beyond their own domestic needs, to realise economic opportunities from supplying foreign customers [39]. In doing so, such countries have become, to a greater or lesser extent, economically dependent on energy resource exports and vulnerable to changes in a range of factors related to production and consumption of those exports. This vulnerability has not been widely evaluated in the way that energy security has for importing countries even though the economic vulnerability of countries dependent on energy exports may be quite considerable. To provide balance in understanding the producer-consumer energy trading relationship, a study of the energy exporter's own economic vulnerability is therefore needed to match the attention paid to importer energy security. One of the purposes of this research is to contribute to this balance.

In this chapter, energy exporter economic vulnerability is specifically defined as the potential for loss of export revenue and domestic economic activity generated from export facing energy resource production and related activities. There are a wide range of potential vulnerability factors for a country's economy related to energy from a lack of energy supply locally, to dependence on income from energy exports. Energy exporters are also potentially vulnerable to distortions in domestic energy prices due to the influence of export markets such as has been experienced in eastern Australia's gas and electricity pricing related to the commencement of LNG exports [40]. The vulnerability of energy exporters to the so-called resource curse [41] is well documented in the effects on an energy exporter's domestic economy from windfall resource export income. Supply disruptions due to adverse weather events [42], production reliability [43], or geo-political choke-points [8] are potential vulnerabilities for producer and consumer alike. Vulnerability factors can be generally grouped into external influences and internal sensitivities; those beyond the country's control that the country is subject to, and those within the country's control. This chapter specifically concentrates on exploring external vulnerabilities that may affect the producer's exports of energy resources, and internal vulnerabilities that may limit energy resource exports, as well as internal vulnerabilities that render the exporter's economy more vulnerable to loss of export income.

Increasing global action to decarbonise human activity to limit the extent of anthropogenic climate change has a direct impact on demand patterns for $CO_2$-emitting fossil fuels. Worldwide economic disruption due to the COVID-19 pandemic has further accelerated this trend, as reported by the International Energy Agency [44], with coal fired and gas fired electricity production down 10%, and 7% respectively. Reduced electricity demand (one month of lockdown measures reduces annual electricity demand approximately 1.5% [44]) has largely been absorbed by the curtailment of fossil fuel generation while lower marginal cost renewable energy sources have continued to operate largely unaffected, thus increasing their share.

Although from a resource-production perspective different energy types such as coal or gas may be as distinct from each other as other natural resources, when compared to other natural resources such as iron ore or bauxite that cannot be directly substituted in producing their end-products of steel or aluminium, energy resources share a much closer end-use demand inter-relationship than other natural resources. Notwithstanding important industrial process uses of gas, coal and oil, the majority (58% in 2018 [39] ) of global demand of these fuels is from electricity production and transport. Coal, gas and oil are each widely used fuels for electricity production, with fuel selection based on availability, price, conversion technology efficiency, investment cost, and increasingly $CO_2$ emissions intensity. In countries or regions with a competitive electricity market [45], electricity generated from each of these fuels as well as from other sources such as wind, solar, hydro, geothermal, nuclear, biomass, tidal, etc., is constantly in competition for market share of electricity demand. Fuels are not usually inter-operable in the same power station (dual fuel gas turbines are a notable exception) although at a grid-wide or national level a reduction in demand for coal at one power station would potentially be balanced with an increase in demand for gas at another power station. Transport energy use has been dominated by oil products for decades but is experiencing increases in shares of natural gas and electricity as energy inputs in recent years, and the increase in uptake of electric vehicles and development of electric public transport systems will continue this growth trend [46]. Due to the multiple inter-relationships of the end use of different energy resources, and the significance of $CO_2$ emissions from all fossil fuels, there is significant benefit to assessing exporter economic vulnerability to energy resources together, rather than as distinct, individual exports [47].

Following this introduction, this chapter is composed of four main sub-sections; section 2.2 presents a review of related frameworks and methodologies. Section 2.3 provides a synthesis of related frameworks and identifies solutions to their shortcomings and gaps to produce a novel conceptual framework for energy exporter vulnerability. Section 2.4 develops the novel conceptual framework by defining a scorecard of specific assessment metrics and their related quantitative evaluation methods. Section 2.5 applies the assessment metrics with economic data to produce a time-based scorecard for 5 selected energy exporting countries. Conclusions for this chapter are summarised in section 2.6.

## 2.2 Review of Related Frameworks and Methodologies

### 2.2.1 Energy Exporting Countries

There is an apparent lack of policy and academic literature on conceptual frameworks for the economic vulnerability of energy exporters. This stands in stark contrast with the considerable body of knowledge in academic, policy and business literature on the related topic of energy security of import-dependent countries. The few publications found that do treat this or related topics also acknowledge this lack [48] [47].

Papers by Dike [48], Bhattacharyya & Blake [47] and Kanchana, McLellan & Unesaki [49], are among the handful to directly address the concept of energy exporter vulnerability, and although each has their respective limitations, they provide a useful starting point for developing a broad-based framework of energy exporter vulnerability through this research. Dike focusses on oil and gas production and exports by OPEC members, Bhattacharyya & Blake focus particularly on oil production and exports, while Kanchana et al. expand the scope of study to interdependence in energy trading relationships and assessing both exports and imports of all major energy resources for selected countries in South East Asia.

Dike proposes a unitary index based on the multiplication of four unweighted factors, being the economy's dependence on exports of any type (X), the economic significance of oil exports in particular I, monopsony risk, or the degree of diversity of customers (M), and a transaction cost-risk metric based on transit distance (D). Export dependence (X) is calculated as the ratio of Energy Exports to Total Exports. The economic significance factor (E) is calculated as the ratio of energy exports to total GDP. Monopsony risk indicates the level of market concentration or diversity and is calculated using the widely recognised Herfindahl-Hirschmann Index (HHI), where M is the sum of the squares of the ratios of exports to each individual customer over total exports. Transaction cost-risk applies a simple rating based on distance between the capital cities of the exporter and importer. The scores of each factor are multiplied, with no weighting applied, to yield the "REED" (Risky Energy Exports Demand) index, calculated as shown in Equation 2-1.

*Equation 2-1 - Risky Energy Exports Demand Index*

$$REED = X \times M \times D \times E$$

Where;

X = Export dependence, calculated as shown in Equation 2-2.

*Equation 2-2 - Energy Dependence Factor*

$$X = {}^{Energy\ Exports}/_{Total\ Exports}$$

M = Monopsony factor, calculated as shown in Equation 2-3.

*Equation 2-3 - Monopsony Factor*

$$M = {x_{country\ 1}}^2 + {x_{country\ 2}}^2 + \cdots + {x_{country\ n}}^2$$

Where;

x = share of oil and gas imports by country, out of total exports

D = rating based on distance between capitals of the exporter and importer (if <1500km, D=1, if >1500 and <4000km, D=2, if >4000km, D=3)

E = export economic impact, calculated as shown in Equation 2-4.

*Equation 2-4 - Export Economic Impact Factor*

$$E = {Value\ of\ Oil\ \&\ Gas\ Exports}/{Exporter\ GDP}$$

Bhattacharyya & Blake [47] proposes a decomposition of the ratio of oil export revenue to GDP down into four subset ratios of oil export revenue to oil export volume (price variation), oil export volume to primary oil supply (proportion exported), primary oil supply to primary energy consumption (ratio of exports to domestic use), and primary energy consumption to GDP (domestic energy intensity). This approach thus allows for the study of each of the component ratios as indicators of different driving factors.

Kanchana et al [49] propose consideration of a country's energy trading exposure, sensitivity and resilience, as potentially both importer and exporter across the basket of traded fuels. An Energy Dependency Index is developed, consisting of two sub indicators; vulnerability to external energy dependence, and tolerance and resilience to the dependence. Within the former, two components are established; sensitivity to external dependence, and exposure to geopolitical uncertainty, with quantifiable indicators as set out in Table 2-1.

*Table 2-1 Energy Dependency Index Factors (Kanchana)*

| | |
|---|---|
| **Sensitivity to external dependence** | |
| X1 | share of net energy imports to primary energy mix |
| X2 | share of energy import expenditures to GDP |
| X3 | energy export to energy production ratio |
| X4 | share of energy export revenues to GDP |
| **Exposure to geopolitical uncertainty** | |
| X5 | diversity of energy trade partners, measured with the Herfindahl-Hirschmann Index (HHI) |
| X6 | political stability of major energy trade partners, assessed using the Gupta method[11] |
| **Tolerance and resilience to dependence** | |
| X7 | openness to global energy trade |
| X8 | diversity of primary energy mix, measured with the Shannon Wienner Index (SWI) |
| X9 | domestic reserves to production ratio |
| X10 | energy self sufficiency |
| X11 | diversity of energy trade partners, measured using SWI |

While many energy security frameworks for energy importers consider the full energy mix, Kanchana et al [49] is apparently unique in considering multiple fuels from the exporter perspective, although index assessments are segregated by fuel.

### 2.2.2 United Nations Economic Vulnerability Index

Vulnerability has been widely examined from perspectives outside the sphere of energy economics. For example, the Economic Vulnerability Index (EVI) developed by the United Nations (UN) Development Policy and Analysis Division, Committee for Development Policy [50] was developed [51] in response to the need expressed by the UN General Assembly for a tool along with other indicators including GNI (Gross National Income) [52] and HAI (Human Assets Index) [53] to assess the development status of nations, and hence as a guide for aid allocation. In the context of this research, the EVI provides a useful reference for factors relevant to economic development of highly vulnerable nations, some of which can be applied to the subject matter of this research. The EVI was implemented in 2000 and has been revised multiple times. The latest version [54] of the EVI is structured as a unitary index with 3 levels of unweighted contributing factors.

The EVI itself is composed of an exposure index and a shock index. The exposure index is in turn composed of a size subindex (population size), a location subindex (based on an assessment of remoteness), an environment subindex (based on the share of population in low-lying coastal areas), and an economic structure subindex (based on indices for export share and share of agriculture and natural resource related activities). The shock index is composed of a trade shock subindex (derived from assessing instability of exports of goods and services) and a natural shock subindex (based on a combination of instability of agricultural production and victims of natural disasters). The structure of the EVI in its two components of exposure index and shock index are represented as shown in Figure 2-1.

Various authors including Guillaumont [55]–[58], Briguglio [59], [60] and Cariolle [54] have applied the basic EVI framework to case studies of developing countries, with variations and additions including comparing vulnerability to shocks and recovery resilience.

While much of the EVI relates to factors not related to energy exporter vulnerability such as the fragility of agricultural resource based economic activity or population exposure to flooding and other natural disasters, some useful insights can nonetheless be gained which are instructive to the theme of this research. At its first level, the EVI framework considers both temporary or sudden disruptions largely related to weather condition variations, and also underlying structural factors such as population distribution and make up of economic activity. It is likewise essential to examine the significance of both temporary disruptions and the fundamental economic and energy production structure for exporter energy vulnerability. Further, some specific factors in the EVI are already familiar from the previous section, such as concentration of exports in total GDP and share of energy exports in total exports.

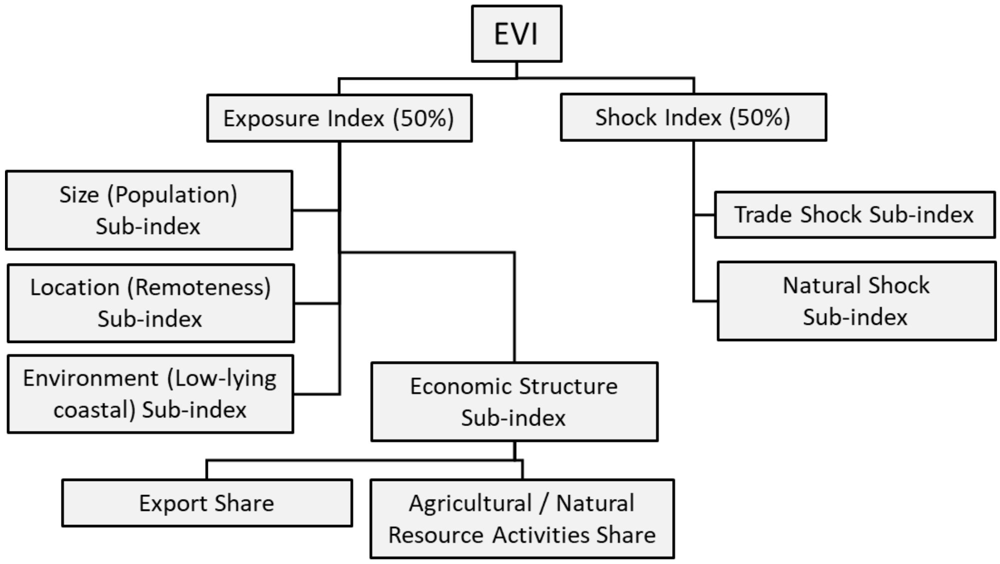



*Figure 2-1 - Structure of the UN Economic Vulnerability Index* [54]

The use of the EVI framework to produce time-based trends of the performance of different countries, and to show comparison between countries is instructive in the application and use of the scorecard of indices developed in this research.

### 2.2.3 Energy Security Frameworks

As noted above, the energy security of import dependent nations has been quite comprehensively studied and considering the trade linkage between import dependent energy consumers and export dependent energy exporters, various frameworks and indicators for energy security have been examined to inform the development of the present work.

The literature review for this chapter has identified a number of useful and relevant papers on energy security and assessment methods [10]–[29], [31], [32], [61]–[65]. Two papers in particular have been selected for analysis here; Kruyt [28] and Martchamdol [30]. These papers provide comprehensive summaries of the academic body of knowledge on energy security, which is used here to evaluate alternative inputs to the framework for energy exporter vulnerability.

Kruyt conducts a wide-ranging review of various frameworks and indicators related to energy security of supply, including simple indicators and composite indices, which are then mapped on the axes of availability (geological existence), accessibility (geopolitical), affordability (economic) and acceptability (environmental and societal) (the 4A's of energy security). In Table 2-2 the simple indicators are summarised, and constituent factors are extracted from the composite indices where they can be represented on a stand-alone basis. Repetition of indicators is avoided here by combining similar factors.

*Table 2-2 Energy Security Indicators (Kruyt)*[28]

| Indicator | Method / Unit |
|---|---|
| Resource estimates | Tonnes of coal or uranium, PJ of gas, barrels of oil |
| Reserve to production ratio (remaining life of reserves) | Reserve tonnes ÷ production tonnes per year = years of remaining production |
| Diversity indices (energy type, geographical source, supplier) | HHI index (sum of squares of each share), with a weighting factor applied |
| Import dependence (imports relative to total use) | PJ imported LNG per year ÷ PJ of annual total use |
| Political stability | World Bank worldwide governance indicators: "political stability & absence of violence", "regulatory quality". |
| Energy price | $ per PJ |
| Share of zero carbon fuels (vulnerability to environmental and societal constraints) | PJ of renewables and nuclear ÷ PJ of total primary energy |
| Market liquidity, measured as own demand as a proportion of amount available on the market | Primary energy PJ demand of fuel ÷ total global trade in that fuel in PJ |
| Energy intensity per capita | PJ of primary energy ÷ population |
| Energy imports portion of GDP | $ cost of imported energy ÷ $ GDP |
| Energy intensity per GDP | PJ of primary energy ÷ $ GDP |
| GDP per capita | $ GDP ÷ population |
| IEA physical unavailability index | PJ gas supplied through pipelines under oil priced indexed contracts ÷ PJ total primary energy |

Kruyt et al express the view that aggregating various metrics into a composite index hides the underlying dynamics, and that consensus is not easily reached on the relative weighting of component factors. Consequently, it is not possible to represent energy security of supply as a single all-encompassing index. Focussing on different aspects of energy security yields different outlooks, and the segregation of indicators provides for transparency in analysis without black-box distortion of results.

Martchamdol and Kumar, on the other hand, propose a unified index method, the "Aggregated Energy Security Performance Indicator" (AESPI). Martchamdol and Kumar conduct a comprehensive summary of energy security factors and composite indices proposed by others and establish a list of 119 individual elements related to energy security from various sources. The 25 individual indicators selected for AESPI formulation are listed in Table 2-3.

The method of aggregation of the AESPI involves correcting the sign each indicator to positive representing improved energy security, normalising to a scale of 0-10, then combining related indicators in groups, which are then subject to a group factor weighting to calculate the AESPI figure.

*Table 2-3 Energy Security Indicators (Martchamdol and Kumar)* [30]

| Indicator | Method / Unit |
|---|---|
| Total primary energy per capita | PJ of primary energy ÷ population |
| Final energy consumption per capita | PJ of final energy consumption ÷ population |
| Electricity per capita | TWh of electricity produced ÷ population |
| Total primary energy intensity | PJ of primary energy ÷ $ GDP |
| Final energy intensity | PJ of final energy ÷ $ GDP |
| Loss in Transmission | TWh of electricity generated ÷ TWh of electricity used |
| Loss in Transformation | PJ of final energy ÷ PJ of primary energy |
| Reserve production ratio (crude oil) | Barrels reserve ÷ barrels per year production |
| Reserve production ratio (natural gas) | PJ reserve ÷ PJ per year production |
| Reserve production ratio (coal) | Tonnes reserve ÷ tonnes per year production |
| Industrial energy intensity | PJ final energy for industry sector ÷ GDP share from industry sector |
| Agriculture energy intensity | PJ final energy for agriculture sector ÷ GDP share from agriculture sector |
| Commercial energy intensity | PJ final energy for commercial sector ÷ GDP share from commercial sector |
| Household energy per capita | PJ final energy for households ÷ population |
| Household electricity per capita | TWh electricity consumption for households ÷ population |
| Transportation energy intensity | PJ final energy for transportation sector ÷ GDP share from transportation sector |
| Share of capacity of renewable energy per total electricity generation | TWh from renewable sources ÷ total TWh electricity generated |
| Share of non-carbon energy per TPES | PJ of primary energy from renewable and nuclear ÷ PJ of total primary energy supply |
| Share of renewable energy per FEC | PJ of final energy from renewable ÷ PJ of total final energy consumption |
| Net energy import dependency | PJ of imported energy ÷ PJ total primary energy |
| $CO_2$ emissions per capita | Tonnes of $CO_2$ emitted per year ÷ population |
| $CO_2$ emissions per GDP | Tonnes of $CO_2$ emitted per year ÷ $ GDP |
| Household access to electricity | Households with electricity ÷ total households |
| Share of income to pay for electricity | kWh elec consumption x $/kWh elec price ÷ $ GDP per capita |
| Residential energy per household | PJ final energy residential use ÷ total number of households |

Kruyt et al (as summarised above) have included some authoritative works on energy security from a European perspective, including frameworks and indicator lists from Scheepers et al, and the European Commission Joint Research Centre Institute for Energy in their review. This research supplements these findings with authoritative work on energy security from a Japanese perspective. Murakami et al [8] in 2011 on behalf of the Institute of Energy Economic Japan conducted a quantitative assessment of the energy security conditions of Japan compared with China, France, Germany, South Korea, UK and US, using a scorecard of seven indicators. In a 2015 whitepaper [62], the Japanese Ministry of Economy Trade and Industry (METI) applied the same seven indicators, with slight naming differences, reproduced in Table 2-4.

*Table 2-4 Energy Security Indicators (Murakami)* [8]

| Indicator | Method / Unit |
|---|---|
| Primary energy self sufficiency | PJ from domestic and nuclear ÷ PJ total primary energy |
| Supplier country diversification | HHI index of supplier countries and their shares of supply |
| Reduction of risks at supply route choke points (Straits of Hormuz / Malacca) | PJ of primary energy supply passing through recognised choke points of ÷ total primary energy |
| Energy type diversification | HHI index of energy types and the shares primary energy supply of each |
| Reliability of the domestic power system | Hours of supply interruption ÷ hours in a year |
| Demand restraint / energy intensity | PJ primary energy ÷ $ GDP |
| Resilience to supply disruptions | Days of stockpiles of each energy type |

Frondel and Schmidt [66] propose a statistical indicator to quantify countries' long-term primary energy supply risk. Their method looks beyond price and concentrates on the physical availability of fossil fuels, with an indicator composed of four energy security factors: 1. diversification of sources in energy supply, 2. diversification of fuel imports, 3. long-term political and economic stability of energy supplier export countries, and 4. a country's own domestic energy self-sufficiency.

### 2.2.4 Energy Producing Companies

An examination of the perspective of energy producing companies is also considered here for insights into their vulnerabilities to production. This information is obtained from annual reports available in the public domain thanks to the duty of disclosure of publicly listed corporations in many jurisdictions to inform shareholders of risks to their business and changing market conditions.

Energy producing companies play an essential role in carrying out the activities that generate economic benefits for energy resource exporting countries, and their financial interests and vulnerabilities are sufficiently aligned with their host countries to provide a useful input from the commercial world into the framework for the energy exporter vulnerability.

To provide an indicative cross-section of industry, two coal producers (Peabody Energy and Rio Tinto) and two oil and gas producers (Shell and Total Energies) were selected, on the basis of their scale and global diversity of operations in the production of the three main internationally traded fossil fuel types examined in this chapter. Two annual reports from the period 2010-2019 were selected for each company and have been reviewed to extract key risks and vulnerabilities reported annually to shareholders. Table 2-5 summarises the vulnerability factors distilled from the perspective of energy producer corporations internal risk management reporting.

*Table 2-5 Energy Producer Common Vulnerability Factors*

| Risk Factor | Peabody [67], [68] | Rio Tinto [69], [70] | Total [42], [43] | Shell [71], [72] |
|---|---|---|---|---|
| Customer concentration | | ✓ | | |
| Law and regulation changes at operational site host countries | ✓ | ✓ | ✓ | ✓ |
| Community disputes near operational sites | | ✓ | | |
| Energy mix changes | | | | |
| Customer greenhouse gas emissions reductions policies | ✓ | ✓ | ✓ | ✓ |
| New resource exploration less successful | ✓ | ✓ | ✓ | ✓ |
| Operational resource estimates revised | | ✓ | ✓ | |
| Natural disasters and weather disrupt production | ✓ | ✓ | ✓ | |
| Transport availability and infrastructure difficulties | ✓ | ✓ | | |
| Equipment failure and production reliability | | ✓ | ✓ | ✓ |
| Commercial risks | ✓ | ✓ | ✓ | ✓ |
| Financial risks | ✓ | ✓ | ✓ | ✓ |
| Economic and political stability of operational host countries | ✓ | ✓ | ✓ | ✓ |
| Terrorist attack | | | ✓ | ✓ |
| Influence of pandemics | | | | ✓ |
| Demand for electricity | ✓ | | | |
| Ongoing technological innovation | ✓ | | ✓ | ✓ |
| Operational health, safety and environmental issues | | ✓ | ✓ | ✓ |
| Customer demographic changes | | | ✓ | |
| Physical effects of climate change on operations | | | ✓ | |

This list provides a useful validation of vulnerability factors identified through the overall literature review.

## 2.3 Establishing the Assessment Framework

Based on the review of general economic vulnerability frameworks, related energy security and oil exporter frameworks and evaluation of the key vulnerabilities and risk factors in exporting economies, this section describes the construction of the framework. The selection of indicators including additions, exclusions, and numerical methods applied are covered.

### 2.3.1 Adaption of Indices from Energy Security Frameworks

The numerous factors for energy security summarised above and their associated indices are a useful source for the energy exporter vulnerability framework due to the paired relationship of exporter and importer, producer and consumer.

Some factors assessing the consumer's energy security conditions are also directly applicable to assessing energy exporter vulnerability, such as primary energy mix diversification, energy intensity, and import dependence.

Other factors for evaluating importer energy security are quite similar for an energy export-oriented country and can be re-scoped for the export country. These include supplier diversification, which can be re-scoped as export customer diversification, and energy source diversification, which can be re-scoped as energy export diversification.

Some detailed domestic user-side factors, such as household electricity per capita, can provide useful input into decomposition analysis of changing demand patterns. However, adopting into the exporter vulnerability framework factors that are highly focussed on sections of energy demand would require inclusion of similar indicators for the full breakdown of energy demand to preserve balance, which then dilutes the overall framework with a collection of small factors with potentially limited influence dominating the framework. High level factors that provide a whole of country energy demand perspective are thus preferred.

Some consumer related energy security factors relate to temporary disruptions in supply at the user's side. This issue is discussed further in section 3.4 below.

The various energy security frameworks examined repeat many common factors and contain many similar and related factors than can be grouped when considering from the exporter's perspective.

One example of this is energy intensity, with various scope definitions; total primary energy supply or final energy consumption, energy consumed by sector and economic activity by sector. While these various subcategories make for interesting analysis, the results are primarily of benefit to the energy consumer. From the exporter perspective, seeing a customer as a whole, the definition of total primary energy per unit GDP is considered sufficient. User side energy efficiency, transmission losses and transformation losses can be integrated in the same way.

Some publications take interest in energy (primary, final, electricity) use per capita. Again, this provides for interesting decomposition analysis for the importing energy consumer, however from the exporter's perspective, the value is limited compared to energy intensity as a ratio of energy to economic activity, since, as Yanagisawa [73] finds in the case of Japan, energy demand in some countries is more directly linked to economic activity than to population.

In any case, while energy intensity per unit GDP or per capita are beneficial factors for analysis of the energy security of user-side energy system, a clear conceptual link of user energy intensity of either type to exporter vulnerability was not found in the literature reviewed, nor could such a linkage be substantiated in this research. Accordingly, no metric related to customer energy intensity is included in the proposed framework.

### 2.3.2 Influence of Temporary Supply Disruptions on Exporter Vulnerability

A number of factors identified in the literature review relate to temporary disruptions to the energy system at production sites (such as due to planned maintenance or emergency stoppages) and along transport routes - such as due to logistics system equipment reliability, weather disruptions or security issues. This research has considered the sensitivity and resilience of energy systems to supply disruptions including economic impacts of a supply disruption, typical mitigations to disruption of supply, and time period sensitivity to supply disruptions, with the objective of establishing related sensitivities and vulnerabilities of the producer / exporter.

#### 2.3.2.1 Electricity

A disruption in electricity supply will cause material economic impacts in only seconds to minutes. Some examples include road and rail transport signalling going off-line, shut-down of financial industry computer systems, and cooling and setting of metals such as aluminium or manganese in smelter pots. For this reason, the concept of Value of Lost Load (VoLL)[74] is commonly applied by network operators and regulators worldwide as a method of setting electricity spot market maximum price, to reflect the true cost to the economy of unserved electricity demand or of a disruption in supply. In Australia's National Electricity Market, the VoLL setting for the maximum spot price is A$15,000/MWh, an incredible amount considering the average price is closer to A$80/MWh [75]. Mitigations to electricity supply disruption begin with adequate generation spinning reserve, and include a robust transmission network, emergency battery and on-site generator back-up for critical loads (hospitals, air traffic control, etc), and interconnections with other regions or countries.

#### 2.3.2.2 Pipeline Natural Gas

A disruption to pipeline gas supply will cause material economic impacts in only a few hours, interrupting process industries, food preparation, the cooling of gas furnace operations such as brickworks and glass manufacturing, and flow-on impacts to electricity supply through gas fired power stations. Pipeline line-pack is a common mitigation to supply disruptions, giving a buffer of potentially 1-3 days. By increasing the pressure in a gas pipeline, the quantity of gas stored can be increased, and later released even if upstream supply is disrupted.

The Colongra 4x150MW open cycle peaking gas turbine power plant in Australia is an interesting example of the application of line-pack [76]. The gas supply rate and pressure are too low to permit full operation of the gas turbines, so the plant was built with a 9km connecting spur line to the main pipeline, most of which is located in 3 loops around the power plant site itself, to create enough length for a 3.4MPa to 13 MPa line-pack pushing 4 times as much gas into the pipeline that is charged over a 24 hour period to provide storage for 5 hours operation at full output, regardless of supply availability from the gas network. Gas storage in geological caverns is also commonly used in gas pipeline networks [77], which can hold multiple weeks of gas supply, although these storage sites are often not near demand centres and due to location may be subject to supply disruption if the pipeline from the storage location and the load centre is disrupted.

#### 2.3.2.3 LNG Imports

Many energy consumers dependent on imports have implemented sophisticated strategies to ensure energy supply security in the event of disruptions on the production side or along transport routes. The reference example of LNG imports into Tokyo Bay, the world's largest LNG-importing and demand centre is examined. LNG is used predominantly for power generation in combined cycle gas turbine thermal power plants and to supply the city gas distribution system for industrial, commercial and domestic users.

There are seven LNG receiving and storage terminals in Tokyo Bay (shown in Table 2-6), operated by JERA (formerly Tokyo Electric Power Company) and Tokyo Gas, with a total LNG storage capacity of 2,830,500t. In 2017, a total of 34,780,000t of LNG was imported into Tokyo Bay [78], [79]. This storage capacity represents approximately one month (29.7 days to be precise) of 2017 Tokyo Bay LNG imports.

*Table 2-6 Tokyo Bay Area LNG Storage Terminals and Capacity* [78]

| Location | Capacity (t) |
|---|---:|
| Sodegaura LNG Terminal | 638,100 |
| Negishi LNG Terminal | 463,050 |
| Ogishima LNG Terminal | 383,400 |
| Yokohama Thermal Power Station LNG Terminal | 70,200 |
| Sodegaura Thermal Power Station LNG Terminal | 533,250 |
| Ogishima Thermal Power Station LNG Terminal | 243,000 |
| Futsuu Thermal Power Station LNG Terminal | 499,500 |
| Total | 2,830,500 |

From the diversified LNG supply sources shown in Table 2-7, a weighted average shipping time of 16.4 days is calculated, hence considering a complete disruption of LNG deliveries, the buffer storage is approximately equivalent to 1.8 average delivery cycles. When combined with supply diversity, this storage buffer provides considerable protection against supply and transport disruptions. Accordingly, in the event of a disruption to supply, the buffer storage quantity of LNG would be reduced temporarily to satisfy demand, then when supply was restored, the storage would be replenished to its full quantity.

*Table 2-7 Sources of LNG received in Tokyo Bay* [78], [79] *and shipping time* [80]

| Supplier country | % of Tokyo Bay share | Export terminal | Days shipping to Tokyo Bay |
|---|---|---|---|
| Australia | 24.5% | Darwin | 14 |
| Malaysia | 23.0% | Bintulu | 13 |
| UAE | 13.4% | Fateh | 32 |
| Brunei | 8.6% | Brunei | 12 |
| Russia | 9.0% | Sakhalin | 5 |
| PNG | 6.5% | Moresby | 14 |
| Qatar | 7.0% | Ras Lafan | 31 |
| Weighted average delivery time | | | 16.4 |
| Others | 7.0% | | |

#### 2.3.2.4 Coal Fired Power Stations

Coal fired power stations dependent on imported fuel follow a similar fuel buffering strategy, usually at individual power plant sites. The Hitachinaka Thermal Power Station (2 x 1000MW), north of Tokyo, has a 400,000t stockpile adjacent to the plant, which is supplied primarily from the Warkworth mine in Australia, exporting out of the Port of Newcastle [81]. At the plant's coal burn rate of 14.8kt/day, this buffer storage is equivalent to 25 days operation [81]. Considering the typical shipping time from the Port of Newcastle is 19.4 days [80], the buffer storage is equivalent to 1.3 delivery cycles, meaning that a ship could potentially sink on route and following the regular delivery schedule the next ship would still arrive before fuel ran out at the power station.

#### 2.3.2.5 Petroleum

The government of Japan holds a strategic reserve of petroleum of 51.5 M m3 and a further 41.5 M $m^3$ of petroleum and derivative products held privately[82]. This storage is about equivalent to 6 months normal consumption, which is a strong mitigation to the major economic impacts that would flow from potential transport disruptions.

#### 2.3.2.6 Uranium

Although also a baseload firm of power generation like coal, a 4x900MW pressurised water reactor plant such as EDF's Tricastin Nuclear Power Plant in France needs only 2.0t of nuclear fuel for a 4-year refuelling cycle, during which 1/4 of the fuel charge is replaced annually[83]. The considerable economic impacts of a disruption to the operation of all nuclear power stations has already been experienced in Japan, however a disruption to supply of nuclear fuel would not be experienced in full force until at least 2 years later when stocks were depleted by the refuelling cycle.

#### 2.3.2.7 Producer and User Comparison of Disruption Mitigations and Vulnerability

The principle of buffer storage is similarly applied at production sites and export terminals of LNG, coal, and petroleum products, to allow producers to continually satisfy their contracted supply arrangements even with disruptions at the production site. Consequently, so long as the end user's rate of consumption is not affected, over a cycle of a few weeks to a few months, the total aggregate import quantity is unaffected. Accordingly, temporary disruptions to production and transport of energy exports do not necessarily contribute to the economic vulnerability of the exporting country so long as standard industry practice of buffer storage of fuels at both the production / export end and consumer / importer end is applied.

Energy exporters that are directly connected to customer energy networks, such as international electricity transmission lines or gas pipelines can potentially be exposed to similar supply disruptions as customers. However, as shown in Table 2-8 exporters of energy resources requiring transport and that are not physically connected to the customer's energy system are protected from short term disruptions by supply buffers in the both the suppliers and customers systems.

*Table 2-8 - Mitigations to Energy Supply Disruptions*

| Energy Type | User Mitigation to Disruption | Exporter Vulnerability to Disruption |
|---|---|---|
| Electricity | Robust transmission network, excess generation capacity | Loss of generation revenue, possibly during a peak pricing event. |
| Pipeline gas | Line pack, storage caverns | May have to flare excess gas or curtail production |
| LNG | Buffer storage at import receiving points and at power stations | Negligible disruption, since user will need to rebuild buffer storage following disruption event. Production and export quantities not affected when the disruption and recovery phase are considered. |
| Coal | | |
| Petroleum | | |
| Uranium | | |

This research has found that the bulk transport and storage of LNG, coal, petroleum and uranium all yield very similar results for the energy exporter. It is found that, due to energy security concerns on the part of importers, the mitigations for energy supply disruptions that are implemented result in negligible residual energy exporter vulnerability. Accordingly, this finding is fed back into the main research on energy exporter vulnerability to confirm a focus on long term shifts in energy supply and demand.

### 2.3.3 Nuclear Power and Uranium

Uranium is somewhat of a special case among exported energy resources. The primary exported energy resource from which nuclear energy is produced, yellowcake ($U_3O_8$), is typically refined from uranium ore at the mine site for efficient transportation. However, yellowcake contributes only around 40-45% [84], [85] to the total cost of nuclear fuel, which in turn contributes 14-17% [84], [85] to the total cost of nuclear electricity when modern high efficiency centrifuge enrichment is used, as set out in Table 2-9.

*Table 2-9 Nuclear fuel cycle cost breakdown* [84], [85]

| Process | Proportion of total |
|---|---|
| Uranium | 40-45% |
| Conversion | 8-10% |
| Enrichment | 26-29% |
| Fuel fabrication | 21-24% |

Hence, the exported energy resource component of nuclear electricity is only 5.6-7.7%. For similar baseload sources of electricity generation such as coal and LNG (in a combined cycle power plant), fuel costs contribute approximately 45% and 79% of electricity cost respectively [86]. Hence, the share of revenue earned by the energy exporter from nuclear is comparatively quite small.

At the end of June 2021, the spot market prices of uranium oxide (yellow cake) and thermal coal were quite comparable, at USD71 and USD107 per tonne respectively [87]. However, the electrical energy density (quantity of electrical energy that can be produced from a tonne of the fuel) of each fuel is vastly different, with 31,020MWh/t of yellowcake uranium oxide compared to 3.1MWh/t for coal [88], [89]. From an energy exporter's perspective, fuel supplied to an energy customer to provide 1.0TWh of electricity could either earn USD2,289 from 32t of uranium exports or USD 34,240,000 from 320,000t of coal exports. Since the exporter is not in a position to influence the power generation technology choices of its customers, the exporter would obviously choose to export either, or both, if the demand exists and the price is at least above production costs. However, it is clear that the uranium export only makes a negligible economic contribution to the exporter in comparison to the export of fossil fuels.

From a technical perspective, it is clear that nuclear energy relies much more on conversion technologies in both fuel preparation and energy conversion (the nuclear power plant itself) than on the value of the primary export (yellowcake), compared to fossil fuel energy resources. When considering both the contribution to total electricity cost and energy density, uranium as an energy resource export is clearly not directly comparable to other exported energy resources. In the mix of energy resource exports, uranium only makes a negligible economic contribution to the exporter while at the same time provides a massive energy benefit to the importer. Because of these factors, it is determined to exclude uranium from the basket of energy resources assessed in the assessment methodology applied in this work.

### 2.3.4 Principles for Selection of Factors

The process of selecting which of the many potential related factors established above to the energy exporter vulnerability framework necessarily requires some prioritisation. In this work, a strategic approach has been taken to exporter vulnerability and focus on factors quantifiable from energy units as the intrinsic value of energy resources, rather focussing on energy resource prices which are subject to short term volatility. First, a screening process is applied to the large number of potential factors, indicators and metrics that have been established in this chapter. The screening process is structured as show in Figure 2-2.

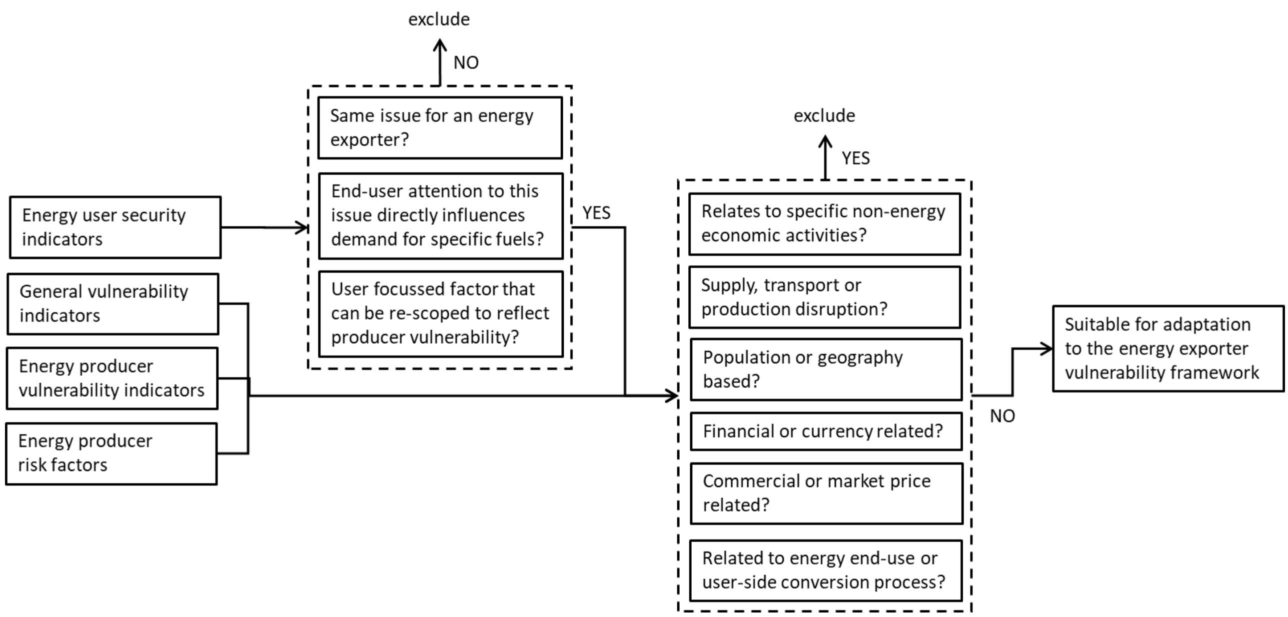



*Figure 2-2 - Screening Process for Selection of Energy Exporter Vulnerability Factors*

The filtered short list of factors was then assessed into according to the following principles:

1. Factors should be sufficiently distinct so as not to give undue emphasis to related issues.
   A number of the factors established from the literature review are quite similar in nature, such as energy intensity in various sectors of the customer's economy. In this case, the most representative factor is selected, to avoid giving disproportionate weight to the importance of a set of similar factors in the final scorecard, which in this example would be total energy intensity of the customer's economy.
2. There should not be any direct dependency relationships between indices.
   Some factors established from the literature review depend on other factors as inputs such as reserve production ratio and resource estimates. For the purposes of this analysis, one

or the other is selected, on the basis of which contributes more directly to the exporter vulnerability framework scorecard.

3. Factors must be quantifiable with objective data.
   The research topic is such that it is realistic for the scorecard to be based on quantitative analysis derived from objective data, which is generally readily available. Expert rating assessments or surveys are not applied for this reason, and descriptive comparisons only figure as explanatory notes.

### 2.3.5 Energy Decarbonisation Implications for Fossil Fuel Exports

Considering the increasing pace of global action to decarbonise human activity to limit the extent of anthropogenic climate change, it is critical to include the subsequent carbon vulnerability faced by energy resource exporters due to the $CO_2$ emissions of their exported fossil fuels in the assessment framework. This carbon vulnerability is present intrinsically as the aggregate $CO_2$ intensity [90]–[92] of the exporter's energy resource export blend. Coal, as a higher $CO_2$ intensity fuel carries a higher risk of reduced future exports, compared to gas which has a lower $CO_2$ intensity. The emergence of international trade in zero $CO_2$ exportable energy resources such as hydrogen produced from renewable electricity, biomass wood pellets, or other potential forms on the other hand have great potential for growth and would reduce a country's export vulnerability based on $CO_2$ emissions intensity. The composition of a country's energy resource exports and hence the $CO_2$ intensity vulnerability is entirely within the control of that country, through such instruments as permits for new resource projects.

Additionally, energy resource exports are subject to customer action to reduce $CO_2$ emissions, increase domestic renewable energy in place of imported fuels, and favour gas as lower $CO_2$ intensity fuel compared to coal. Various organisations that have developed systems for rating the climate change action of countries [93]–[96]. In this chapter the rating system of the Climate Change Performance Index (CCPI)[93] is adopted to quantify vulnerability of fossil fuel exports to climate change action by export customers. CCPI indices for countries are a composite index including past performance, present status and future targets for greenhouse emissions reduction, renewable energy penetration, energy use, and climate policy. The CCPI is selected as the preferred factor because of its underlying detailed quantitative methodology and also the relative granularity of the rating scores compared to other systems and is combined with a customer diversity index to provide proper weighting of the export's customer portfolio.

### 2.3.6 Diversity Indices

#### 2.3.6.1 Comparison of HHI and SWI.

From the literature review a number of diversity indices were established, all of which use either the Shannon-Weiner Index (SWI) approach, or the Herfindahl – Hirschman Index (HHI) approach (also called the Simpson index). Here the difference and select a preferred method for evaluating diversity is considered.

Mathematically, the SWI index is calculated using the natural logarithms of each category, while the HHI index is calculated using the square of each category. From the literature reviewed, both are used in the context of energy security diversity assessment. As noted by Wu & Rai [97], the

SWI index tends to emphasise the contribution of smaller value categories, while the HHI emphasises the contribution of larger value categories. The selection of which diversity index to apply in any situation is ultimately a matter of which is most fit-for-purpose. In the case of this research into energy exporter economic vulnerability, the primary interest is in how diversity (of energy export types, customers, etc) contributes to GDP vulnerability, in which case, the HHI method with its emphasis on the higher value categories is selected as the most applicable.

#### 2.3.6.2 Weighting Methods

The clear shortcoming of any diversity index is that the significance of the different categories to the overall assessment is more than just their pure numerical share of the whole. Accordingly, it is beneficial to introduce a method of weighting to include additional value determinations in the diversity scoring process, as recognised by Gupta[11], Murakami [8], Wu & Rai [97] , and Stirling [98], [99].

The selection of weightings or modifiers has the benefit of adding depth to an indicator, such as customer diversity, or to define a new indicator, such as in the case of adding end use $CO_2$ emissions intensity to the export energy resource mix. Weighting by expert judgements is used in some cases, such as the unified energy security index proposed by Scheepers et al. [64] , however this method is the most arbitrary of all and requires referential scaling to be applied.

In the case of customer diversity, Murakami [8] makes use of the OECD Credit Risk Classification to provide weightings to the energy supplier HHI diversity index from Japan's perspective as an importing customer. Gupta's [11] weighting approach to the HHI for energy suppliers includes both the World Governance Indicators [100], [101] for governance issues and domestic societal outcomes, as well as country credit risk rating by the Economist Intelligence Unit. Kruyt [28] notes briefly the IEA's country diversity weighting which applies parts of the World Bank worldwide governance indicators, which are however quite narrowly based on governance rather than an actual commercial rating.

This work proposes to introduce a novel approach to weighting the export customer diversity HHI by applying a carbon emissions reduction (CER) factor. The diversity index is adjusted by a factor representing the strength of each export customer's actions to reduce $CO_2$ emissions, where stronger actions to reduce $CO_2$ emissions cause greater vulnerability to current fossil fuel exports.

### 2.3.7 Selection of Factors and Formulation of Metrics

A consolidated scorecard of independent metrics has been established from the number of relevant and related factors that passed the filtering process set out above. The full list of factors, their source, action to exclude or integrate into the scorecard metrics is set out in Table 2-10. Since many factors are related, in accordance with the factor selection principles set out in section 2.3.4 above, related factors have been combined to establish a concise, workable list for the purpose of case study assessment. As set out in section 2.3.1, factors sourced from energy security have been adapted to suit the energy exporter perspective.

*Table 2-10 Comprehensive List of Potential Factors for Exporter Energy Economic Vulnerability*

| Factor | Dike [48] | Bhattacharyya [47] | Kanchana[49] | UN EVI [54] | Kruyt [28] | Martchamadol [30] | Murakami [8] | Frondel [66] | Producer Corp[42], [43], [67]–[72] | Action | Rationale for Action (Include or Exclude) | Integrated into Metric # |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Energy exports as a share of total exports | ✓ | | | | | | | | | Include | Significance to total exports is a material consideration for vulnerability | M4 |
| 2. Customer diversity | ✓ | | ✓ | | | | | | ✓ | Include | Diversification is an effective mitigation to vulnerability | M3 |
| 3. Distance to customer | ✓ | | | | | | | | | Exclude | No direct exporter impact | |
| 4. Total exports as a share of GDP | ✓ | | ✓ | ✓ | | | | | | Include | Similar to factor 1, export significance to GDP is a material consideration for overall economic vulnerability | M4 |
| 5. Energy price | | ✓ | | | ✓ | | | | | Exclude | Principally a concern of the importer, since exporter can exercise price and supply control | |
| 6. Energy export to energy production ratio | | ✓ | ✓ | | | | | | | Include | Adapted into exporter resource to production ratio | M5 |
| 7. Ratio of exports to domestic use | | ✓ | | | | | | | | Include | Adapted to customer import dependence as a vulnerability | M1 |
| 8. Domestic energy intensity | | ✓ | | | | ✓ | | | | Exclude | Principally a concern of the importer, exporter is more interested in customer total demand | |
| 9. Share of net energy imports to primary energy mix | | | ✓ | | ✓ | ✓ | | | | Include | Customer import dependence strongly influences their energy security policy, which will impact on supplier countries | M1 |
| 10. Share of energy import expenditures to GDP | | | ✓ | | ✓ | | | | | Include | Adapted from importer-perspective to the exporter's metric of energy exports ration to GDP, as in factor 1 and 4 | M4 |
| 11. Political stability of major energy trade partners | | | ✓ | | ✓ | | | ✓ | ✓ | Exclude | Principally a concern of the importer in energy supply. For the exporter, political stability is a broader issue than just energy export vulnerability. | |
| 12. Openness to global energy trade | | | ✓ | | | | | | | Exclude | Assumed for any international market participants | |
| 13. Diversity of primary energy mix | | | ✓ | | ✓ | | ✓ | ✓ | ✓ | Include | Adapted to reflect the exporter's vulnerability to a customer's potential to diversify energy sources | M2 |
| 14. Reserves to production ratio | | | ✓ | | ✓ | ✓ | | | ✓ | Include | Remaining production before resources are exhausted is central concern of exporters | M5 |

| Factor | Dike [48] | Bhattacharyya [47] | Kanchana[49] | UN EVI [54] | Kruyt [28] | Martchamadol [30] | Murakami [8] | Frondel [66] | Producer Corp[42], [43], [67]–[72] | Action | Rationale for Action (Include or Exclude) | Integrated into Metric # |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15. Energy self-sufficiency rate | | | ✓ | | | | ✓ | ✓ | | Include | Adapted to reflect the exporter's vulnerability to a customer's potential to increase self-sufficiency | M1 |
| 16. Population | | | | ✓ | | | | | ✓ | Exclude | Importer population has no relevance to exporter vulnerability | |
| 17. Location (remoteness) | | | | ✓ | | | | | | Exclude | Supply routes and distances primary concern of importer, not exporter | |
| 18. Environment (low lying coastal) | | | | ✓ | | | | | | Exclude | Not relevant to energy exporter | |
| 19. Agricultural / Natural Resource share of GDP | | | | ✓ | | | | | | Include | Adapted to energy export share of GDP as related to factor 1, 4 and 10 | M4 |
| 20. Trade shock risk | | | | ✓ | | | | | | Exclude | Not relevant to energy exporter | |
| 21. Natural shock risk | | | | ✓ | | | | | | Exclude | Not relevant to energy exporter | |
| 22. Resource estimates | | | | | ✓ | | | | ✓ | Include | Of central concern to exporters, as with factor 14 | M5 |
| 23. Supplier diversity | | | | | ✓ | | ✓ | ✓ | | Include | Adapted from importer-focussed to consider exporter's diversity of customers as with factor 2 | M3 |
| 24. Supply source geographical diversity | | | | | | | | | | Exclude | Location and transport route risk not relevant to exporters; short term disruptions mitigated by buffer storage | |
| 25. Share of zero carbon fuels (vulnerability to climate change policies) | | | | | ✓ | ✓ | | | | Include | Increasingly critical vulnerability for exporters as customers reduce CO2 emissions, adapted from importer factor | M6 |
| 26. Market liquidity, (ratio of own demand to available on market) | | | | | ✓ | | | | | Exclude | Essentially an importer customer concern only | |
| 27. Energy intensity per capita | | | | | ✓ | ✓ | | | | Exclude | Energy intensity primarily concerns the consumer; reduced energy intensity allows the consumer to increase use at higher productivity, not a supplier vulnerability. | |
| 28. Energy intensity per GDP | | | | | ✓ | ✓ | ✓ | | | Include | Adapted to energy export share of GDP as related to factor 1, 4, 10 and 19 | M4 |
| 29. GDP per capita | | | | | ✓ | | | | | Exclude | Consumer side domestic economic indicator only | |
| 30. Loss in Transmission | | | | | | ✓ | | | | Exclude | User side efficiency factor, negligible impact on suppliers (exporters) | |

| Factor | Dike [48] | Bhattacharyya [47] | Kanchana[49] | UN EVI [54] | Kruyt [28] | Martchamadol [30] | Murakami [8] | Frondel [66] | Producer Corp[42], [43], [67]–[72] | Action | Rationale for Action (Include or Exclude) | Integrated into Metric # |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31. Loss in Transformation | | | | | | ✓ | | | | Exclude | User side efficiency factor, negligible impact on suppliers (exporters) | |
| 32. $CO_2$ emissions per capita | | | | | | ✓ | | | | Exclude | CO2 emissions is an important consideration, but ratio per capita is not relevant to the exporter | |
| 33. $CO_2$ emissions per GDP | | | | | | ✓ | | | | Include | CO2 emissions is an important consideration, this factor is adapted into a weighting on customer diversity | M3 |
| 34. Household access to electricity | | | | | | ✓ | | | | Exclude | User equity and access factor, no direct bearing on exporter vulnerability | |
| 35. Share of income to pay for electricity | | | | | | ✓ | | | | Exclude | User equity and access factor, no direct bearing on exporter vulnerability | |
| 36. Residential energy per household | | | | | | ✓ | | | | Exclude | User equity and access factor, no direct bearing on exporter vulnerability | |
| 37. Reduction of risks at supply route choke points | | | | | | | ✓ | | | Exclude | Transport route risk not relevant to exporters; short term disruptions mitigated by buffer storage | |
| 38. Reliability of the domestic power system | | | | | ✓ | | ✓ | | | Exclude | Short term loss of reliability in importer's electricity system has negligible impact on fuel consumption, hence not relevant to exporter vulnerability | |
| 39. Resilience to supply disruptions | | | | | | | ✓ | | | Exclude | Short term loss of reliability in importer's electricity system has negligible impact on fuel consumption, hence not relevant to exporter vulnerability | |
| 40. Law and regulation changes at operational site host countries | | | | | | | | | ✓ | Exclude | Exporter's domestic legal stability is a broader issue than energy export vulnerability, excluded in this analysis | |
| 41. Community disputes near operational sites | | | | | | | | | ✓ | Exclude | Social licence to operate for resource projects is a broader issue than energy export vulnerability, excluded in this analysis | |
| 42. Customer greenhouse gas emissions reductions policies | | | | | | | | | ✓ | Include | Increasingly critical vulnerability for exporters as customers reduce CO2 emissions | M3 |
| 43. Natural disasters and weather disrupt production | | | | | | | | | ✓ | Exclude | Production disruption from weather events is typically mitigated by buffer storage at various | |

| Factor | Dike [48] | Bhattacharyya [47] | Kanchana[49] | UN EVI [54] | Kruyt [28] | Martchamadol [30] | Murakami [8] | Frondel [66] | Producer Corp[42], [43], [67]–[72] | Action | Rationale for Action (Include or Exclude) | Integrated into Metric # |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | stages of the supply chain, hence no material vulnerability impact | |
| 44. Transport availability and infrastructure difficulties | | | | | | | | | ✓ | Exclude | Logistics disruption is typically mitigated by buffer storage at various stages of the supply chain, hence no material vulnerability impact | |
| 45. Equipment failure and production reliability | | | | | | | | | ✓ | Exclude | Production equipment reliability disruption is typically mitigated by buffer storage at various stages of the supply chain, hence no material vulnerability impact | |
| 46. Commercial risks | | | | | | | | | ✓ | Exclude | Corporate concerns of producer companies, not directly impacting exporter vulnerability | |
| 47. Financial risks | | | | | | | | | ✓ | Exclude | Corporate concerns of producer companies, not directly impacting exporter vulnerability | |
| 48. Terrorist attack | | | | | | | | | ✓ | Exclude | For the exporter, terrorist risk is a broader issue than just energy export vulnerability, and beyond the scope of this study. | |
| 49. Influence of pandemics | | | | | | | | | ✓ | Exclude | For the exporter, pandemic risk is a broader issue than just energy export vulnerability, and beyond the scope of this study | |
| 50. Demand for electricity | | | | | | | | | ✓ | Include | Related to demand for imported fuels | M1 |
| 51. Ongoing technological innovation | | | | | | | | | ✓ | Exclude | Beyond the scope of this study | |
| 52. Operational health, safety and environmental issues | | | | | | | | | ✓ | Exclude | Operational concerns, not directly related to exporter vulnerability | |
| 53. Physical effects of climate change on operations | | | | | | | | | ✓ | Exclude | Production disruption from weather events is typically mitigated by buffer storage at various stages of the supply chain, hence no material vulnerability impact | |

The consolidated scorecard of energy exporter vulnerability metrics derived from these factors is as follows:

External vulnerability factor metrics

M1 - Customer Energy Import Dependence
M2 - Customer Energy Mix Diversity
M3 - Export Customer Diversification Weighted by Carbon Emissions Reduction Rating

Internal vulnerability factor metrics

M4 - Energy Exports Significance to GDP
M5 - Resource to Production Ratio
M6 - Carbon Emissions Intensity of Energy Export Blend

Efforts have been made to avoid and minimise ambiguities and conflicts in the process of defining the scorecard. The selection of a total of 6 metrics is hence intentionally set with 3 each for internal and external vulnerabilities for balance.  . It has also been important to avoid thematic overlaps between metrics and inter-relationships as seen with some energy security indicators, where multiple metrics use the same inputs, or where the output from one metric is an input to another. Although the metrics selected are generally intended to avoid price-based, financial, currency exchange rate or commercial factors, the metric of energy exports significance to GDP is included on an export revenue basis as it is considered of central importance to assessing the exporter's vulnerability to loss of export revenue.

and provides a scorecard that does not present so much data that it loses its effectiveness as an aggregated analysis tool.

### 2.3.8 Unitary Index or Scorecard of Indices

Through the literature review of various economic and energy exporter vulnerability frameworks as well as energy security frameworks it is observed that the number of publications proposing a unitary composite index and those proposing a scorecard of distinct indices are roughly equal. Both approaches have their merits and shortcomings.

The method of aggregating to a single unitary index is a pragmatic means of making sense of what might otherwise be a large number of relevant indicators for comparison and trending, however the aggregation process by necessity removes granularity of insight into specific indicators. Further, the process of combining necessitates weighting and comparative scaling of scores of unrelated metrics, which strongly influence the final result and reduce visibility of the actual underlying factors.

The scorecard approach of separate indicators was found to be frequently used in energy policy decision making and commercial energy production operations, and this method definitely allows for greater depth of insight into various metrics. With so many different metrics available, those relevant to the analysis can be selected, however in order to avoid an unmanageable data set, some metrics are typically excluded from the final scorecard.

For the purposes of this research, a scorecard of multiple distinct indices has been selected to represent energy exporter economic vulnerability with granular transparency of specific issues to facilitate subsequent deeper analysis of individual factors. The scorecard of six indices is selected to allow for separate analysis of distinct factors to observe distinct trends factor-by-factor, while combining similar factors into a manageable list without individual factors becoming diluted in significance in a longer list and to avoid thematic overlaps. Three indices each have been selected for internal and external factors to provide balance in these two perspectives on vulnerability. In addition, combined indices are also developed and applied for the case studies as a simplified, supplementary analysis.

### 2.3.9 Scaling of Metrics in the Scorecard

In order to bring the scores for disparate indicators to a common scale for ease of comparison and trending, normalisation of values is required. Tongsopit et al [65], Gupta [11], Kanchana et al [49], in their work related to quantifying energy security or exporter vulnerability, each apply min-max method of linear transformation to normalise data and bring all indicators to a common scale.

Others, such as Martchamadol & Kumar [30] apply a standardisation method designed to align the mean and standard deviation of indicators with different units. This method specifically results in positive and negative values for each indicator.

The min-max method of linear transformation has been selected for application in the assessment methodology applied in this research over the mean and standard deviation method, since it produces normalised results on a scale of 0 to 1, rather than standard deviation scores that are + / - around a zero neutral point with no clear upper or lower limit. The linear transformation is applied separately to each metric’s full range of values of all case study countries and all years assessed, such that the “0” score for any metric after normalisation equates to the lowest score for the metric's full dataset, and the maximum score returns a "1". In addition, the signs (+ve or -ve) of the metrics are adjusted to make them positively related to the exporter's vulnerability if necessary. This method is applied to allow for cross-comparison between different metrics on the same scale, and combination into unified metrics. The operation is set out in Equation 2-5.

*Equation 2-5 - Method for Normalisation of Scores*

$$M_n' = \frac{M_n - Min_n}{Max_n - Min_n}$$

Where:
$M_n'$ is the normalised value for metric "n" on a scale of 0 to 1
$M_n$ is the value of metric "n"
$Min_n$ is the minimum value of the data set for metric "n"
$Max_n$ is the maximum value of the data set for metric "n"

## 2.4 Assessment Framework and Quantitative Metrics

The assessment framework is composed of six distinct metrics. Vulnerability to external factors on the supplier side and the underlying internal vulnerability of the exporting economy are represented with 3 metrics each. These six metrics are derived from the comprehensive review of related factors shown in Table 2-10, with each related vulnerability factor that was identified extracted and included in the scorecard. The longer list of relevant factors identified in Table 2-10 is compiled to the scorecard of six metric by combining similar and related factors into a single metric to avoid thematic overlaps and ensure the size of the scorecard of metrics is manageable for meaningful appraisal by less expert audiences.

### 2.4.1 Customer Energy Import Dependence

This metric is the same as that used domestically to assess import dependence as a factor of energy security, calculated as the ratio of the export customer country's energy imports to its total primary energy supply, calculated as shown in Equation 2-6.

*Equation 2-6 - M1 (Customer Energy Import Dependence)*

$$M1_{countryA} = \frac{E_{countryA}}{TPES_{countryA}}$$

From the importing customer's energy security perspective, reduction in import dependence for energy supplies is desirable, so high import dependence represents a vulnerability for the exporter that the import customer will reduce imports. Energy import dependence may practically be reduced by measures such as increased development and utilisation of domestic fossil fuel reserves, development of renewable energy and nuclear power.

In addition to assessing individual export customers, it is beneficial to form a portfolio view encompassing all export customers. To do so, the import dependence ratio of each export customer is multiplied by the share of energy exports to that customer, and then the total is divided by the exporter's total energy exports, as shown in Equation 2-7.

*Equation 2-7 - M1 (Customer Energy Import Dependence) - Detail*

$$M1 = \frac{Q_A \times ({}^{E}/_{TPES})_A + \ Q_B \times ({}^{E}/_{TPES})_B + \cdots + \ Q_n \times ({}^{E}/_{TPES})_n}{Q_{total\ exports}}$$

Where;
Q = quantity of energy exports to country A, B, n, or the total energy export (in PJ)
E = energy imports by country A, B, n (in PJ)
TPES = total primary energy supply of country A, B, n (in PJ)

For practicality of computation of the metric, the largest customers representing 80% of exports by petajoules are selected, and the quantity of total exports to those customers is applied as the denominator. In case the 80% threshold does not cover at least 5 export customers, the energy share of up to 5 export customers is assessed to ensure customer diversity is sufficiently captured.

### 2.4.2 Customer Energy Mix Diversity

The HHI index is used to assess energy mix diversity of individual export customers. From the importer's perspective greater diversity (represented by a lower HHI score) is preferred to enhance energy security. Therefore, a higher score represents higher vulnerability to the exporter, since the importer can be expected to make efforts to diversify their energy mix and potentially reduce imports of existing fuels in the total primary energy supply mix.

The exporter's total export portfolio position weighted by export energy share of each customer is thus calculated as shown in Equation 2-8.

*Equation 2-8 – M2 (Customer Energy Mix Diversity)*

$$M2 = \frac{(Q \times HHI_{TPES})_A + \ (Q \times HHI_{TPES})_B + \cdots + \ (Q \times HHI_{TPES})_n}{Q_{total\ energy\ exports}}$$

Where;
Q = quantity (in PJ) of energy exports to country A, B, …, n, or the total energy export quantity
$HHI_{TPES}$ = HHI diversity index for total primary energy supply for country 1, 2, n

$= (x_{coal})^2 + (x_{gas})^2 + (x_{oil})^2 + (x_{nuclear})^2 + (x_{hydro})^2 + (x_{wind})^2 + (x_{solar})^2 + (x_{biomass})^2 + (x_{geothermal})^2$

$X_{fuel\ type\ A}$ = consumption of fuel type A / TPES

For practicality of computation of the metric, the largest customers representing 80% of exports by petajoules are selected, and the quantity of total exports to those customers is applied as the denominator. In case the 80% threshold does not cover at least 5 export customers, the energy share of up to 5 export customers is assessed to ensure customer diversity is sufficiently captured.

It is also a valid approach to pursue a more targeted fuel diversification analysis based on electricity generation only rather than whole-of-economy TPES, however here the TPES approach to ensure inter-regional comparability has been selected in recognition of a number of factors that blur the electricity-only boundary including the potential for use of either electricity or thermal fuels for building heating and industrial process heat, and the emerging nexus of energy and transport due to increasing rates of electric vehicle uptake.

### 2.4.3 Export Customer Diversification Weighted by Carbon Emissions Reduction Rating

Exporter vulnerability is reduced as diversity of energy export customers is increased. To measure this diversity, the HHI index is used to establish a metric for export customer diversification. The diversity index is adjusted by a factor representing the strength of each export customer's actions to reduce $CO_2$ emissions, where stronger actions to reduce $CO_2$ emissions cause greater vulnerability to current fossil fuel exports. This metric is calculated as shown in Equation 2-9.

*Equation 2-9 - M3 (Export Customer Diversification Weighted by Carbon Emissions Reduction Rating)*

$$M3 = CER_A \times (X_A)^2 + CER_B \times (X_B)^2 + \cdots + CER_n \times (X_n)^2$$

Where;

CER = $CO_2$ emissions reduction rating index of country A, B, n, using the CCPI rating method as set out in Section 2.3.5.

X = share of energy (PJ) exported for export customer country A, B, n, as a figure out of 1.

For this metric, greater diversity of customers yields a lower score, which is the desired objective of the exporter to reduce vulnerability to one or two large customers. The preferred CER input (CCPI [93] ) rates poor performance with a low score out of 100, hence countries with a high CER score represent heightened exporter vulnerability to future exports of fossil fuels. The rationale for selecting CCPI for the CER weighting factor is set out above in section 3.3.

### 2.4.4 Energy Exports Significance to GDP

This metric is a simple ratio of revenue from energy exports divided by total GDP, calculated as shown in Equation 2-10.

*Equation 2-10 - M4 (Energy Exports Significance to GDP)*

$$M4 = \frac{R_{fuel\,A} + R_{fuel\,B} + \cdots + R_{fuel\,n}}{GDP}$$

Where;

R = revenue for each exported fuel (oil, gas, coal, biomass, biofuels, hydrogen, etc)

GDP = gross domestic product

A lower figure indicates that the contribution of energy resource exports to total GDP is low and hence the country's economy is less vulnerable to economic disruption due to changes in energy export revenue of specific fuels, or for all fuels combined.

### 2.4.5 Resource to Production Ratio

The usual reserve to production ratio is adapted here to provide a novel indicator for the purpose of assessing exporter vulnerability. By using total demonstrated (including sub-economic) resources estimates instead of economically recoverable reserves, the results return a strategic insight and are insulated from short term price volatility and technology changes. Ongoing development of resource extraction technology has historically and will likely periodically continue to lead to material reductions in extraction costs and enable previously uneconomic reserves to be economically extracted. Perhaps the most recent notable case is with the US shale oil and gas boom and Australian coal seam gas boom, where new technologies in directional drilling and hydraulic fracturing have made previously uneconomic resources newly accessible [102], [103]. In addition, this approach also protects against changes in the threshold for economic reserves due to price increases from changes in global demand and depletion of currently economically recoverable resources. Since resource estimates are periodically revised based on additional exploration activity and production experience, in this analysis resource estimates and production rates from the appropriate year will be applied to demonstrate vulnerability to this factor as it would have been understood at the time, which also shows the effect of increased resource estimates in reducing vulnerability.

This metric establishes a vulnerability score which increases linearly as the expected depletion time for total demonstrated resources reduces from 100 years to zero, calculated as shown in Equation 2-11.

*Equation 2-11 – M5 (Resource to Production Ratio Metric)*

$$M5 = \frac{100 - RPR_{aggregated}}{100}$$

Where RPR = the resource to production ratio for each energy resource type (years), calculated as shown in Equation 2-12.
with an upper limit to RPR of 100. i.e., for RPR≥100; M5 = 0

The additional reduction to exporter vulnerability for any potential increment of expected depletion time of total demonstrated resources over 100 years is considered to be negligible.

A greater RPR score indicates a longer period of remaining production and hence lower exporter vulnerability. However, for consistency with other metrics, the RPR is transformed so that a high score of M5 represents higher vulnerability.

To assess a country's position holistically, the aggregate of each fuel's resource to production ratio is weighted based on contribution to total energy exports.

*Equation 2-12 - Resource to Production Ratio (basic)*

$$RPR_{aggregated} = \frac{S_{coal} \times ({Q_{coal}}/{P_{coal}}) + S_{gas} \times ({Q_{gas}}/{P_{gas}}) + S_{oil} \times ({Q_{oil}}/{P_{oil}})}{X}$$

Where;
$RPR_{aggregated}$ = Resource to production ratio (aggregated)
Q = total demonstrated resource of each energy resource type, in petajoules
P = annual production rate of energy resource type, in petajoules per year
S = export quantity from each energy type, in petajoules per year
X = total export quantity from all energy types, in petajoules per year

The resource to production ratio is sensitive to changes in production rate due to the commissioning of new energy resource projects or closure of existing operations, and also to the level of resource exploration activity driving new resource deposit discoveries, which is a leading (early stage) indicator of future production development to respond to forecast demand.
For consistency, data for coal, oil and gas resources from the BP Statistical Review of World Energy [1], [104] is used. Production data for coal, oil and gas is obtained from the IEA [39].

### 2.4.6 Carbon Emissions Intensity of Energy Export Blend

Exporter carbon risk is a critical vulnerability that is introduced here as a novel indicator not found in other publications addressing energy exporter vulnerability. The calculation method is shown in Equation 2-13. The $CO_2$ emissions intensity of the total mix of exported fuels mix is calculated by multiplying the share of each fuel (coal, oil, gas) by an emissions factor. The emissions factors applied are sourced from the IPCC Emissions Factor Database [90] including reference data from

European [91] and Japanese [92] sources for $CO_2$ emissions per unit mass of each fuel, multiplied by standard energy density conversion factors.

*Equation 2-13 - M6 (Carbon Emissions Intensity of Energy Export Blend)*

$$M6 = \frac{(S_{coal} \times f_{coal}) + (S_{gas} \times f_{gas}) + (S_{oil} \times f_{oil}) + (S_{zero\ carbon\ fuels} \times f_{zero\ carbon\ fuels})}{X}$$

Where;

S = export quantity from each energy type, in PJ

X = total export quantity from all energy types, in PJ

f = $CO_2$ emissions adjustment factor for each energy type, as per Table 2-11.

*Table 2-11 Fossil Fuel Emissions Factors* [90]–[92]

| Energy type | Emissions factor (t $CO_2$/TJ) | f, $CO_2$ emissions adjustment factor |
|---|---|---|
| Coal | 96.3 | 1.00 |
| Crude Oil | 73.3 | 0.76 |
| Natural gas | 56.1 | 0.58 |
| Zero-carbon fuels | 0.0 | 0.00 |

Although lignite is commonly used as a domestic fuel, it is typically not exported due to its low energy content and high moisture content and is hence excluded from the coal emission factor. Emissions factors for oil and gas are quite uniform globally, however coal has considerable variation by type. The figure used is the average of the emissions factor attributed by the IPCC[90] for exportable grades of coal (anthracite, bituminous and sub-bituminous).

Since coal has the highest $CO_2$ emissions factor of the fuels considered, the emissions adjustment factors are normalised to set coal at 1.0. An export blend of 100% coal would thus yield a score of 1.0. A lower score represents less $CO_2$ emissions from the exported fuel blend, and hence less vulnerability to $CO_2$ emissions reduction programs. These emissions factors consider only $CO_2$ released from combustion of the fuel itself and do not consider incidental $CO_2$ emissions from extraction or transport activities, which are highly variable and region-specific. The method applied assesses $CO_2$ emissions per unit energy exported and is not sensitive to the electrical conversion efficiency on the user's side.

Future exports of material quantities of low- or zero-$CO_2$ energy types, such as hydrogen produced from renewable electricity can also be included in this metric, with the effect of lowering the final score. An export mix composed entirely of zero-carbon fuels would yield a score of 0.0, representing zero vulnerability to customer $CO_2$ emissions reduction programs.

### 2.5 Case Studies

The assessment framework is applied to case studies of 5 energy exporting countries, Australia, Canada, Indonesia, Norway and Russia. Countries selected for case studies are exporters of multiple fuels, since this work is particularly focussed on examining interactions of various energy resource exports. Australia is established as the primary case study, and two other comparable developed economies that are major energy exporters with similar GDP per capita [2] are selected (Canada, Norway). Considering Australia's own energy exports predominately supply east Asian customers with significant growth over the period examined, Indonesia is selected as another case study with a similar export customer portfolio. Russia is selected as the fifth case study because it's energy exports to east Asia have also increased significantly over the period studied, it also supplies the European market's demand along with Norway, and together with Indonesia represents an emerging / middle economy for balance in the assessments. Country results are compared after the individual case studies. Since data related to energy exports does not change significantly year on year, the time intervals of years 2000, 2008 and 2019 are applied.

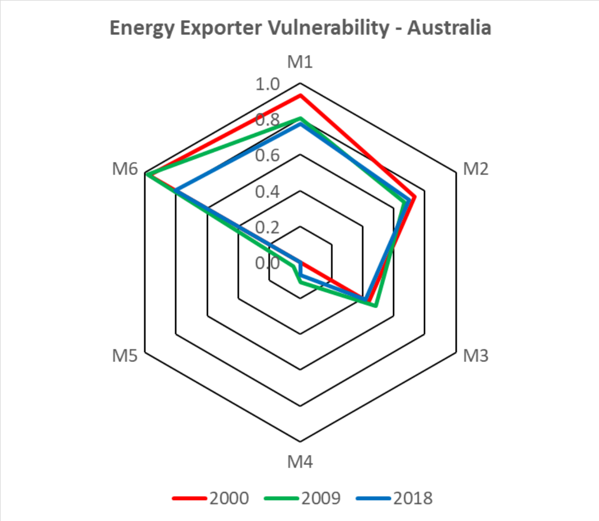
#### 2.5.1 Australia

Australia's key data as an energy exporter over the period studied is shown in Table 2-12.

*Table 2-12 Economic and energy export key data (Australia)* [2], [39]

| | 2000 | 2009 | 2018 |
|---|---|---|---|
| GDP (Billion USD 2021$) | 415.2 | 927.8 | 1,432.9 |
| Total exports (Billion USD 2021$) | 64.5 | 164.0 | 263.0 |
| Gas exports (PJ) | 388 | 756 | 3,402 |
| Oil exports (PJ) | 811 | 583 | 458 |
| Coal exports (PJ) | 5,084 | 7,078 | 10,333 |
| Total energy exports (PJ) | 6,283 | 8,416 | 14,193 |

As seen in Figure 2-3, compared to the cohort of energy exporters studied, Australia scored comparatively well for very low vulnerability in M4 (energy exports significance to GDP) and M5 (resource to production ratio). The relatively high vulnerability score for M1 (customer energy import dependence) is a function of the high proportion of exports to Japan and South Korea. The high score for M6 (carbon intensity of the energy export blend) primarily due to the high proportion of coal, has improved a little since 2009 due to a significant increase in LNG exports.




M1 - Customer Energy Import Dependence
M2 - Customer Energy Mix Diversity
M3 - Export Customer Diversification
M4 - Energy exports significance to GDP
M5 - Resource to Production Ratio
M6 - Carbon intensity of energy export blend

*Figure 2-3 - Energy Exporter Vulnerability Scorecard (Australia)*

The notable changes in Australia's vulnerability scorecard are reductions in M1 (Customer Energy Import Dependence) and M6 (Carbon intensity of energy export blend). The former is primarily as a result of a reduction in the share of energy exports to Japan and an increase to China which is less import-dependent (this change is also reflected in a slight reduction in M3 – export customer diversification). The latter is driven by a significant increase in LNG exports thus reducing the carbon intensity of the energy export blend even though coal exports also increased over the period studied.

### 2.5.2 Canada

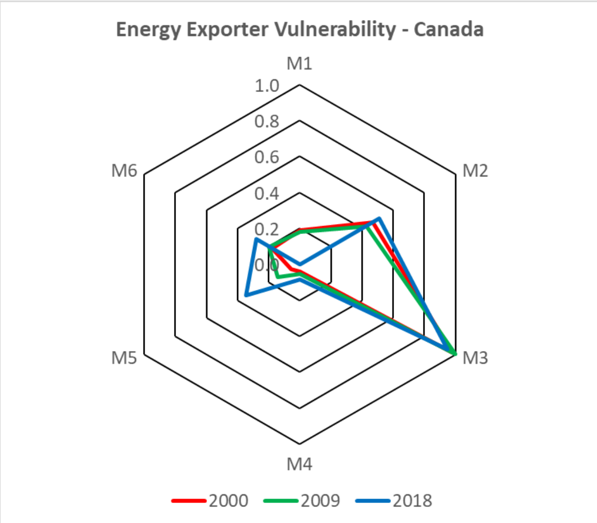
Canada's key data as an energy exporter over the period studied is shown in Table 2-13.

*Table 2-13 Economic and energy export key data (Canada)* [2], [39]

| | 2000 | 2009 | 2018 |
|---|---|---|---|
| GDP (Billion USD 2021$) | 744.6 | 1376.5 | 1721.8 |
| Total exports (Billion USD 2021$) | 268.0 | 306.0 | 437.0 |
| Gas exports (PJ) | 3462 | 3294 | 2804 |
| Oil exports (PJ) | 3284 | 4201 | 8212 |
| Coal exports (PJ) | 807 | 728 | 837 |
| Total energy exports | 7553 | 8223 | 11853 |

Canada's energy export profile is dominated by an almost total dependence on exports to the USA, as shown in M3 (export customer diversification), and by extension M1 and M2 also reflect the USA's domestic energy profile, as seen in Figure 2-4. As seen by a very low score for M5, Canada's resource to production ratio is very high compared to the cohort of countries studied, which, notwithstanding oil production increasing by a factor of 2.5 over 18 years, is representative of considerable oil reserves. Canada's GDP reliance on energy exports, as represented by M4, is consistently low.

A reduction in the score for M1 (customer energy import dependence) from 2009 to 2018, which was already very low, reflects the USA's recent significant increase in domestic energy production with the boom in unconventional oil and gas production displacing imports from other sources in the same period.




M1 - Customer Energy Import Dependence
M2 - Customer Energy Mix Diversity
M3 - Export Customer Diversification
M4 - Energy exports significance to GDP
M5 - Resource to Production Ratio
M6 - Carbon intensity of energy export blend

*Figure 2-4 - Energy Exporter Vulnerability Scorecard (Canada)*

The slight reduction in M3 (export customer diversification) is due to the share of oil and gas exports to the USA falling from 100% each in 2000 falling to 95% and 97% respectively in 2018. An increase in M6 (carbon intensity of the export blend) is due to an increase in oil exports at the same time as a decrease in gas exports.

### 2.5.3 Indonesia

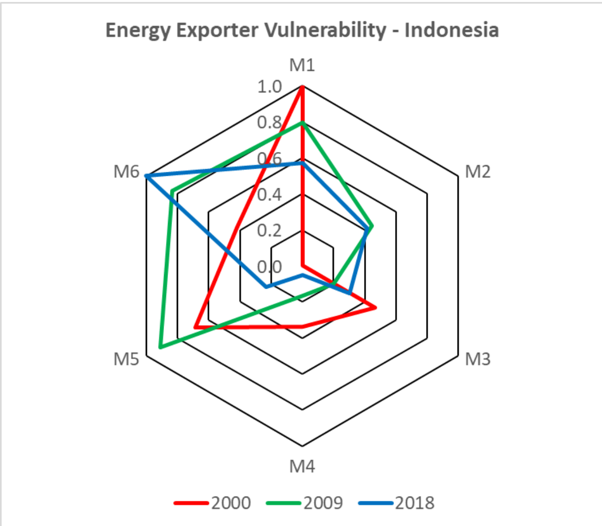
Indonesia’s key data as an energy exporter over the period studied is shown in Table 2-14.

*Table 2-14 Economic and energy export key data (Indonesia)* [2], [39]

| | 2000 | 2009 | 2018 |
|---|---|---|---|
| GDP (Billion USD 2021$) | 165.0 | 539.6 | 1042.0 |
| Total exports (Billion USD 2021$) | 69.8 | 136.0 | 198.0 |
| Gas exports (PJ) | 1449 | 1369 | 991 |
| Oil exports (PJ) | 1625 | 891 | 588 |
| Coal exports (PJ) | 1404 | 5708 | 9880 |
| Total energy exports | 4478 | 7968 | 11459 |

M1 - Customer Energy Import Dependence
M2 - Customer Energy Mix Diversity
M3 - Export Customer Diversification
M4 - Energy exports significance to GDP
M5 - Resource to Production Ratio
M6 - Carbon intensity of energy export blend

Figure 2-5 reveals significant changes in every vulnerability metric in Indonesia’s scorecard over the period studied, indicative of major changes in Indonesia’s economy, including energy exports; GDP increased by over six times, total exports and energy exports both almost tripled, coal became the dominant energy export and the portfolio of customers became more diversified.





M1 - Customer Energy Import Dependence
M2 - Customer Energy Mix Diversity
M3 - Export Customer Diversification
M4 - Energy exports significance to GDP
M5 - Resource to Production Ratio
M6 - Carbon intensity of energy export blend


*Figure 2-5 - Energy Exporter Vulnerability Scorecard (Indonesia)*

Indonesia's vulnerability scores in 2018 for external factors M1 – M3 are mostly in the moderate range compared to other countries in the cohort studied, while internal factors are interesting outliers. M4 (energy exports significance to GDP) has improved as GDP boomed. M5 (resource production ratio) has also improved even as exports increased, as a result of more investment in exploration causing significant upward revision of coal resource estimates. Only M6 (carbon intensity of the energy export blend) has significantly increased Indonesia's vulnerability due to an increased reliance on coal exports.

### 2.5.4 Norway

Norway's key data as an energy exporter over the period studied is shown in Table 2-15.

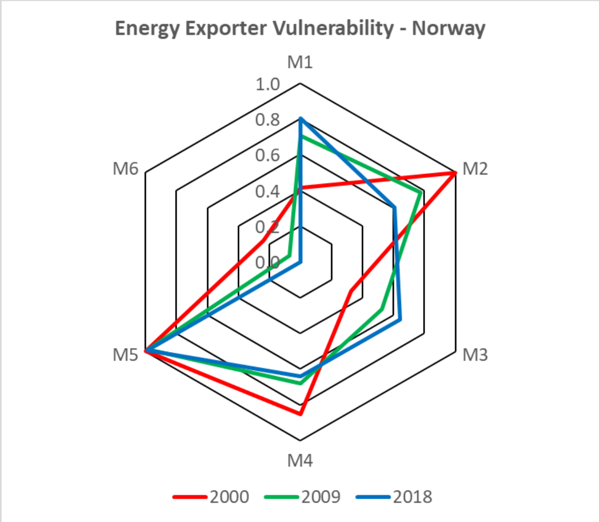
*Table 2-15 Economic and energy export key data (Norway)* [2], [39]

| | 2000 | 2009 | 2018 |
|---|---|---|---|
| GDP (Billion USD 2021$) | 171.2 | 386.2 | 437.0 |
| Total exports (Billion USD 2021$) | 60.7 | 119.0 | 127.0 |
| Gas exports (PJ) | 1764 | 3598 | 4240 |
| Oil exports (PJ) | 6377 | 3688 | 2657 |
| Coal exports (PJ) | 0 | 0 | 0 |
| Total energy exports | 8141 | 7285 | 6897 |

Norway's moderately high score for M1 (customer energy import dependence) compared to the cohort of countries studied (as observed in

M1 - Customer Energy Import Dependence
M2 - Customer Energy Mix Diversity
M3 - Export Customer Diversification
M4 - Energy exports significance to GDP
M5 - Resource to Production Ratio
M6 - Carbon intensity of energy export blend

), is predominantly a function of the lack of domestic energy resources of its mostly European export customers. The absence of coal in Norway's energy exports is clearly reflected in a low relative vulnerability to carbon intensity of the export blend (M6).




M1 - Customer Energy Import Dependence
M2 - Customer Energy Mix Diversity
M3 - Export Customer Diversification
M4 - Energy exports significance to GDP
M5 - Resource to Production Ratio
M6 - Carbon intensity of energy export blend

*Figure 2-6 - Energy Exporter Vulnerability Scorecard (Norway)*

Even though Norway's total energy exports have increased over the period studied, GDP has increased at a greater rate hence producing a lower vulnerability rating for M4 (energy export significance to GDP). The high score for M5 (resource to production ratio) reflects vulnerability of future exports to dwindling resources (at 2018 production rates; 13 years for gas, 14 years for oil). The slight reduction seen in M5 is due to a moderate reduction in oil production and upward revision of oil resource estimates from 2009 to 2018.

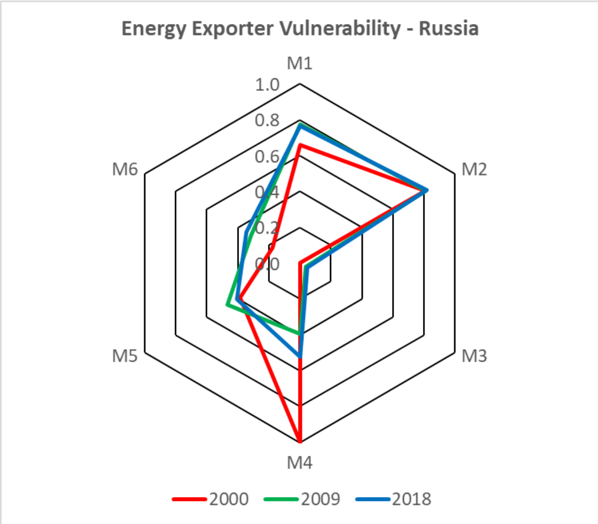
### 2.5.5 Russia

Russia's key data as an energy exporter over the period studied is shown in Table 2-16.

*Table 2-16 Economic and energy export key data (Russia)* [2], [39]

| | 2000 | 2009 | 2018 |
|---|---|---|---|
| GDP (Billion USD 2021$) | 195.9 | 1223.0 | 1687.0 |
| Total exports (Billion USD 2021$) | 101.0 | 285.0 | 430.0 |
| Gas exports (PJ) | 6556 | 5873 | 8434 |
| Oil exports (PJ) | 8309 | 14707 | 16403 |
| Coal exports (PJ) | 1067 | 2875 | 5576 |
| Total energy exports | 15932 | 23455 | 30413 |

Figure 2-7 reveals that Russia has exceptionally low vulnerability scores for M3 (export customer diversification) and M5 (resource to production ratio). The score for M3 is primarily a function of Russia's proximity to a large number of customers in former soviet republics and European states.




M1 - Customer Energy Import Dependence
M2 - Customer Energy Mix Diversity
M3 - Export Customer Diversification
M4 - Energy exports significance to GDP
M5 - Resource to Production Ratio
M6 - Carbon intensity of energy export blend

*Figure 2-7 - Energy Exporter Vulnerability Scorecard (Russia)*

The M5 score reflects the massive natural resource in fossil fuels possessed by Russia, with this score not noticeably changed even as production rates have increased. Input data reveals that increased investment in exploration over the period has expanded known resources at approximately the same rate as production.

While M3 has stayed very low compared to the cohort of countries studied, increases in vulnerability in M1 (customer energy import dependence) is a result of a change in the customer portfolio to customers that are more dependent on imports and less diversified in their energy mix. The significant reduction in vulnerability in M4 (energy export significance to GDP) is primarily a result of considerable growth in the domestic economy even though exports generally and energy export specifically also increased over the same period. An increased vulnerability score for M6 (carbon intensity of the energy export blend) is a result of oil and coal exports increasing at a greater rate than gas, particularly over the period 2000-2009.

### 2.5.6 Metric Comparisons between Countries

In all cases, a higher score represents greater vulnerability for the energy exporter.

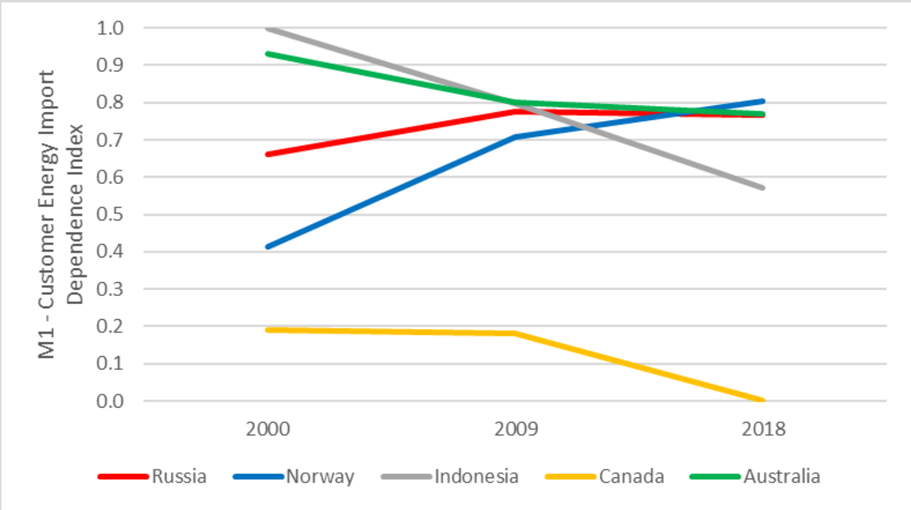



*Figure 2-8 - Customer Energy Import Dependence (M1)*

Over the time period 2000-2018, Figure 2-8 shows a notable change in each country's customer energy import dependence.  Canada, almost exclusively reliant on exports to the USA, improved it's score due to the shale gas and oil boom in the USA increasing domestic energy production.  On the other hand, Russia and Norway, which both export primarily to European countries, experienced a worse score as their customers became more import-dependent.  Australia's and Indonesia's increasing part of exports to China reduced their overall import dependence score.

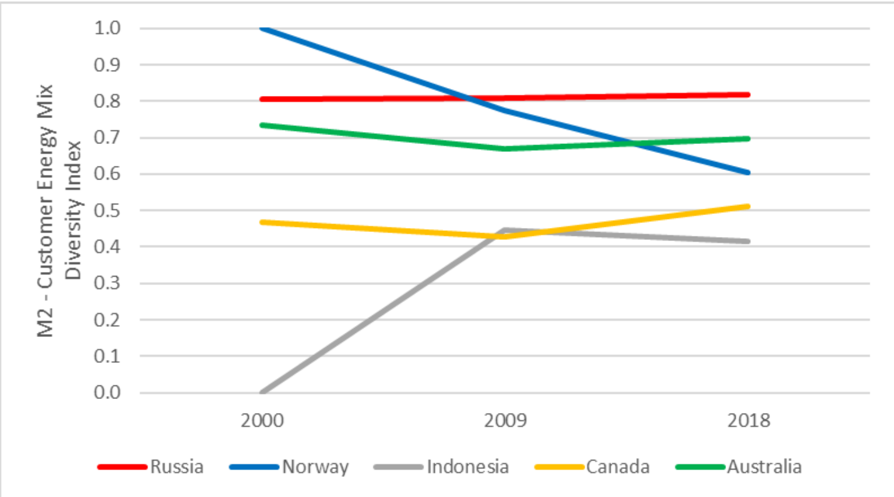



*Figure 2-9 - Customer Energy Mix Diversity (M2)*

Figure 2-9 shows somewhat unchanged scores for customer energy mix diversity for Russia, Canada and Australia, however a reduced vulnerability score is a pleasing outcome for Norway from increased primary energy supply diversity of its top two customers, the UK and Germany. Indonesia's increase then decrease stems from an initial increase in exports to Japan, overtaken by 2018 to exports to China and India.

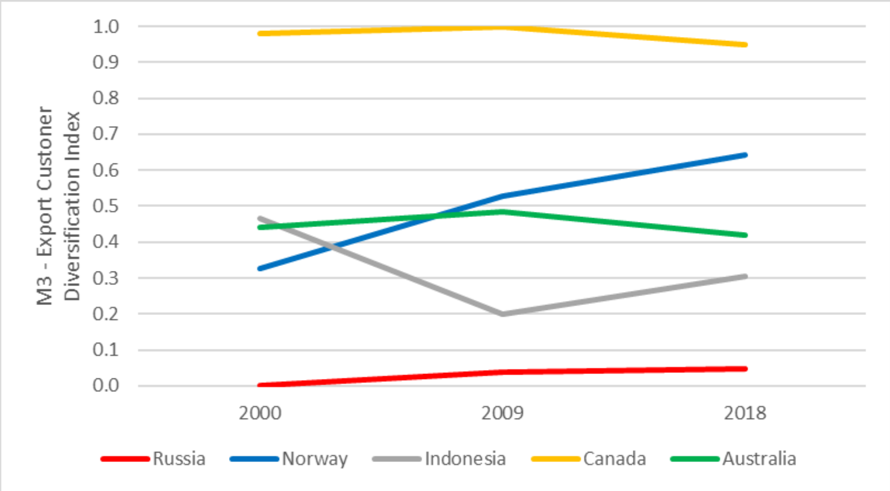



*Figure 2-10 - Export Customer Diversification (M3)*

In Figure 2-10, export customer diversification shows Russia's highly diversified customer portfolio of European countries and former Soviet republics largely unchanged. Canada's almost total dependence on exports to the United States lessened only slightly, while Australia's exports diversified slightly with the addition of significant energy exports to China and India reducing a little the dominance of Japan as a customer. Indonesia's massive growth in coal exports to an increasingly diversified Asian customer base is noted, however increasing exports to India which has a relatively low carbon emissions reduction rating was a main driver of a slight uptick to 2018. Norway's M3 vulnerability score increase is due in part to greater concentration of exports to the top two customers (the UK and Germany) and an increase in Germany's share compared to the UK, magnified by Germany's higher carbon emissions reduction rating than the UK.

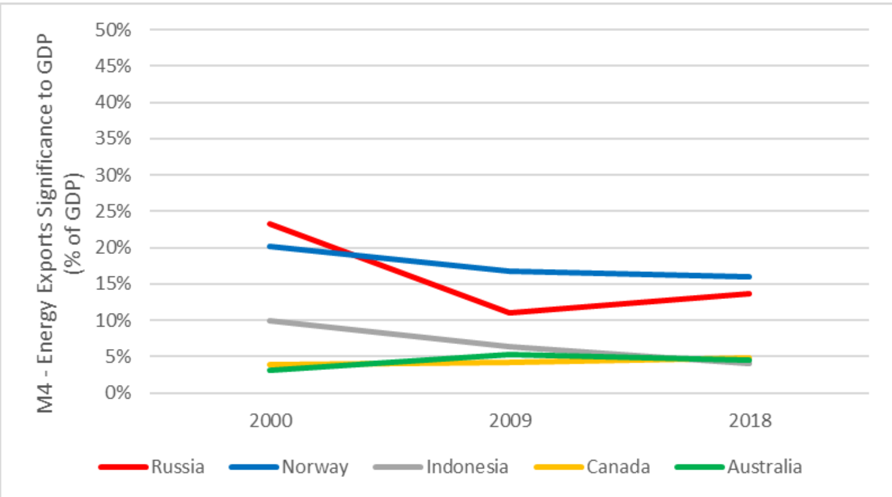



*Figure 2-11 - Energy Exports Significance to GDP (M4)*

Over the period studied, Figure 2-11 shows that Russia and Indonesia both reduced their share of energy exports to GDP, which despite significant increases in energy exports is due to the greater growth of their domestic economies. Norway's reduced score, however, is due to a reduction in energy exports caused by declining oil production even though gas exports increase. Canada's score remained essentially unchanged, while Australia became a little more export dependent (although admittedly from a very low vulnerability starting point) due to major increases in coal and gas exports.

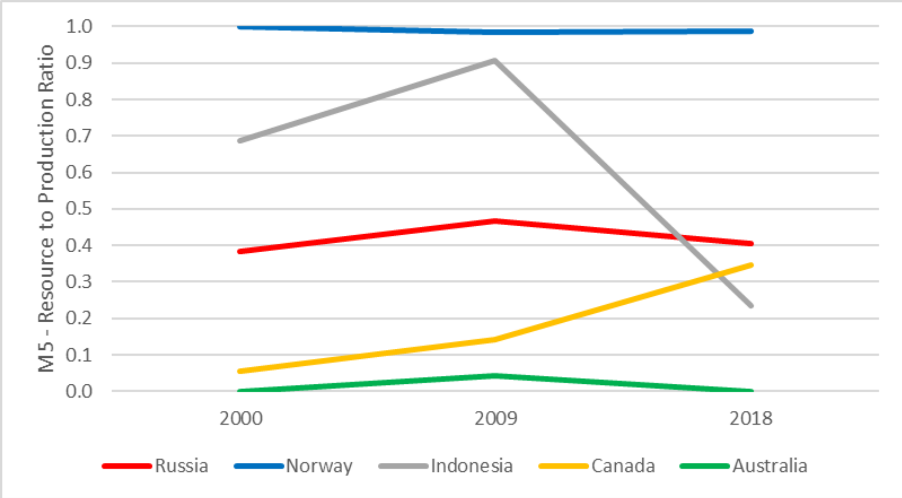



*Figure 2-12 - Resource to Production Ratio (M5)*

The clear messages from Figure 2-12 are that Norway remains highly vulnerable to dwindling resources although slightly improved by reduced oil production, Indonesia's coal export boom led to increased exploration subsequently increasing resource estimates, while Russia, Canada and Australia are largely unchanged with extensive resources compared to production rates.

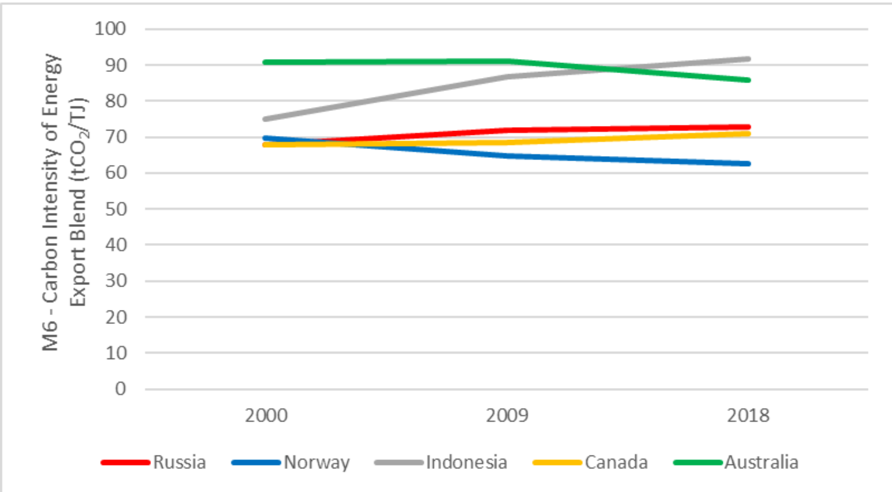



*Figure 2-13 - Carbon Intensity of Energy Export Blend (M6)*

According to the data for carbon intensity of each country's export blend shown in Figure 2-13, Australia and Norway reduced their vulnerability to M6 with increased shares of gas exports, while Indonesia's coal export expansion has driven up its $CO_2$ intensity vulnerability. Canada and Russia are essentially unchanged.

### 2.5.7 Unified Metrics

For ease of observation, a unified metric approach is also proposed. As set out above, metrics M1 to M3 represent external vulnerability factors essentially beyond the direct control of the exporting country, while metrics M4 to M6 represent internal vulnerability factors due principally to the exporting country's domestic conditions. Accordingly, separate unified metrics representing the external factors, M.Ext, and the internal factors M.Int are proposed, and calculated as follows, with equal weighting of the individual indicators in each category:

*Equation 2-14 - M.Ext (External Vulnerability Unified Metric)*

$$M.Ext \; = \; (M1 + M2 + M3)/3$$

*Equation 2-15 - M.Int (Internal Vulnerability Unified Metric)*

$$M.Int \; = \; (M4 + M5 + M6)/3$$

Table 2-17 and Figure 2-14 set out the unified index for energy exporter external vulnerabilities (M.Ext) for each of the case study countries for the same time intervals as per the detailed analysis above.

*Table 2-17 M.Ext for Case Study Countries*

| M.Ext | 2000 | 2009 | 2018 |
|---|---|---|---|
| Australia | 0.70 | 0.65 | 0.63 |
| Canada | 0.55 | 0.54 | 0.49 |
| Indonesia | 0.49 | 0.48 | 0.43 |
| Norway | 0.58 | 0.67 | 0.68 |
| Russia | 0.49 | 0.54 | 0.54 |

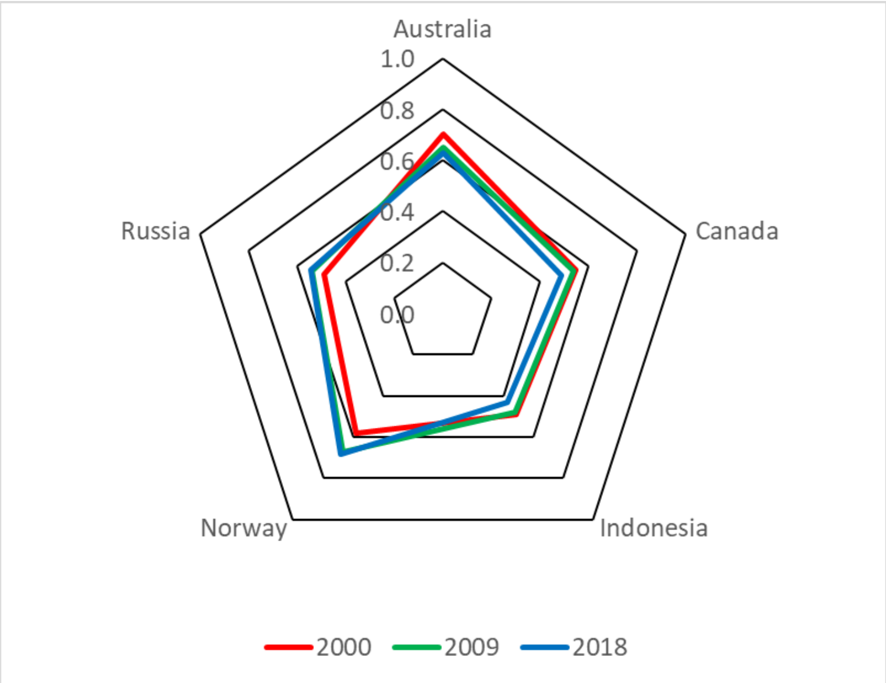


*Figure 2-14 - M.Ext for Case Study Countries*

Considering external vulnerabilities to energy exports, Canada benefits from a relatively low score which, notwithstanding a heavy concentration of exports (M1) to a single majority customer (USA), is outweighed by the USA's reduced energy import dependence (M2) and greater energy source diversity (M6) and has slightly improved (reduced) over the period studied. Australia has a slightly improving mid-range score, mainly driven by the emergence of China as a significant export customer increasing customer diversity (M3), and the flow-on effect of China's lower energy import dependence (M1) than other major customers Japan and Korea whose share has reduced. The emergence of China as a significant export customer for Indonesia has led to a similar reduction in M.Ext to that experienced by Australia. However, over the same time period it is observed that Norway`s M.Ext vulnerability has increased, due in large part to an increase in the export share to the UK followed by Germany while export share to other countries diminished, hence a more concentrated customer base with higher dependence on imported energy supplies and rising vulnerability for Norway to the expected energy security response in those two countries to reduce import dependence and diversify energy supply and source. Russia`s M.Ext score has deteriorated over the period studied from equal best to middle of the sample. Russia benefits from a very high level of export customer diversification driving a very low M3 score, however notwithstanding this diversification, the customer portfolio has become increasingly dependent on energy imports (from Russia) and has lost energy mix diversity. While this may be a convenient situation for immediate supply, policy makers in Russia's customer states will likely have an eye on their domestic energy security and geopolitical exposure, and potentially seek to diversify energy supply and reduce import dependence which presents a clear vulnerability to Russia's future exports.

Table 2-18 and Figure 2-15 set out the unified index for energy exporter internal vulnerabilities (M.Int) for each of the case study countries for the same time intervals as per the detailed analysis above.

*Table 2-18 M.Int for Case Study Countries*

| M.Int | 2000 | 2009 | 2018 |
|---|---|---|---|
| Australia | 0.32 | 0.38 | 0.29 |
| Canada | 0.09 | 0.13 | 0.24 |
| Indonesia | 0.48 | 0.64 | 0.43 |
| Norway | 0.70 | 0.58 | 0.54 |
| Russia | 0.52 | 0.39 | 0.43 |

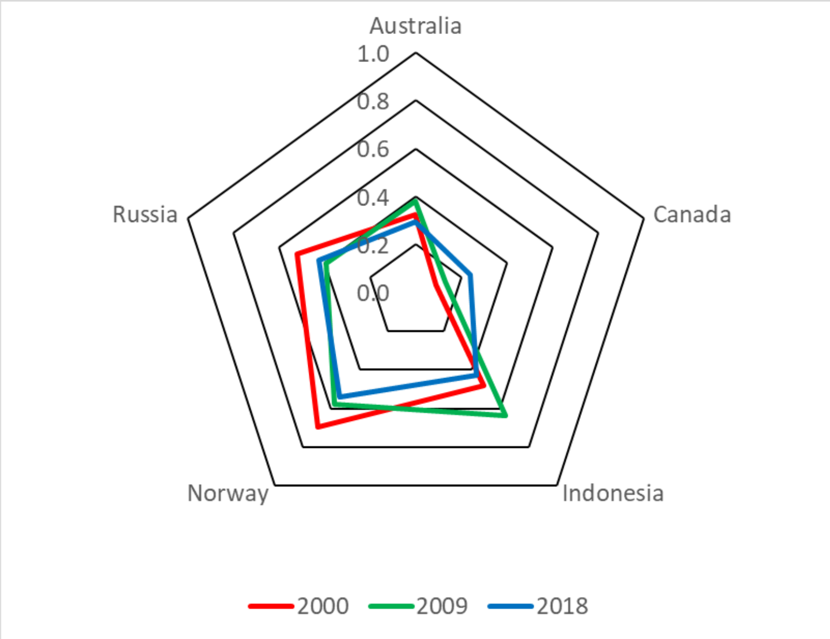



*Figure 2-15 - M.Int for Case Study Countries*

Considering internal vulnerabilities to energy exports, each of the case study countries have ended the period examined with scores in the low to mid-range, led by Canada with the lowest scores across the time period, albeit rising a little by 2018 driven by increased vulnerability to reduction in resource levels and increasing production rates. Norway and Russia have notably improved (reduced) their scores over the period, while Australia and Indonesia settled back to close to the starting point after a troubling worsening (higher score) in the middle of the time period. The principal driver for Australia's reduced M.Int vulnerability to the end of the period studied has been an overall reduction in the $CO_2$ emissions intensity of its export mix due to a significant ramp-up in LNG exports offsetting the higher emissions intensity of coal exports. Over the period studied, Indonesia and Russia have both experienced significant GDP growth which, despite considerable growth in energy exports, has reduced their economic dependence on energy exports. Additionally, Indonesia has benefited from a significant increase in resource estimates outweighing production rate increases.

Finally, a single unified index for energy exporter economic vulnerability, M.V can be calculated by combining M.Ext and M.Int, as shown in Equation 2-16. Since each country's vulnerability to external factors is magnified by the extent of its exposure to exports, a weighting is applied based on each country's ratio of energy exports to energy production in energy units.

*Equation 2-16 M.V (Unified Metric for Energy Exporter Economic Vulnerability)*

$$M.V = (M.Ext \times eF) + M.Int$$

Where;

Energy export exposure factor, eF = 1 + ( $E_E$ / $E_P$ ), shown in Table 2-19 (calculated as shown in Equation 2-17).

*Equation 2-17 - eF (Energy Export Exposure Factor)*

$$eF = 1 + ({}^{E_E}/_{E_P})$$

$E_E$ = the country's combined energy resource exports in PJ

$E_P$ = the country's total energy resource production in PJ

*Table 2-19 Energy Export Exposure Factor*

| | eF weighting factor | | |
|---|---|---|---|
| | 2000 | 2009 | 2018 |
| Australia | 1.661 | 1.694 | 1.829 |
| Canada | 1.580 | 1.607 | 1.625 |
| Indonesia | 1.600 | 1.675 | 1.703 |
| Norway | 1.908 | 1.856 | 1.854 |
| Russia | 1.412 | 1.498 | 1.517 |

Over the period studied, all countries except Norway have become more vulnerable to external factors, although it is noted that Norway's reduction is from a very high level and is still the highest of the cohort. Russia is observed to be the least vulnerable to external factors compared to internal factors.

As the ratio of energy exports to energy production tends to 1.0 (the limiting case of all energy production being exported), the energy export exposure factor tends to 2.0, thus doubling the weight of external factors while the weight of internal factors remains constant. Considering that the possible score range for M.Ext and M.Int is 0 to 1.0, the M.V is limited to a range of 0 to 3.0, with a score of 3.0 representing maximum energy export vulnerability according to the methodology set out in this chapter.

Table 2-20 and Figure 2-16 below show the M.V scores for each of the case study countries examined in this chapter, at time intervals of 2000, 2009 and 2018.

*Table 2-20 M.V for case study countries*

| M.V | 2000 | 2009 | 2018 |
|---|---|---|---|
| Australia | 1.49 | 1.48 | 1.44 |
| Canada | 0.95 | 0.99 | 1.03 |
| Indonesia | 1.26 | 1.44 | 1.16 |
| Norway | 1.80 | 1.82 | 1.81 |
| Russia | 1.21 | 1.20 | 1.25 |

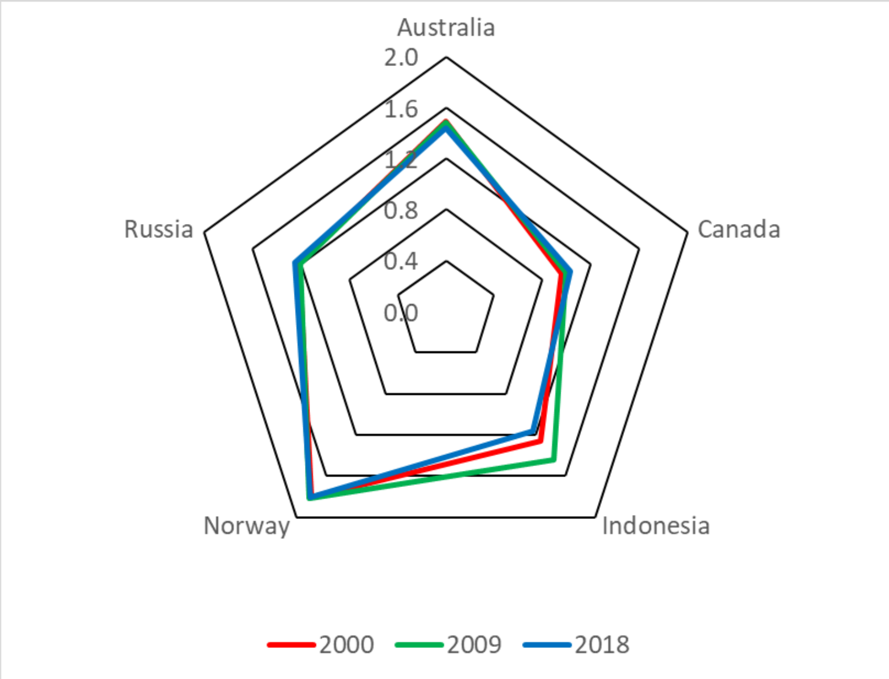



*Figure 2-16 - M.V for Case Study Countries*

The primary observation of M.V values is that Australia, Canada, Norway and Russia have remained remarkably stable in terms of energy export economic vulnerability over the period studied, despite significant increases in some metrics and decreases in others for each country as set out above in the discussion of each country and the aggregated M.Ext and M.Int findings. Only Indonesia was found to have experienced a material reduction in energy export economic vulnerability, due to a combination of positive changes in greater customer diversity, reduction in customer import dependence, a reduced share of GDP due to energy exports and increased resource estimates.

## 2.6 Conclusions

This study has established a diversified scorecard of six metrics to quantitively evaluate energy exporter vulnerability from a wide ranging and comprehensive review of the existing body of work related to general economic vulnerability, corporate risks of energy resource companies, energy security frameworks, and the little body of related work on energy exporters. This research has introduced a key new consideration to this field of study related to energy exporters carbon vulnerability, manifested in the internal factor $CO_2$ emissions intensity in the export blend, and the external factor carbon emissions reduction rating of export customers. The assessment framework developed has been codified into numerically based metrics allowing quantitative evaluation of energy exporting countries in a scorecard, over time and compared to other countries. Each country's scorecard over time and international comparative benchmarking allows for comparative evaluation by countries against peers, and the insights gained may also indicate specific areas for further research. Finally, unified indices grouping external metrics, internal metrics, and a single unified weighted index have been proposed and case study countries performance has been considered. This approach could be used by decision-makers in order to test appropriate policy strategies that could lessen energy export vulnerability.

# Chapter 3 - Exposing the Blind Spots in Domestic Energy Security of Major Energy Exporters

## 3.1 Chapter Introduction

The history of global energy bodies such as the Organisation of Petroleum Exporting Countries (OPEC)[105] and the International Energy Agency (IEA) [7] may lead the observer to consider the global energy market as being composed of a neat dichotomy of energy resource producing and exporting countries (such as OPEC members) and countries dependent on energy imports for their economic survival (such as IEA members). It therefore comes as no surprise that the existing body of knowledge on the topic of energy security primarily originates from and is highly focussed on the concerns of major energy-import-dependent economies such as Japan [8] and the European Union [9].

However, the reality of the global energy market is much more complex than a simplistic supplier-consumer dichotomy. While some countries are almost entirely dependent on energy imports, many countries produce a significant part of their own energy needs, some are net exporters in one or a number of fuels (but not others), and critically for the topic of this chapter, every energy exporter is themselves a consumer with a domestic energy system that may be to varying degrees integrated with export operations.

Following on from the previous chapter's examination of energy exporter vulnerability in relation to the economic value of energy resource exports, this chapter examines the equally unaddressed energy exporter vulnerability of domestic energy security faced uniquely by energy exporters. Since major energy resource exporting countries themselves are also energy users, their domestic energy systems are potentially also prone to energy security vulnerabilities, many of which are consistent with those experienced by net energy importing countries, but some of which stem directly from energy resource exporting activities and hence are unique to energy exporters and not widely recognised in the importer-dominated energy security body of knowledge.

A wide-ranging review of literature on the topic of energy security [8], [9], [12], [16]–[18], [21]–[26], [28]–[34], [63], [65], [106], [107] reveals a considerable range of factors and indicators to quantify various dimensions of energy security. In particular, Sovacool & Mukherjee [33] provide a comprehensive analysis of various methods of energy security analysis and logically organise the myriad of specific indicators into five broad dimensions (availability, affordability, technology development, sustainability and regulation). Additionally, Kruyt et al. [28] provide a valuable overview of detailed factors for security of energy supply along with a discussion of the strengths and weaknesses of each. Also, Kanchana et al. [49] for example, set out a matrix of energy dependency index factors and also develop the idea of domestic energy security and energy resource export vulnerability as related issues. These together could be broadly considered as the prevailing energy security framework. Recently, there is more attention to the situation of energy exporters, such as from Bigerna et al. [108] which consider different aspects of the economic vulnerability of energy exporters. This paper continues to develop this emerging theme with specific attention to the energy security consequences and impacts to the exporter's own domestic energy system as a result of energy resource export activity.

Following this introduction and literature review, an indicative list of energy security indicators is filtered for their relevance to energy exporters is shown. In section 3.2 we briefly consider the resource curse hypothesis finding that this issue has already been well established for natural resource exporters, however it does not specifically relate to the exporter's domestic energy security. From the review in this section and Table 3-1, and the more extensive discussion in [109]Chapter 2 of this report, it is evident that importer-centric energy security frameworks have likely missed some critical factors specific to energy exporters. Therefore, in section 4 we set out a systems approach as the methodology applied to establish potential energy security blind-spots. Section 5 focusses on the first blind-spot identified: the definition of and calculation method for primary energy self-sufficiency for an energy exporter. This is followed in section 6 by a focus on the second such energy security blind spot, that of the extent of domestic energy system linkage to exports and hence exposure to international market forces. These blind spots identified in sections 5 and 6 are addressed with new quantitative metrics, which are applied to a number of case studies. Conclusions, policy implications and opportunities for further work are set out in section 7.

Energy security is a topic which has been widely evaluated, in different guises historically, but formally since the oil shocks of the 1970`s. To measure energy security, various frameworks and sets of indicators have been developed – with many having significant overlap. As these have been reviewed thoroughly by others elsewhere and also in section 2.3.7 and Table 2-10 of this report, in this section we present a summary of factors proposed by Kruyt [28] and Kanchana [49] are combined into Table 3-1, which used as a representative set here. Comments on the applicability of each factor are also added in the right-hand column.

*Table 3-1 – Major Energy Security Indicators (Kruyt et al.*[28]*, Kanchana et al.* [49]*) and Their Suitability for Exporter Energy Security*

| Energy Security Indicator | Evaluation Method / Unit | Exporter Suitability | Rationale for Suitability to Exporter Energy Security |
|---|---|---|---|
| Resource estimates | Tonnes of coal, PJ of gas, barrels of oil | Yes | Whether for domestic use alone or export also, greater resource estimate is desirable |
| Reserve to production ratio (remaining life of reserves) | Reserve tonnes ÷ production tonnes per year = years of remaining production | Yes | Remaining life of reserves affects both exports and domestic use |
| Diversity of energy type / primary energy mix | Herfindahl-Hirschmann Index (HHI) | Yes | Desirable whether exporter or not |
| Diversity of trade partners | Herfindahl-Hirschmann Index (HHI) or Shannon Wienner Index (SWI) | No | Only applicable for import dependence |
| Import dependence (imports relative to total use). Also expressed as primary energy self-sufficiency. | PJ imported LNG per year ÷ PJ of annual total use.<br>Total domestic primary energy production (PJ) ÷ Total primary energy supply (PJ) | No | Primary energy self-sufficiency requires examination of method in exporter case |
| Political stability | World Bank worldwide governance indicators: political stability & absence of violence, regulatory quality. | No | Only applicable for import dependence, when evaluating supplier risk |
| Energy price | $ per PJ | Yes | Energy security impact of price is independent of importer or exporter status |
| Share of zero carbon fuels (vulnerability to environmental and societal constraints) | PJ of renewables and nuclear ÷ PJ of total primary energy | Yes | Decarbonisation of the domestic energy system applies similarly to importer and exporter alike |
| Market liquidity (own demand as a proportion of amount available in market) | Primary energy PJ demand of fuel ÷ total global trade in that fuel in PJ | Yes | Benefits are the same whether importer or exporter |
| Energy intensity per capita | PJ of primary energy ÷ population | Yes | Regardless of importer or exporter status, reducing energy intensity is beneficial |
| Share of energy import expenditures to GDP | $ cost of imported energy ÷ $ GDP | No | By definition only applicable for import dependent countries |
| Energy intensity per GDP | PJ of primary energy ÷ $ GDP | Yes | Regardless of importer or exporter status, reducing energy intensity is beneficial |
| GDP per capita | $ GDP ÷ population | Yes | Generally applicable base indicator |
| IEA physical unavailability index | PJ gas supplied through pipelines under oil priced indexed contracts ÷ PJ total primary energy | Yes | Applies to countries importing gas by pipeline, does not preclude exports of other energy types |
| Energy export to energy production ratio | PJ / PJ | Yes | Applicable to exporters by definition |
| Share of energy export revenues to GDP | $ energy exports ÷ $ GDP | Yes | Applicable to exporters by definition |

Broadly, most of these dimensions and factors are found to be applicable to the domestic energy security situation of net energy exporters, however, some are only applicable for import-dependent countries, while a few require deeper consideration to reflect the unique conditions of an energy exporter. This overview of factors has established that there has been limited attention in literature to energy security issues unique to energy resource exporting countries.
This opens the door to a more focussed analysis of potential energy security blind spots experience uniquely by net energy resource exporters. This issue has been highlighted in chapter 2 but remains an area of significant research need [109]. This chapter therefore is intended to add to this under-represented perspective by first of all establishing some of the energy security blind-spots that energy resource exporting countries may experience in relation to their own domestic energy systems if they become distracted in becoming an energy superpower [110]. Then, having established some such blind spots and examined specific case studies as validation of the reality of these blind spots, new energy security indicators are proposed as a means of quantitatively evaluating the unique domestic energy security risks of energy resource exporters.

### 3.2 Resource Curse

In developing a wider understanding of the domestic implications of energy resource exports, the so called "resource curse" or "paradox of plenty" is a good place to start [111]–[114]. At a high level, the basic premise of the resource curse is that without careful governance and financial management, countries experiencing a significant increase in GDP due to natural resource exports have frequently experienced considerable wider negative economic outcomes. These may include or be related to the increase in exports distorting the foreign currency exchange rate and making local manufacturing suddenly less internationally competitive as an export, and also making imported goods cheaper, thus undermining local employment and manufacturing capacity.
Additionally, the capital-intensive nature of natural resource extractive industries tends to supress economic growth compared to labour-intensive industries that drive employment and skill development. Further, failures in governance related to tax and royalty policies are unfortunately common, with the result that the exporting country may not receive adequate government revenue to balance the effects on foreign currency and unemployment.
Although there has been considerable depth of analysis of the resource curse, studies typically focus on the broader economic impacts, while there is a definite gap in analysis due to the export of energy resources and impacts on the domestic energy system, which in turn will have their own energy security related economic risks. Ultimately, if a nation is producing fossils but their own energy security does not improve as a result, this situation is a distributional injustice[115].

## 3.3 Methodology

A systems approach has been applied to identify a number of potential blind spots when the prevailing importer-oriented energy security framework approach is applied to energy exporters. Figure 3-1 shows a theoretical configuration of a domestic energy system with both imports, local production and exports of all energy resources. In practice, such a system would not exist, since if domestic production were sufficient to supply local needs and exports, there would be no need to import the same fuel.

In order to conduct a thorough analysis of export interactions with the domestic energy system, the comprehensive theoretical energy system shown is Figure 3-1 is divided up into various combinations of energy system that might practically be experienced by a country. Each energy system configuration, including the role of imports and exports is set out diagrammatically in Figure 3-2 to 3-8. A discussion of the suitability of the prevailing energy security framework approach as established through the literature review in this chapter as applied to each energy system case is also given.

Due to the complexity of cases and potential number of combinations, oil system cases have been separated out and are shown below.

Although nuclear fuel and its precursor yellowcake ore concentrate is internationally traded, we have excluded it from consideration here since the value of uranium mining and export is only weakly linked (5.6-7.7%) to the final value of nuclear generated electricity, which is in considerably less than the natural resource product value contribution of coal (45%) or natural gas (79%) to their respective power generation types [109].

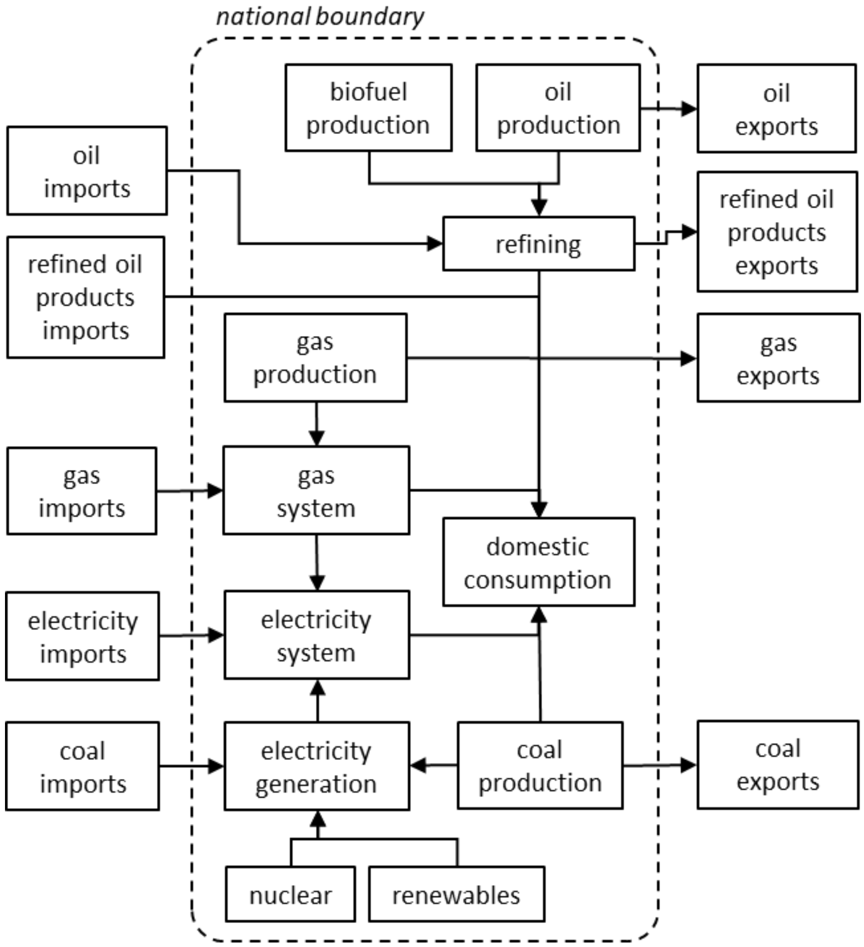



*Figure 3-1 - Theoretical Domestic Energy System Showing Import and Export Interactions*

Case 1, shown in Figure 3-2, represents the energy system of a completely import dependent country, with its only domestic energy supply from renewables and nuclear (if present). This case fits the import-dependent country profile of the prevailing energy security framework approach.

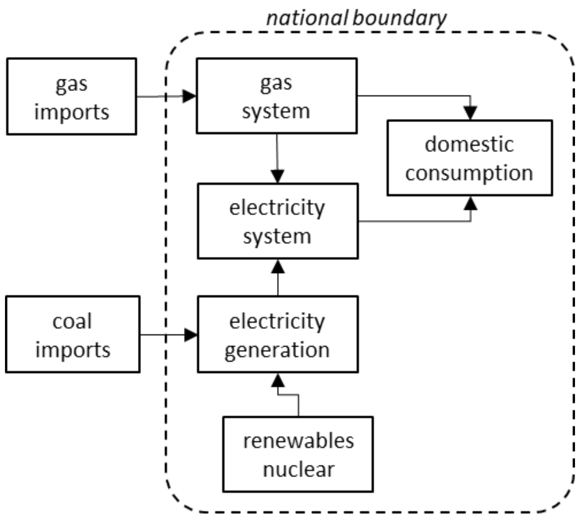



*Figure 3-2 - Case 1: Import Dependent Energy System*

Case 2, shown in Figure 3-3, represents the energy system of a country with some of its own domestic energy resource production, but that still requires imports due to geographical separation within the country or growth in consumption with fixed or falling local production from declining resource stocks. This case also fits the import-dependent country profile of the prevailing energy security framework approach as per the introduction to this chapter.

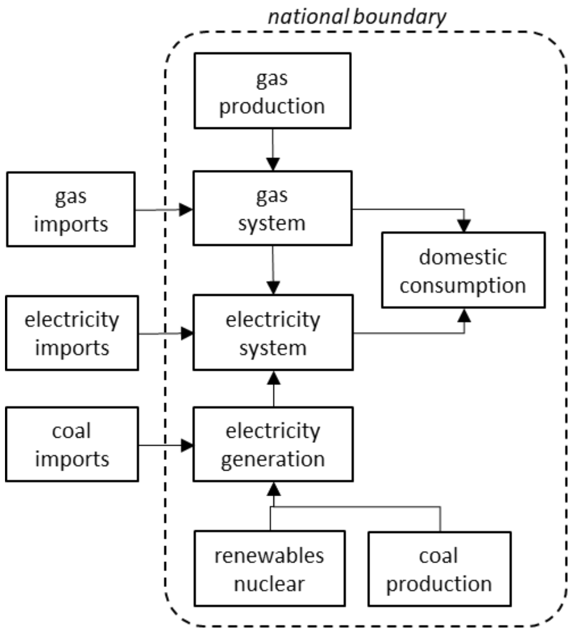



*Figure 3-3 - Complex Energy System with Domestic Production Supplemented by Imports*

Case 3, shown in Figure 3-4, represents the energy system of a self-sufficient country that neither requires any imports nor has any exports. In the modern interconnected global energy trading economy, this is an unusual case, perhaps more likely to be found in the early part of the 20th century. With no exports, this case fits the profile of the prevailing energy security framework approach as per the introduction to this chapter.

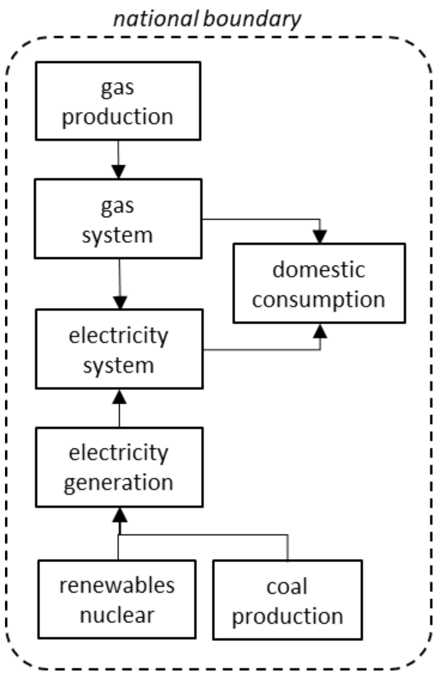



*Figure 3-4 - Case 3 Internally Self-Sufficient Energy System*

Case 4, shown in Figure 3-5, represents the energy system of a country that is self-sufficient in its own primary energy needs and also exports energy resources, but production for export is either physically separated from the domestic energy system, or somehow protected by regulatory mechanisms. The prevailing energy security framework approach is well suited to this case, as it applies to the domestic energy system and exports are treated as any other type of natural resource export.

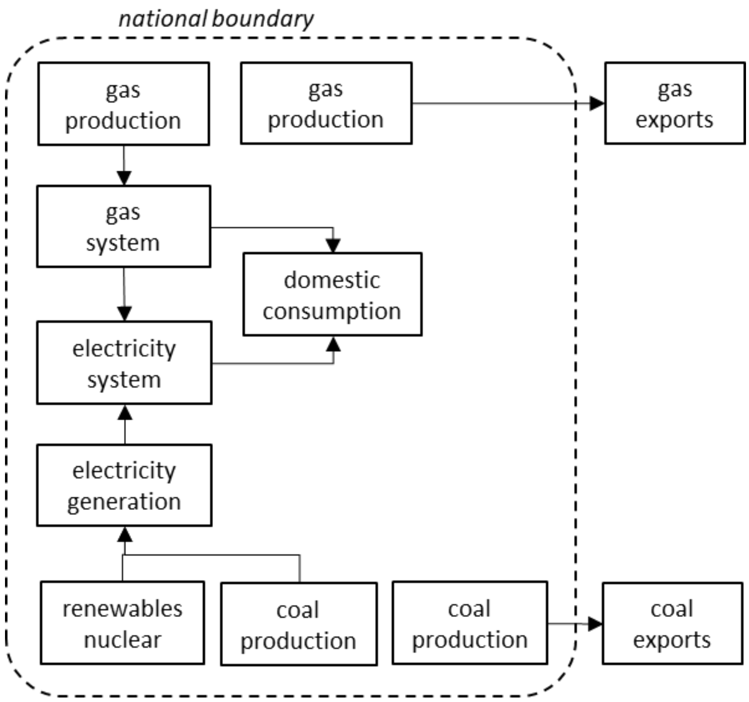


*Figure 3-5 - Case 4: Independent Energy System with Separated Exports*

Case 5, shown in Figure 3-6 represents the energy system with two complicating features. First, the country imports some of one fuel to supplement domestic shortfall while exporting another fuel of which it has excess production to domestic needs.  Second, production for export and for domestic use of the same fuel are physically linked (or have the potential to be linked, thus forming a single energy supply market). The prevailing energy security framework approach breaks down in this case, for the following reasons. First, the typical energy security measure of total net primary energy self-sufficiency (the ratio of production to consumption) does not capture the net shortfall in one fuel that cannot necessarily be cross-substituted by another fuel with excess, and also does not recognise export commitments - without which the excess production capacity would potentially not have been developed. Second, the fuel that is both used domestically and exported is subject to a bi-directional demand, which has not been seen in any of the other preceding cases. The exposure of domestic energy supply to export market influence, possibly as a transition case from an earlier state of zero exports is not considered.

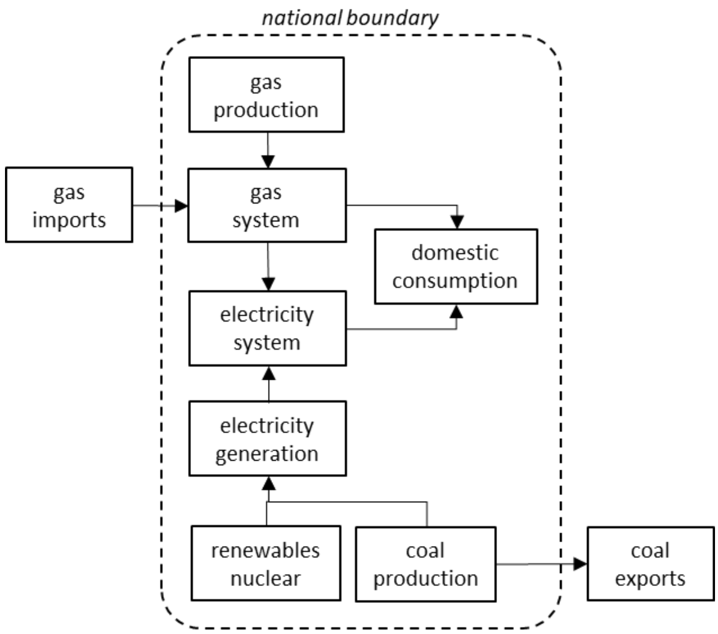



*Figure 3-6 - Case 5 : Complex Energy System*

As noted above, oil system cases have been treated separately due to the complexity of representing the various combination cases. Figure 3-7 shows the cases of oil import dependence, with complete reliance on imports for supply of refined oil products in case 6. Case 7 is a development on case 6, where a country is able to invest in refining capacity and take some control over supply of refined oil products (and benefit from the value-add), although still remaining fully dependent on imports of crude oil. These cases fit the import-dependent country profile of the prevailing energy security framework approach as per the introduction to this chapter.

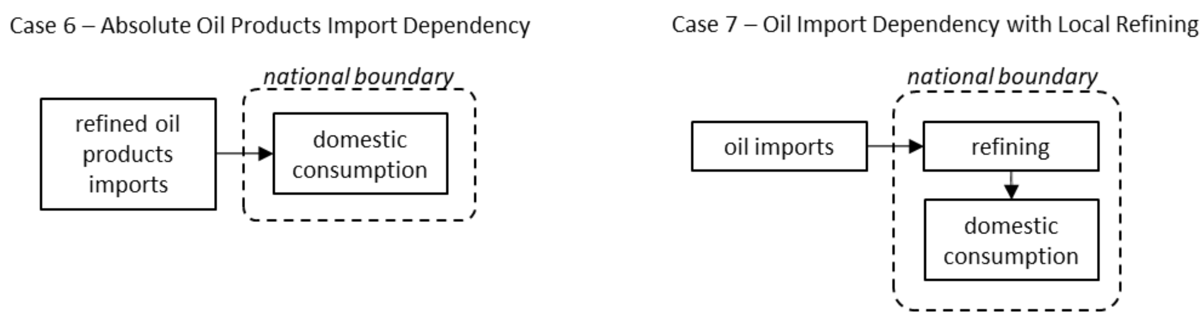



*Figure 3-7 - Oil and Oil Refined Products Import Dependency Cases*

Figure 3-8 shows the cases of oil production and export. Case 8 represents a country with domestic oil production but that lacks the investment in domestic refining capacity and is therefore dependent on external refining of its own oil to supply domestic requirements for refined oil products. The prevailing energy security framework approach breaks down in this case, for a similar reason given first in case 5, where the typical energy security measure of total net primary energy self-sufficiency (the ratio of production to consumption) does not capture the absence of refining capacity and subsequent absolute reliance on imports of refined oil products despite the domestic origin of the crude oil.

Case 9 represents a development on case 8, where a country is able to invest in refining capacity and take control over supply of refined oil products for domestic needs from its own oil production, as well as exporting both crude oil and refined oil products.  The prevailing energy security framework approach breaks down in this case, for a similar reason to that given second in case 5 above, where both the crude oil and refined oil products are subject to a bi-direction demand being used domestically and exported.

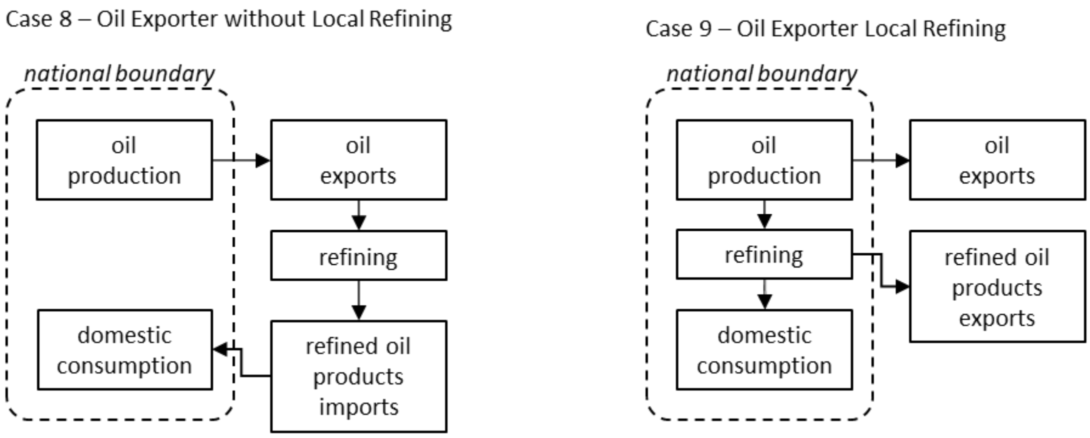



*Figure 3-8 - Oil Exporter Cases*

Through the application of this systems approach to the various potential configurations of energy systems, some conditions under which the prevailing energy security framework approach is not effective have been established, summarised as follows:

- The total net primary energy self-sufficiency (the ratio of total domestic energy production to total energy supply) which is one of the most common energy security indicators, does not recognise the potential net shortfall in one fuel that can not necessarily be cross-substituted by another fuel with excess. It also does not recognise export commitments without which the excess production capacity would potentially not have been developed that mean the excess is likely not available for domestic use. It also does not recognise that in the case of oil, both crude oil production and refining capacity need to be considered.
- The situation where an energy resource that is both used domestically and exported is subject to a bi-direction demand, and hence domestic energy supply system becomes exposed to export market influence, is not recognised in the prevailing energy security framework approach. That such as situation may arise as a transition case from an earlier state of zero exports introduces further unaddressed energy security risks for the domestic energy system.

These two critical blind spots in the domestic energy security of energy exporting countries are addressed in sections 4 and 5.

### 3.4 Blind Spot #1 : Actual Primary Energy Self Sufficiency

Primary energy self-sufficiency, or its inverse, import dependence rate, is considered among one the main measures of energy supply security for countries that depend on energy imports[8], [28], [30], [32], [33], [106], [107].

The basic definition of this measure is quantified as follows:

*Equation 3-1 - Primary Energy Self Sufficiency (Basic Definition)*

$$PESS = {}^{TDEP}/_{TPES}$$

Where;

PESS = primary energy self sufficiency

TDEP = total domestic (and quasi-domestic) energy production

TPES = total primary energy supply

This measure is of particular interest to countries heavily dependent on energy resource imports such as Japan.

For example, in 2019 Japan's total primary energy supply (production and imports) was 18.6TJ, of which 16.5TJ was in imported fuels. The balance of 2.1TJ was provided from domestic sources (including nuclear). Japan's primary energy self-sufficiency rate was thus 2.1/18.6 = 11.3%[116]. This measure is clearly a useful means of quantifying primary energy self-sufficiency, or a lack of it. From an energy security policy perspective, the implicit assumption is that countries with a net energy production surplus, hence, net energy exporters, are in a better position with regards to their own domestic energy security. For example, Australia's primary energy self-sufficiency rate in 2019 was calculated using the same computational method as follows[117].

TDES = 18.7TJ, TPES = 6.0TJ

PESS = 18.7/6.0 = 309.1%

Energy import dependent countries may look at Australia's PESS with envy, however, it should not be surprising that energy security for major energy resource exporters is somewhat more complex than it may seem.

Here some situations are explored where actual conditions for net energy exporters are considerably less secure than the basic PESS measure might indicate.

### 3.4.1 Decomposition of Net Energy Surplus

In order to assess the usefulness of primary energy self-sufficiency as an indicator of energy security for a net energy exporting country, a decomposition analysis of total primary energy into constituent energy types is required.

When a decomposition is applied to Australia's headline PESS in 2019 of 309.1%, it becomes apparent that significant net exports in gas and coal are overshadowing import dependence in refined oil products, as shown in Table 3-2 below[117].

*Table 3-2 - breakdown of Australia's Energy Resource Production, Consumption and Self-sufficiency*

| Energy Resource | TDEP | TPES | PESS |
|---|---|---|---|
| Oil & products | 719 | 2218 | 32.4% |
| Coal | 12596 | 1984 | 634.9% |
| Gas | 4938 | 1434 | 344.4% |
| Biomass | 207 | 207 | 100.0% |
| Solar / Wind | 135 | 135 | 100.0% |
| Hydro | 56 | 56 | 100.0% |
| Total | 18651 | 6034 | 309.1% |

Exports of coal and gas dominate shares of production over domestic consumption (some of the consequences of which will be addressed later in this chapter). However, Australia produces only 32.1% of its domestic oil needs, 80.2% of which are used as transport fuels. Australia's energy security position is therefore much less secure when it comes to transport fuels.

Australia's massive production surplus in coal and gas, developed for export purposes, also requires examination from a broader energy security perspective. Production capacity of energy resources above 100% of domestic needs has been developed and financed for export customers (often under strict and exclusive contracts) and as such may not always be considered of benefit to domestic energy security. There are also further negative implications to domestic energy security from the linking of domestic and export-oriented production of energy resources, which will be explored later in this chapter. Accordingly, when calculating PESS, the rate of total domestic energy supply per energy type should be capped at 100%, and ideally should only reflect the production capacity that can practically and contractually be utilised domestically.

### 3.4.2 Oil Exporters Lacking Refining Capacity

Even for oil exporting nations, energy security for domestic transport fuel needs is not always assured since adequate domestic oil refining capacity is required to match domestic demand for refined fuels with domestic oil production. Where this is not true, the crude oil must be exported for refining elsewhere, then ultimately re-imported at higher cost to provide for domestic demand.

For example, in the national energy balance, Mexico achieves a PESS rate of 79.0%. Regarding its net oil supply / demand balance, Mexico produces oil that would account for 114% of its domestic petroleum needs, hence having some excess for export.

Mexico's net oil supply / demand balance in 2019 is set out in Table 3-3 as follows [118]

*Table 3-3 - Analysis of Mexico's Crude Oil and Refined Oil Products* [118]

| Category | Unit | Quantity |
|---|---|---|
| Petroleum products demand | PJ | 3,619 |
| Oil production | PJ | 4,109 |
| Net oil self-sufficiency | | 114% |
| Unrefined oil export | PJ | 2,586 |
| Refinery consumption | PJ | 1,455 |
| Refinery output | PJ | 1.379 |
| Refined oil product imports | PJ | 2,240 |
| Refined products ESS | | 38% |

However, on closer examination, Mexico's oil refineries only produced 38% of domestic refined oil products demand in 2019. Therefore, although it is a net oil exporter, Mexico is dependent on imports for 62% of its refined oil products demand, due to a limitation in refining capacity. Mexico's 62% dependence on imported refined oil products can then be analysed using conventional energy security assessment tools such as a supply source diversity index. This indicator, represented in various energy security literature [8], [28], [66] is typically based on the Herfindahl-Hirschmann Index (HHI) method. In the case of Mexico's fuel imports in 2019, the HHI score for supply source diversity is 0.77, indicating a high degree of supply source concentration. This is borne out by the raw data showing 88% of Mexico's fuel imports come from the United States [119]. Notwithstanding the high degree of economic integration between the United States and Mexico [120], the existence of frequent trade disputes between the two countries [121] and even political promises from US elected officers to compel Mexico to pay billions of dollars for a border wall [122] suggest that supplies of refined petroleum fuels imported into Mexico from the

US may not be quite so secure as might be hoped? If the country had sufficient domestic refining capacity to meet domestic needs the energy security would be higher, and any surplus could provide extra GDP through value added to petroleum production and export of the refined product rather than exporting only unrefined crude oil.

The situation is even worse for major oil producer Nigeria[123]. With oil production of 4,295PJ in 2019, and a domestic demand of 978PJ for refined petroleum products (88% for transport fuel), the country's net oil self-sufficiency appears to be a very healthy 439% (producing over 4 times domestic demand). However, Nigeria's troubled refineries only produced 22PJ in 2019 (2% of demand) and were completely out of operation in 2020. Nigeria is therefore completely dependent on imports for petroleum transport fuels.

This was not always the case for Nigeria, which was previously self-sufficient in refining of oil products with refining production peaking in 1991 at 611PJ. However, since that time domestic refining capacity has declined due to under-investment in aging refineries to only 79PJ by 2015, and zero in 2020[123].

In Nigeria's case, notwithstanding a complete reliance on imported refined petroleum products, application of the supply source diversity indicator [28] based on the HHI method yields a result of 0.19 representing a reasonable level of supply source diversity. The raw trade data [124] shows that Nigeria's sources of refined fuels are Netherlands (36%) and Belgium (23%), followed by 11 countries supplying between 5% and 1%.

Despite the diversity of supply sources from an energy security perspective, lack of maintenance on existing refineries combined with an absence of investment in new refining capacity to keep up with demand growth has meant that in addition to having no domestic security of supply of refined petroleum fuels, Nigeria pays 26 Nigerian Naira (USD0.06 as at 15/9/2022) per litre in freight [125] alone simply to ship its own oil offshore for refining and return shipping of the refined fuels, increasing local petrol prices by 18% [126].

The lack of domestic refining capacity is not only a disaster for energy security, but also a clear economic loss. The situation appears hopeful however, with plans to rehabilitate out-of-service government-owned refineries and private investment in new refining capacity underway [125].

### 3.4.3 A New Method of Calculating Primary Energy Self Sufficiency

The preceding examples of Australia, Mexico and Nigeria prompt a reconsideration of the simplistic calculation of primary energy self-sufficiency rate that is common in energy security assessments, but which is primarily suitable for net energy importers. The traditional energy security measure of primary energy self-sufficiency can hide domestic energy security blind spots experienced by energy exporters, notably; net exports of some energy resources obscuring import dependence for others and a lack of domestic processing capacity for local needs even while considerable resource production drives increases in net exports.

Decomposition into the main energy uses of transport, electricity generation, industry and other, is proposed as an initial means of matching actual demand types with supply. In this way, energy security can be expressed relative to sectoral demand, with correlation to the primary energy inputs to the specific sector.

A new indicator for exporter primary energy self-sufficiency (Ex.PESS) is proposed, which is designed to accommodate the particular circumstances of energy exporters. In order to capture energy supply to end use and avoid duplication of counting of fuels which can be either used directly or have conversion steps such as refineries and power stations prior to end use, the calculation of Ex.PESS is divided into the categories of electricity, oil and oil products and gas, for which domestic supply self-sufficiency (DSS) is calculated separately, according to the rules set out below.

This new metric is defined in Equation 3-2:

*Equation 3-2 - Calculation Method for Exporter Primary Self-Sufficiency*

$$Ex.PESS = \frac{(TES \times DSS)_{electricity} + (TES \times DSS)_{oil}(TES \times DSS)_{gas}}{TPES}$$

Where;
Ex.PESS = Exporter Primary Energy Self Sufficiency
TES = total energy supply in each category
DSS = domestic supply self-sufficiency, as defined below for each category
TPES = total primary energy supply (sum of all TES categories; electricity, oil and gas)

DSS for gas is calculated as the ratio of domestic production to domestic demand.

DSS for oil and oil products takes the minimum value of domestic production capacity and domestic refining capacity, divided by domestic demand for petroleum products excluding electricity generation use. Biofuels that are combined into the refined petroleum products supply chain either as blended fuels or direct substitutes are also include in this category, although in most cases the effect is negligible.  For clarity, the calculation method is set out in Equation 3-3:

*Equation 3-3 - Calculation Method for Domestic Supply Self-Sufficiency of Oil*

$$DSS_{oil} = \frac{MIN(DPO, DRO)}{Domestic\ Demand}$$

Where;

DPO = domestic production output

DRO = domestic refinery output

DSS for electricity generation is calculated as the rate of domestic supply in each source of electricity generation, proportionally weighted by the contribution of each electricity generation energy source to the total. Efforts to transition away from fossil fuels and reduce the greenhouse gas emissions intensity of the electricity system by increasing electricity generation from renewables such as solar, wind and hydro have the supplementary benefit of reducing reliance on imported fuels and increasing the DSS score for electricity, thus enhancing domestic energy security.

DSS for each energy category is capped at 100%, representing the maximum rate of production that can be applied for domestic use, as discussed above.

Comparison of energy self-sufficiency rate calculated using the typical importer-perspective measure (PESS) and the newly defined indicator adapted for energy exporters (Ex.PESS) using the near-present pre-pandemic case of 2019 is shown below in Table 3-4.

*Table 3-4 - Comparison of Energy Self Sufficiency (Old and New methods) 2019 (Australia, Mexico and Nigeria)*

| Country | PESS | Ex.PESS |
|---|---|---|
| Australia | 309.1% | 71.3% |
| Mexico | 79.0% | 45.9% |
| Nigeria | 163.2% | 39.3% |

As with traditional PESS method, a higher score for Ex.PESS represents a better energy security position, with the range of potential scores being from 0% (no domestic supply of primary energy) to 100% (full domestic supply of primary energy). From an energy security policy perspective, the difference is quite significant, and with this potential blind-spot of energy exporter domestic energy security now clear, it is possible to develop policies and undertake appropriate actions. As there is clearly considerable difference between the traditional PESS method and Ex.PESS, a historical comparison is provided as shown in Table 3-5.

*Table 3-5 - Ex.PESS Historical Comparison 2013-2019 (Australia, Mexico and Nigeria)*

| | 2013 | 2019 |
|---|---|---|
| Australia | 75.2% | 71.3% |
| Mexico | 79.4% | 45.9% |
| Nigeria | 52.6% | 39.3% |

## 3.5 Blind Spot #2 : Linkage of the Domestic Energy System to Export Markets

In addition to technical limitations in supplying domestic final energy needs, the commercial pull of export revenue on a resource shared with domestic energy supply can also lead to some perverse energy security outcomes for net energy resource exporting countries.

### 3.5.1 Case Study – Commencement of Queensland LNG Exports

Queensland's domestic gas supply was for many decades supplied from conventional sources, then, from the early 2000s unconventional gas extraction technologies such as hydraulic fracturing and directional drilling enabled the development of tight gas deposits associated with deep, or coal seams that not economically recoverable (due to depth, thickness or size)[127], [128]. Access to this new and abundant gas resource underpinned investment in 3 new LNG production and export facilities near the central Queensland port city of Gladstone, for which the development of additional unconventional gas production capacity was accelerated[129]. Coal seam gas (CGS) production requires a relatively large number of small wells for extraction due to the tight coal seam formations within which it is interspersed, compared to the relatively fewer number of gas wells for an equivalent production capacity of conventional gas from a large contiguous gas reservoir[130]. The development of Queensland's CSG production shows this; in 2004 when CSG contributed only 15% to the state's total gas production, gas production was achieved with approximately 1.3 wells per PJ of gas produced per year. By 2015, when CSG contributed 92% of gas production, this production was achieved with approximately 7.1 wells per PJ per year [129]–[131].

The time required to develop the CSG production fields including well bores, hydraulic fracturing of the coal seam, as well as interconnecting pipelines and electrical networks is an incremental process with production capacity steadily increasing over time as additional wells are brought into production. This process takes considerably longer in the case of CSG due to the larger number of widely distributed small gas wells required to be constructed and commissioned. The CSG production field development is ideally timed to reach full capacity at the same time as the completion of the LNG export facility to allow full LNG production as soon as the LNG production plant is completed. However, CSG wells must be kept in operation producing gas to prevent flooding from the surrounding water table. The result is steadily increasing production of gas before the LNG facility is ready to take it, ramping up to full production. This "ramp gas" effectively created a gas glut in the Queensland market [132]. Figure 3-9 below shows the ramp gas phenomenon, with total gas production increasing well above pre-CSG domestic demand levels, with ramp gas peaking at 180PJ/year in 2014-15, being 106% of the baseline production rate of 170PJ/year for domestic demand. We have calculated the quantity of ramp gas assuming a baseline of gas production using Queensland state government data [133]. Production in 2000/2001 is applied as the base case of conventional (non-CSG) gas production solely for domestic consumption prior to the start of CSG production destined for export. From around 2007/2008, a gradual, then rapid increase in CSG production was observed, which was not intended for long term domestic use but instead represents the run-up to LNG export operations.

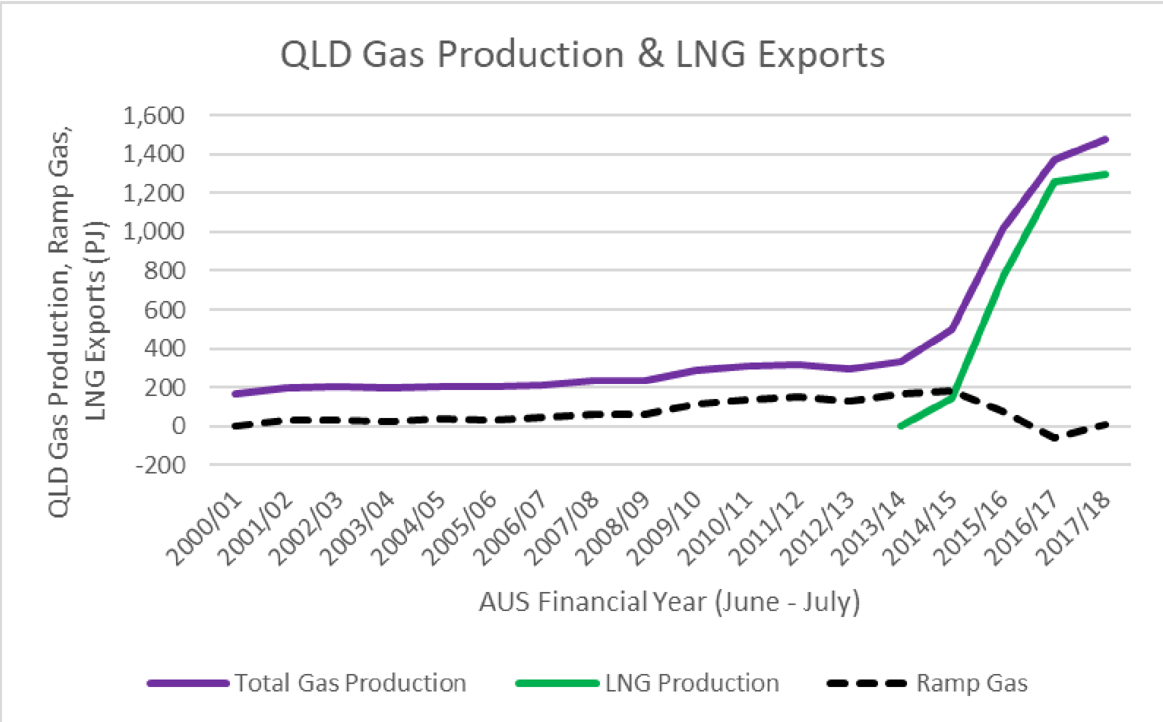



*Figure 3-9 - Queensland Gas Production and LNG Exports*

After domestic gas demand has been satisfied, the residual gas supply is either flared (burned on site in a flare stack, having no value), or used as a fuel for power generation. Since the gas supply is at negligible cost, the result is an increase in very low-cost electricity dumped onto the electricity market. The operation of gas fired power stations using ramp gas might well be called "electrical flaring" (flaring by way of electricity generation) as a result. Once LNG facility operation is commenced, the ramp gas is withdrawn (often suddenly) from the domestic market to supply LNG production for export customers.

The process described above contains two phases that are of interest in the context of energy security, and which require further detailed examination;

- Pre-LNG start-up: The glut of ramp gas prior to LNG plant start-up
- Post-LNG start-up: The sudden removal from the market

As ramp gas flooded into the Queensland market, gas fired electricity generation increased operating with fuel effectively at zero cost. The direct physical effect was to displace coal fired electricity generation. As seen in Figure 3-10, the aggregate capacity factor of Queensland's approximately 7GW of baseload coal fired electricity generation fleet closely follows an inverse trend to the availability of ramp gas. This capacity factor is calculated using National Electricity Market open-source data for the generation output at 30 minutes dispatch intervals for each coal fired generation unit in Queensland from 2000/2001 to 2017/2018. At the height of ramp gas dumping, generators with higher short term marginal costs (including coal prices) as well as limited turn-down capability due to plant age, were forced to shut down generation units temporarily or permanently. At Gladstone Power Station, scheduled maintenance shut-downs were extended by reducing work-rate and holding off returning to operation for a month or two longer after the generation unit was ready to restart. At Tarong Power Station, generation units were shut down and put into long term storage (Tarong unit 2 for 39 months from November 2012 to February 2016, Tarong unit 4 for 19 months from December 2012 to July 2014). Although not in operation, these generators still incur operating costs while under "care and maintenance" in anticipation of their restart when LNG export operations would soak up excess ramp gas and curtail zero cost gas fired electricity generation.

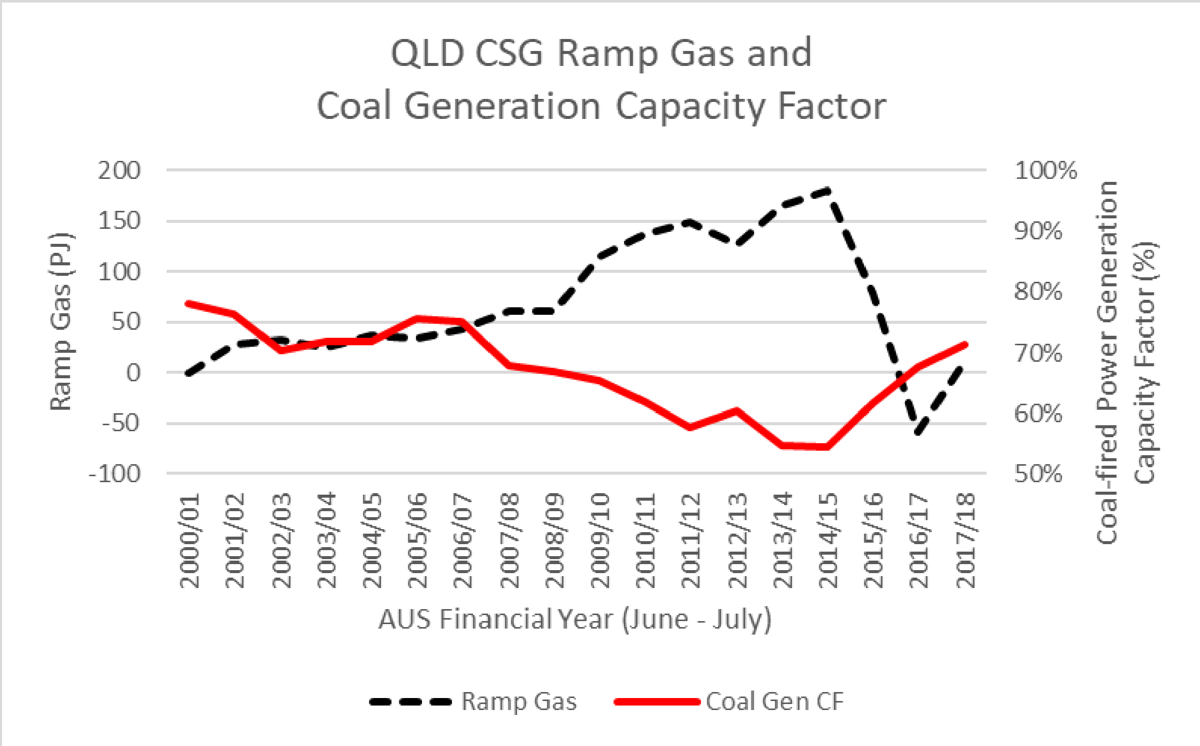



*Figure 3-10 - Queensland CSG Ramp Gas and Coal Fired Electricity Generation Capacity Factor* [133], [134]

Additionally, in Figure 3-11 the increase in gas fired generation capacity factor over the ramp gas period due to availability of gas can be seen, tracking the opposite trend of coal fired generation capacity factor which reduces then returns to pre ramp gas levels once LNG exports commence

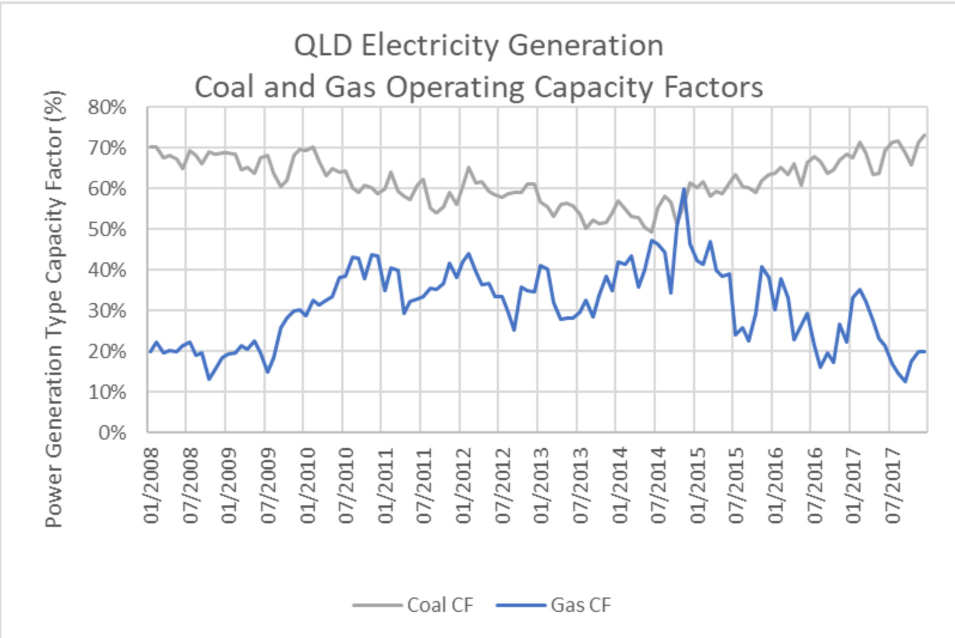



*Figure 3-11 - Queensland Coal and Gas Fired Electricity Generation Capacity Factors Over the Ramp Gas and LNG Export Start Period*

Notwithstanding the excess of gas available, producers clearly understood that ramp gas was a temporary phenomenon. As a result, even though the spot market was flooded with ramp gas, gas users seeking long terms contracts for supply covering a period after LNG export start-up experienced challenging conditions as future gas supply was already being priced at LNG-export-parity prices, a considerable jump from solely domestic supply pricing based on actual production and capital investment costs.

The long-term price level of Queensland gas which had generally been 2-3 AUD/GJ experienced an extreme jump to be linked to the east Asian LNG price of 12-14 AUD/GJ [131]. In the absence of protective policies such as domestic gas reservation, this alone is a massive disruption to the domestic energy system, but it is not the only disruption experienced post LNG start-up. Following the immediate effects of ramp gas being removed from market and the cessation of electrical flaring, gas fired power generation capacity factor fell from highs of 40-50% during the ramp gas peak to return to the pre-ramp gas level of around 20%. However, even with approximately half the prior gas fired electricity generation in the system, the increased cost of gas fired power generation due to the LNG export price linkage caused the monthly average electricity price to suddenly rise from around AUD40/MWh to AUD60-80/MWh, as shown in Figure 3-12. In addition, coal fired generators that had been placed in extended storage along with associated coal mining capacity were promptly restarted to cover the loss of gas fired generation. The costs of refurbishing and recommissioning these major energy production assets are not insignificant for the asset owners who derive no benefit from CSG or LNG operations. Further, any ongoing benefit from reduction in $CO_2$ emissions while gas fired generation had displaced coal fired generation during the ramp gas phase is lost.

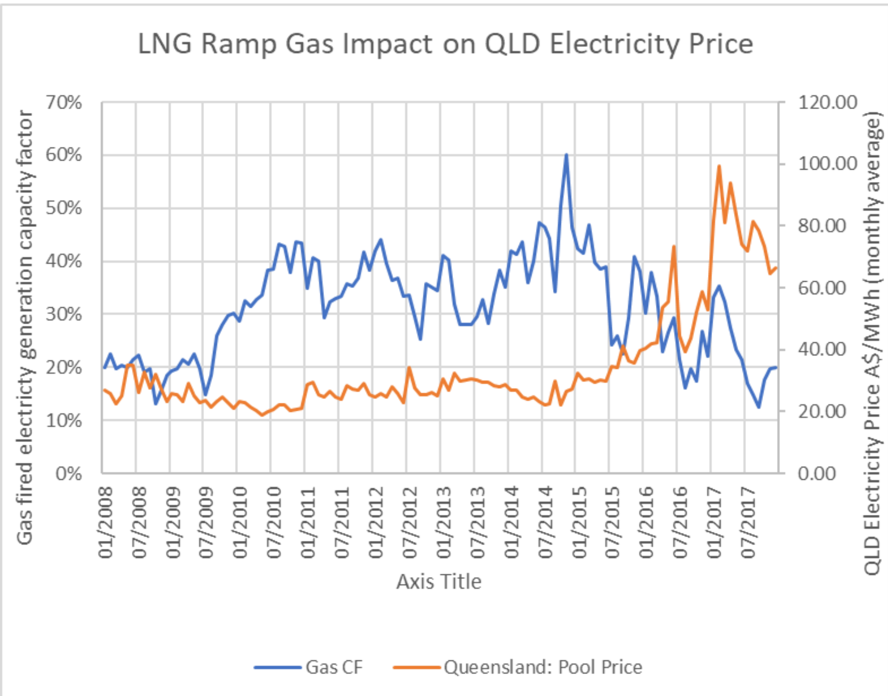



*Figure 3-12 - LNG Ramp Gas Impact on Queensland Electricity Price*

The anticipated shortfall of CSG supply for LNG operations eventuated as expected with LNG operators pulling gas out of the domestic supply market to meet their shortfall, thus both increasing price and limiting supply and the ability of domestic commercial and industrial gas users to obtain supply contracts.

During the CSG ramp gas phase, 5 gas fired power stations were constructed to manage the excess gas supply. With the start-up of LNG export operations, gas fired power generation units suddenly changed from operating at high capacity factor, to operating only as standby generation used by gas producers to consume temporary excesses in the CSG to LNG supply-demand balance, or as peaking generation when electricity market spot prices exceeded LNG export parity gas price, if gas supply was available at the time required. This sudden change is quite disruptive to the electricity system; not only is there significant underutilised generation capacity recognised by the system operator but effectively idle, but also the stability of the electricity system may be impacted in situations where there is a shortfall to meet demand when peaking generation is required.

As set out in this chapter have seen, not only did domestic gas supply system become linked to the international LNG pricing, but also by extension, the electricity system also became linked. As a result, Queensland and Australia effectively lost their natural energy security advantage from domestic gas reserves.

It should also be noted that adding more gas supply is not guaranteed to improve domestic energy security either. As set out above when discussing actual primary energy self-sufficiency, production capacity developed above the level required to match domestic demand serves no net benefit as long as the systems remain physically linked and especially when export customers are willing to pay a higher price for the fuel than domestic customers who have not previously been exposed to international market prices.

#### 3.5.1.1 Gas Production and Domestic Greenhouse Gas Emissions Intensity

The relationship of $CO_2$ emissions to fossil fuel based energy use is well understood, and can be related to population, economic activity and energy use to derive some useful ratios for energy economic analysis, as set out in the block diagram model shown in Figure 3-13

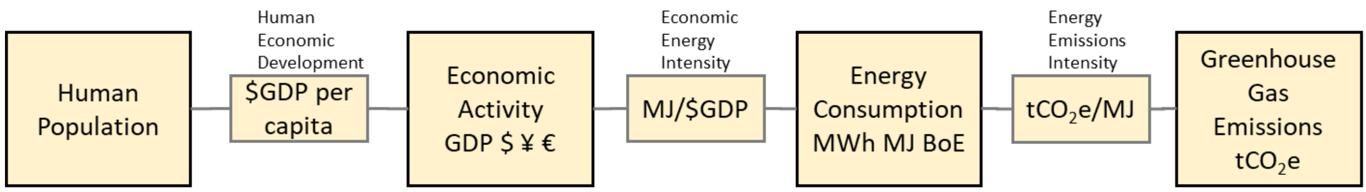



*Figure 3-13 - Model for Greenhouse Gas Emissions Intensity from Fossil Fuel Energy Use*

This can also be expressed as the function shown in Equation 3-4.

*Equation 3-4 - Function for Greenhouse Gas Emissions Intensity from Fossil Fuel Energy Use*

$$C = P\left({}^{G}/_{P}\right)\left({}^{E}/_{G}\right)\left({}^{C}/_{E}\right)$$

Where;

C = $CO_2$ emissions;

P = population

G = GDP

E = primary energy consumption

Analysis of the function ratios E/G (economic energy intensity) and C/E (energy emissions intensity) yield particularly useful results in assessing actual $CO_2$ emissions reduction progress. These two functions can be combined as C/G (emission per unit of economic activity).

Gas is widely considered a transition fuel from higher emissions power generation fuels such as coal or oil[135] and as such, an increase in gas production and use as a power generation fuel to displace coal will reduce the overall energy emissions intensity of a country. However, since gas production and processing involves the separation of naturally occurring $CO_2$ from the gas stream, and also some fugitive emissions of methane, as well as emissions from the energy required for pumping, compression, and liquefaction the activity of producing natural gas and LNG is itself a cause for some emissions[127], [129], [136]. At the same time, the emissions reduction benefit is realised by the end user who can reduce coal consumption for power generation by using gas instead.

At the same time as Queensland's CSG development boom, the United States also experienced a boom in the development and production of natural gas, increasingly from unconventional sources, however a key difference has been the increase in gas production in Australia has been overwhelmingly export oriented while in the United States increased gas production has been almost entirely used domestically. Figure 3-14 and Figure 3-15 compare the increase in gas production, rate of domestic gas use, and change energy emissions intensity of Australia and the

United States over the period 2000 – 2019, during which time Australia's gas production increased from 1,195PJ to 4,938PJ (an increase of 313%) and that of the United States increased from 18,713PJ to 33,492PJ (an increase of 79%).

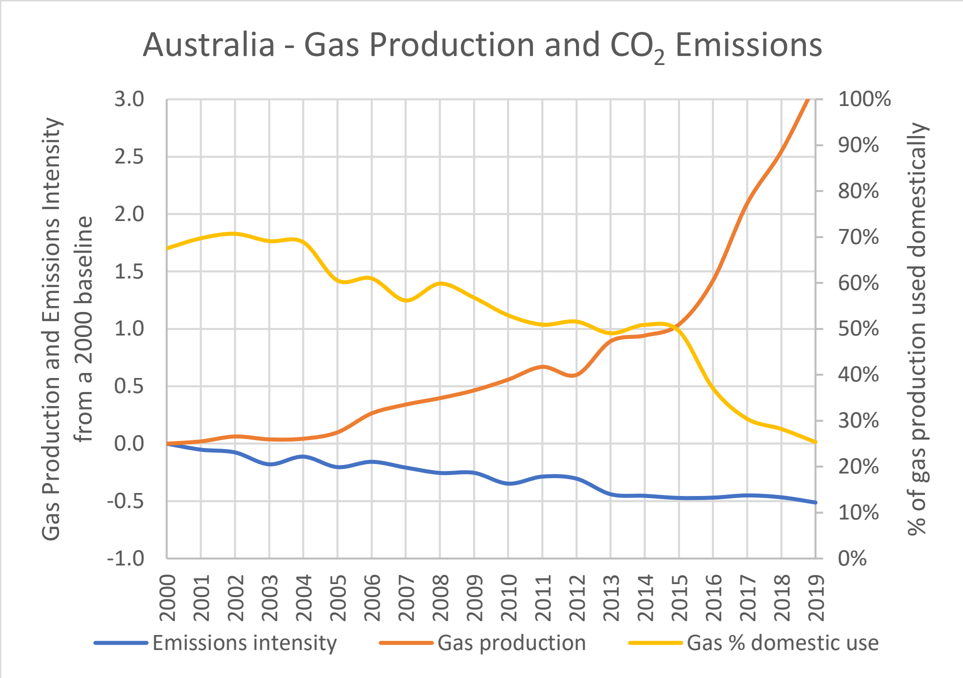



*Figure 3-14 - Gas Production and $CO_2$ Emissions Trends (Australia) 2000-2019*

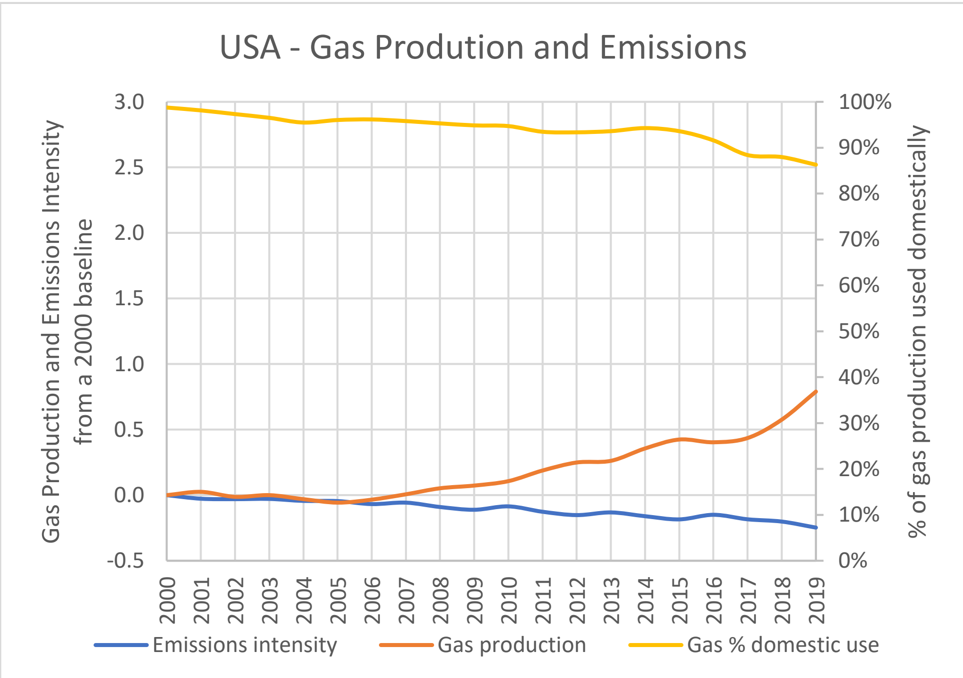



*Figure 3-15 - Gas Production and $CO_2$ Emissions Trends (United States) 2000-2019*

While the magnitude of gas production increase was greater in the United States, since Australia began with a lower initial production, the proportional increase is greater. Either way, both countries experienced a significant gas production boom due to new technologies allowing access to previously inaccessible or uneconomic reserves, as set out earlier in this section.

In Figure 3-14, declining emissions intensity overall can be seen through the ramp gas period however this trend is essentially stalled at the point of commencement of LNG export operations, when ramp gas is withdrawn from power generation, as shown by the trend line for gas % for domestic use suddenly dropping.

Conversely, as seen in Figure 3-15, gas production in the United States has remained above 85% hence the benefits in gas fired power generation replacing coal generation can be seen with a continuing decline in emissions intensity, inversely proportional to the increase in gas production. In summary, this research has found that gas production primarily for export also exports the $CO_2$ emissions reduction benefits of gas as a power generation fuel to the importing country, while the exporting country retains only the $CO_2$ emissions associated with production activities.

### 3.6 A New Indicator for Exporters' Domestic Energy System Exposure to Export Impacts

A new energy security indicator is proposed to assess the extent of an energy exporter's domestic energy system exposure to the international market for energy resources through exports, as follows:

*Equation 3-5 - Calculation Method for Energy Exporter Domestic Energy System Exposure*

$$Ex.DES = \frac{(Ex.DES_{gas} \times TES_{gas}) + (Ex.DES_{electricity} \times TES_{electricity})}{TES_{gas} + TES_{electricity}}$$

Where;
Ex.DES is the export exposure of the domestic energy system).
TES is the total energy supply of the given energy type.

The calculation method is configured such that a higher score represents less export exposure and hence a preferable energy security situation, with the possible range of scores being from 0.0 to 1.0.

Ex.DES(gas). This sub-index is calculated as 1 minus the proportion of domestic gas production that has a physical connection to export and is not covered by measures such as domestic gas reservations or similar policies. If all gas production is physically connected to export, either by pipeline or LNG terminal, then the rating is 0.0. If none of the gas system has an existing physical export pathway, then the rating is 1.0.

Ex.DES(elec). This sub-index is calculated as 1 minus the proportion of electricity generated in a given year from sources that are export connected. Specifically;

- Gas fired electricity generation is evaluated based on whether the generator's gas supply is export linked as per the definition for Ex.DES(gas) above.
- Electricity from coal is evaluated as 0.0 if the mines supplying that power station have an existing operational physical export route, such as a rail line to a coal export terminal, otherwise, 1.0.
- Electricity generation from oil or any refined petroleum products is evaluated at 0.0, due to the globally integrated nature of the oil supply market.
- Electricity from wind, solar, hydro, nuclear, geothermal, and biomass are evaluated at1.0, since these energy sources are used purely for domestic electricity generation and are not export-exposed fuels.

Due to the global nature of the oil market, any significant quantity of oil production will be linked to international markets, and based on the above approach used for gas and electricity this figure would always be 0.0. Since there is no possibility of a different result, considering Ex.DES for oil does not add any value to assessing a country's overall domestic export exposure and would in fact weight the overall indicator toward a lower score, oil is excluded from the calculation method for this indicator, except as covered by Ex.DES(elec) as an energy source for electricity generation . Using this new indicator, Australia's domestic energy system export exposure before and after the commencement of LNG operations in Queensland has been assessed, comparing 2012-2013 to 2018-2019[117], [134], [137]. Over this time interval, Australia's domestic gas consumption increased 4.9%, while electricity demand increased 5.7%[137].

*Table 3-6 - Ex.DES (gas) 2012-2013 Financial Year (Australia)*

Ex.DES(gas) 2012-2013

| Region | Production (PJ) | Total domestic use (PJ) | Export exposed? | Export exposed (PJ) |
|---|---|---|---|---|
| ALL STATES | 2,439 | 1,010 | 0 | 0 |
| TOTAL | 2,439 | 1,010 | | 0 |
| Ex.DES(gas) | | | | 1.00 |

In 2012-2013, only Western Australia's domestic gas network had a physical connection to gas production that also supplied LNG exports, however due to the domestic gas reservation policy of the Western Australian state government, that state's domestic gas system can be considered protected from export parity pricing impacts[138]. Meanwhile the interconnected eastern Australian gas system spanning the states of Queensland, New South Wales, Victoria, South

Australia and Tasmania was nearing the end of its domestic isolation as the three Queensland LNG projects approached completion. Accordingly, in 2012-2013, the entire Australian gas system can be rated Ex.DES$_{(gas)}$ = 1.0, as shown in Table 3-6.

In 2018-2019, with LNG exports in operation from Queensland, the eastern Australian gas system has become fully export exposed, and only Western Australia, with 37% of national domestic gas consumption is protected as set out above. As a result, Australia's gas system rating for export exposure is Ex.DES$_{(gas)}$ = 0.37, as shown in Table 3-7.

*Table 3-7 - Ex.DES (gas) 2018-2019 Financial Year (Australia)*

Ex.DES(gas) 2018-2019

| Region | Production (PJ) | Total domestic use (PJ) | Export exposed? | Export exposed (PJ) |
|---|---|---|---|---|
| All States excl. WA | 3,232 | 670 | 1 | 670 |
| WA | 1,706 | 390 | 0 | 0 |
| TOTAL | 4,938 | 1,060 | | 670 |
| Ex.DES(gas) | | | | 0.37 |

Evaluating Ex.DES(elec) requires a more detailed analysis in some cases down to the level of individual power stations. The breakdown and calculation for 2012-2013 is shown in Table 3-8, and for 2018-2019 is shown in Table 3-9.

As set out above, all electricity generation from oil products is considered export exposed, exposed hence returning a score of 1.0 for their share, while all renewables (biofuels / biomass, solar, wind and hydro) are not exportable hence scoring 0.0.

Brown coal, used for power generation in Victoria alone, is not an exportable fuel due to its high water content and low calorific value, hence Victoria's brown coal fired electricity is not exposed to export linkage effects and thus also scores 0.0. A project demonstrating gasification of brown coal and conversion to hydrogen, which is liquefied and shipped to Japan commenced periodic operation in 2021. Although only at demonstration scale at present, the project participants, supported by the governments of Japan and Australia, have aspirations to scale up to commercial production of hydrogen using brown coal from Victoria's Loy Yang mine[139] which if it is achieved in the future would cause Victorian brown coal fired electricity generation input fuel price to be in competition with this export route.  The situation is reversed in New South Wales, where the black coal supply to every one of the state's coal-fired power stations is interlinked to rail transport to coal export terminals at either Newcastle or Port Kembla. In Queensland, some coal fired power stations are supplied from dedicated mines with no rail pathway to a port (thus scoring 0.0), while others share their coal supply with rail-enabled exports (scoring 1.0 accordingly) [140]

*Table 3-8 - Ex.DES (electricity) 2012-2013 Financial Year (Australia)*

| Ex.DES(elec) 2012/2013 | Generation Type | GWh | Sub region | GWh | Power Station | GWh | Export Exposed? | GWh Export Exposed |
|---|---|---|---|---|---|---|---|---|
| | Oil products | 4,464 | | - | | | 1 | 4,464 |
| | Biofuels | 3,144 | | - | | | 0 | - |
| | Solar / wind | 11,786 | | - | | | 0 | - |
| | Hydro | 18,270 | | - | | | 0 | - |
| | Nuclear | - | | - | | - | 0 | - |
| | Brown coal | 47,555 | VIC only | 47,555 | | | 0 | - |
| | Black coal | 113,436 | | | | | | |
| | | | QLD | 44,419 | | | | |
| | | | | | Callide A | 116 | 1 | 116 |
| | | | | | Callide B | 3,874 | 1 | 3,874 |
| | | | | | Callide C | 4,587 | 1 | 4,587 |
| | | | | | Gladstone | 6,394 | 1 | 6,394 |
| | | | | | Kogan Creek | 5,683 | 0 | - |
| | | | | | Millmerran | 7,194 | 0 | - |
| | | | | | Stanwell | 8,440 | 1 | 8,440 |
| | | | | | Tarong Nth | 2,736 | 0 | - |
| | | | | | Tarong | 5,395 | 0 | - |
| | | | NSW | 58,739 | | | 1 | 58,739 |
| | | | WA | 10,278 | | | 0 | - |
| | Gas | 51,053 | | | | | 0 | - |
| | TOTAL | 249,709 | | | | | | 86,614 |
| | Ex.DES(elec) | | | | | | | 0.65 |

A number of differences are noted in Ex.DES(elec) from 2012/2013 to 2018/2019. Electricity generation increased by 14,318GWh (5.7%), from 249,709GWh to 264,027GWh. The start-up of LNG export operations in Queensland as set out above in the discussion of calculation of Ex.DES(gas) have resulted in all of Australia's gas fired electricity generation with the exception of Western Australia became export exposed.

*Table 3-9 - Ex.DES (electricity) 2018-2019 Financial Year (Australia)*

| Ex.DES(elec) 2018/2019 | Generation Type | GWh | Sub region | GWh | Power Station | GWh | Export Exposed? | GWh Export Exposed |
|---|---|---|---|---|---|---|---|---|
| | Oil products | 4,923 | | - | | 4,923 | 1 | 4,923 |
| | Biofuels | 3,496 | | - | | 3,496 | 0 | - |
| | Solar / wind | 32,560 | | - | | | 0 | - |
| | Hydro | 15,967 | | - | | | 0 | - |
| | Nuclear | - | | - | | - | 0 | - |
| | Brown coal | 34,460 | VIC only | 34,460 | | | 0 | - |
| | Black coal | 119,845 | | | | | | |
| | | | QLD | 52,156 | | | | |
| | | | | | Callide B | 4,816 | 1 | 4,816 |
| | | | | | Callide C | 6,236 | 1 | 6,236 |
| | | | | | Gladstone | 8,327 | 1 | 8,327 |
| | | | | | Kogan Creek | 6,285 | 0 | - |
| | | | | | Millmerran | 6,137 | 0 | - |
| | | | | | Stanwell | 8,523 | 1 | 8,523 |
| | | | | | Tarong North | 3,254 | 0 | - |
| | | | | | Tarong | 8,578 | 0 | - |
| | | | NSW | 57,735 | Mt Piper | 9,285 | 0 | - |
| | | | | | Rest | 48,450 | 1 | 48,450 |
| | | | WA | 9,954 | All | 9,954 | 0 | - |
| | Gas | 52,775 | | | | | | |
| | | | QLD | 9,934 | | 9,934 | 1 | 9,934 |
| | | | NSW | 2,360 | | 2,360 | 1 | 2,360 |
| | | | VIC | 3,334 | | 3,334 | 1 | 3,334 |
| | | | SA | 7,246 | | 7,246 | 1 | 7,246 |
| | | | TAS | 620 | | 620 | 1 | 620 |
| | | | WA | 25,778 | | | 0 | - |
| | | | NT | 3,503 | | 3,503 | 1 | 3,503 |
| | TOTAL | 264,026 | | | | | | 108,272 |
| | Ex.DES(elec) | | | | | | | 0.59 |

Non-export-exposed brown coal generation fell by 13,095GWh with the closure of Hazelwood Power Station in Victoria, although this was more than replaced by an increase in total renewable electricity generation of 18,824GWh which is also not export-exposed, as illustrated in Figure 3-16.

Generally, the export-linked status of black coal fired power stations remained unchanged except for Mt Piper Power Station, due to the closure of one mine in its supply area and subsequent cessation of exports, hence Mt Piper's export exposure score is changed from 1.0 to 0.0.

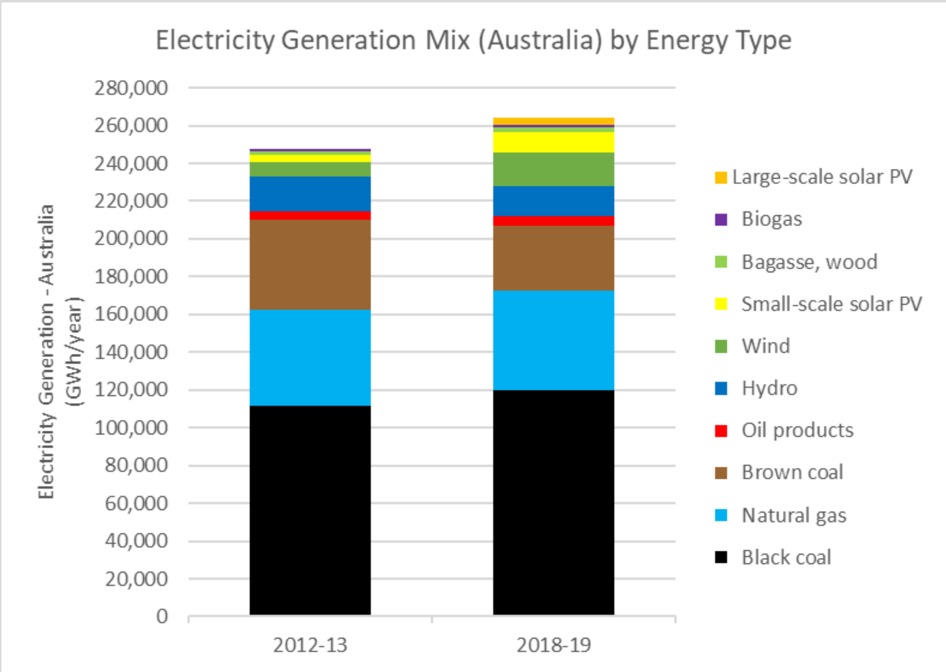



*Figure 3-16 - Electricity Generation Mix (Australia) 2012/2013 and 2018/2019*

Due to these changes, Ex.DES(elec) for Australia decreased from 0.65 to 0.59, representing a worsening of energy security conditions for Australia's electricity generation due to increasing physical linkage of energy sources to export markets.

*Table 3-10 - Ex.DES (aggregated) 2012/2013 and 2018/2019 Financial Years (Australia)*

| | 2012/2013 | 2018/2019 |
|---|---|---|
| Gas (domestic use) (PJ) | 1,010 | 1,060 |
| Electricity (domestic use) (PJ) | 899 | 950 |
| Ex.DES (gas) | 1.00 | 0.37 |
| Ex.DES (elec) | 0.65 | 0.59 |
| Ex.DES (aggregate) | 0.84 | 0.47 |

The aggregated calculation of Ex.DES for Australia comparing the financial year 2012/2013 (the full 12-month period before the commencement of Queensland LNG exports) and 2018/2019 (once

LNG exports from Queensland were fully operational and the domestic energy system had re-stabilised) is shown in Table 3-10.

As can be seen, notwithstanding an increase in domestic renewable electricity generation from 13.3% to 19.7% of the electricity generation mix, this is outweighed by a reduction in brown coal generation from 19.0% to 13.1%, and the linkage of all east coast gas supplies (affecting both electricity generation and industrial, commercial and retail gas users) to export LNG has driven a significant worsening of Australia's domestic energy system export exposure.

### 3.7 Conclusions

In this chapter it has been established that the domestic energy security situation of energy resource exporters is considerably more complex than is suggested by the simple indicator of primary energy self-sufficiency that is often used in energy security literature and policy of net import dependent countries as one of the key indicators. In fact, being a major exporter of energy resources can cause material blind spots in understanding a country's own energy security situation.

Two key energy security blind spots unique to energy exporting nations have been identified with examples, and quantitative indicators developed, as shown in Table 3-11.

*Table 3-11 - Exporters Energy Security Blind Spots and Indicators to Evaluate Them*

| Energy Security Blind Spot | Indicator | Notation |
| --- | --- | --- |
| Actual primary energy self-sufficiency by energy type | Exporter primary energy self sufficiency | Ex.PESS |
| Exposure of the domestic energy system to international markets through physical linkages to exports | Export exposure of the domestic energy system | Ex.DES |

The application of these indicators in the development of holistic energy policy in major energy exporting countries will better inform planning of the domestic energy system, the development of energy resource export projects, and the application of programs such as domestic gas reservations and price caps. The use of these indicators will also allow for a quantitative counterpoint to forecasts of increased GDP from exports, royalties and tax revenue to introduce some balance to the broader economic discussion of the net benefits of new energy resource export projects.

The research has also established a tentative relationship between export-oriented gas production and $CO_2$ emissions intensity while the $CO_2$ emissions reduction benefits of gas as a lower emissions intensity fuel compared to other fossil fuels is transferred to the importing country.

The clear conclusion from this chapter is that an energy exporting country's domestic energy security is enhanced by decoupling the domestic energy system from export-oriented activities, in the following ways:

Regulatory – application of instruments to protect the domestic energy system from supply and pricing issues due to export linkage as conditions of doing business in that jurisdiction, such as domestic gas reservation, or a price cap on the portion of the export-linked resource consumed locally.

Technical – reorientation of the domestic energy system to reduce reliance on export-linked energy sources. In practice, this can be achieved with the largely the same actions undertaken to decarbonise energy supply, by increasing electrification to reduce gas demand, and by increasing electricity generation from domestic renewable sources such as hydro, wind and solar, and nuclear. The one notable exception is the use of low-grade fossil fuel deposits such as brown coal that have no export value, for domestic electricity generation.

In regard to this technical reorientation, pursuing the energy transition to a zero-$CO_2$ domestic energy system allows energy resource exporting countries to enhance their overall energy security position and treat energy resources in a similar manner to any other natural resource exports, increasingly decoupled from their domestic energy system.

# Chapter 4 - Domestic Energy System Vulnerabilities from Major Exports of Green Hydrogen

## 4.1 Chapter Introduction

As shown in Chapter 1 for fossil fuel deposits [109], renewable energy resources such as rivers with hydro-electrical potential, accessible geothermal resources, large open spaces with high solar radiation levels, or available land with high wind speeds are also not evenly distributed worldwide. Countries with high population density and high energy demand such as Japan and South Korea, which already experience energy supply challenges due to a lack of domestic fossil fuel reserves [1] are similarly challenged with access to sources of renewable electricity generation which is a significant limitation in their efforts to achieve a zero-carbon society [36]. The importation of hydrogen produced by means that do not contribute to anthropogenic climate change is emerging as a key method for countries deficient in renewable energy resources to decarbonise their domestic energy systems [36], [141]. Through the process of electrolysis, hydrogen produced from low-cost and plentiful renewable electricity in a supplier country can be used as a vector to transport that renewable energy internationally, without the need for contiguous land borders or undersea cables.

In chapters 2 and 3, this work concentrated on the current status and historical trends of energy exporting countries and their exports of fossil fuels. In doing so, the emerging exporter vulnerability of carbon risk has been identified and novel quantitative methods developed to assess this vulnerability. In this chapter we now consider a future scenario where energy exporters respond to this carbon risk vulnerability and shrinking international demand for fossil fuels, and transition to production and exporting of green hydrogen. In doing so, we draw upon the conceptual frameworks and quantitative tools developed in this research presented in chapters 2 and 3 and apply them to a green hydrogen export future scenario.

Australia in particular has in recent years had well publicized aspirations to become a hydrogen-exporting renewable energy superpower [110], [142]–[144]. These aspirations have crystalised into clear government policy with the National Hydrogen Strategy released in 2019 jointly by the federal and state governments, supported by the National Hydrogen Roadmap [143] prepared by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Following a change in federal government in May 2022 from the centre-right Liberal-National coalition to the centre-Left Labor party [145], the hydrogen strategy has been re-affirmed, and with it the objective of

Australia being a global leader by 2030 in hydrogen for export and for domestic industry decarbonisation [146]. Not only does Australia hope to capitalize on emerging demand for zero carbon hydrogen in places like Japan and South Korea by establishing a new export industry, it also desperately needs to mitigate the built-in carbon risk (an exporter's vulnerability to loss of export revenue as customers take climate change action and reduce fossil fuel consumption, related to the $CO_2$ emissions intensity of exported fuels, measured using tools including metrics M3 and M6 introduced in section 2.4 of this work) of its export revenue from of coal and liquefied natural gas (LNG) as major customers such as Japan [36]and South Korea [37] move to decarbonise their energy systems. The Australian government's focus on these two countries as its hydrogen export customers is abundantly clear in the National Hydrogen Roadmap from the CSIRO [143], the National Hydrogen Strategy from the Coalition of Australian Government (COAG) [144] and the Opportunities for Australia from Hydrogen Exports report prepared for the Australian Renewable Energy Agency (ARENA) [147], emphasised even further by the National Hydrogen Strategy document being available for download in English, Japanese and Korean language versions.

### 4.1.1 Hydrogen Sources

An informal colour-coding system of hydrogen has been developed as a shorthand means of describing its means of production and $CO_2$ footprint [148]. While the colour label "green" has been used for many decades for environmentally friendly technologies, in the case of hydrogen it has been taken to specifically refer to hydrogen produced from electrolysis with renewable energy, generally via electrolysis. These hydrogen colours still lack consensus (e.g., sometimes biomass is considered to be green, other times it is considered to be brown; yellow may refer to grid-electricity-based electrolysis, or nuclear-based or solar-based hydrogen production, or catalytic water-splitting), and can be considered mostly a marketing gimmick.

Scientifically, hydrogen can be produced by various routes – each of which has different implications for the carbon footprint of the produced hydrogen and for other environmental and economic factors. The general potential supply chains are shown in Figure 4-1.

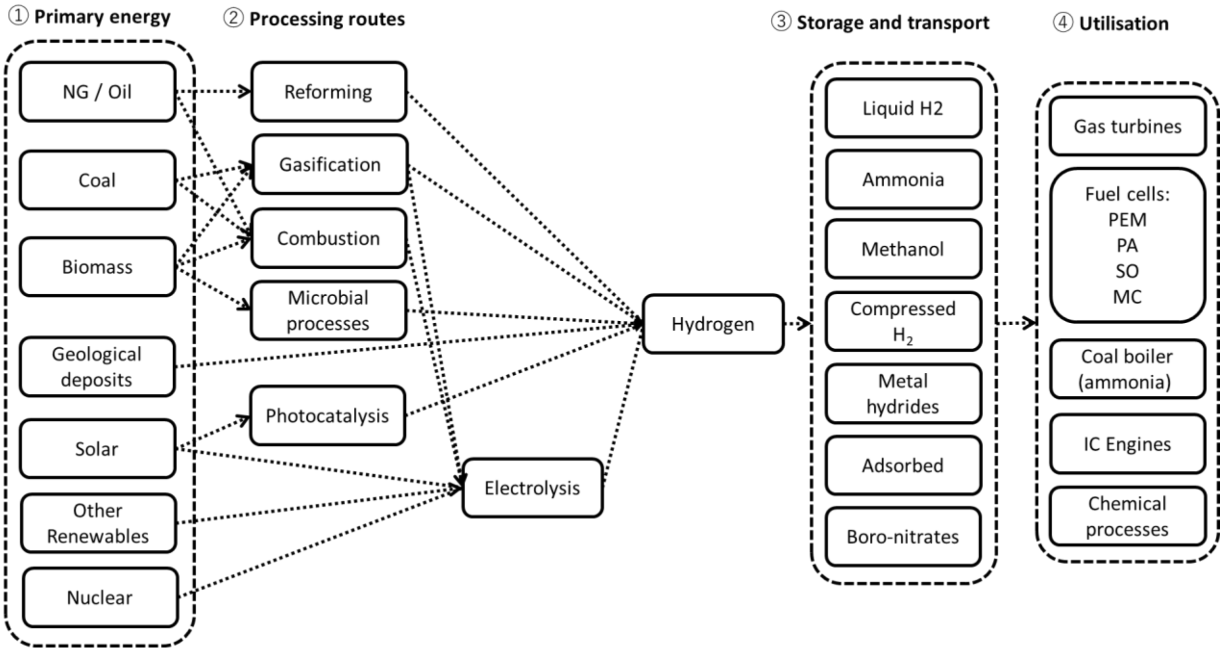



*Figure 4-1 - Hydrogen Production, Supply Chains and End Uses*

It should be noted that hydrogen cannot typically be considered a primary energy source – unless it is extracted from geological deposits. It is more accurately defined as an energy carrier – although it is sometimes considered a form of energy storage and also requires storing itself, often in compounds such as ammonia or as metal hydrides. Through using renewable energy to electrolyse water and produce hydrogen, "green" hydrogen is a medium to make it possible for energy import dependent countries to essentially import renewable electricity from sources worldwide.

Australia currently hosts the Hydrogen Energy Supply Chain (HESC) demonstration project in Victoria's Latrobe Valley [149], developed and operated with a number of major Japanese energy players, producing hydrogen from brown coal (without CCS). The HESC project currently has capability to produce "brown" hydrogen and has begun making trial shipments of liquefied hydrogen ($LH_2$) to Japan. Future commercial expansion of this project proposes to capture carbon dioxide ($CO_2$) from the hydrogen production process and inject it into offshore geological sequestration sites. This would then make any hydrogen produced "blue". Brown coal for the HESC project is currently sourced from the Loy Yang mine, however the Loy Yang A Power Station is scheduled to cease operation in 2035 [150]. As brown coal fired electricity generation is phased out in Victoria, this resource will be available without any other use. While this project represents an interesting source of potentially zero carbon hydrogen supply, the project itself will have no material interaction with the Australian energy system since it will not compete with power stations for fuel and the hydrogen produced is intended to be solely for export.

Hydrogen from fossil fuels without CCS does not achieve the intended purpose of displacing $CO_2$ emissions from fossil fuels. In the absence of a commercial nuclear power industry for the foreseeable future, “pink” hydrogen production in Australia is not considered. Other production routes are unlikely to be commercially scalable options for the foreseeable future [148].

Since the purpose of this work is to explore interactions of hydrogen exports with the Australian energy system, a focus solely on “green” hydrogen produced from renewable electricity is decided.

### 4.1.2 Electrolyser Technology

The two main commercially available and technically mature electrolysis technologies applicable to the production of green hydrogen are alkaline electrolysis (AE) and polymer electrolyte membrane (sometimes also called proton exchange membrane) (PEM). Historically AE has been the more widely deployed [151] and has a lower capital cost. However, PEM has a number of operational benefits, and while it currently has a higher capital cost the PEM share of electrolyser capacity globally has been increasing [151]. Many forecasts for future green hydrogen production [143], [152]–[154] use PEM with future cost reduction due to scale assumed. CSIRO [143] data for current and expected AE and PEM electrolyser efficiencies in Table 4-1 shows that while there is a difference, the uncertainty range for potential improvement for each technology is greater than the difference between them at either the current case or expected best case.

*Table 4-1 - Comparison of Electrical Efficiency of Mature Electrolyser Technologies*

| Technology | Current ($kWh/kgH_2$) | Best Case ($kWh/kgH_2$) |
|---|---|---|
| PEM | 54 | 45 |
| AE | 58 | 49 |

Therefore, since the purpose of this chapter is primarily the electricity consumption of hydrogen production, there is not a material difference between the selection of either AE or PEM technology, hence the PEM base case is applied, which is also used as the reference case in future scenarios by CSIRO and the Australia Energy Market Operator (AEMO). To examine the sensitivity of results to this assumption, electricity consumption if AE was to be deployed would be 7% greater than PEM on the basis of current technology, or 9% in the future “best case”.

### 4.1.3 Hydrogen Carrier

Green hydrogen is a carrier for renewable electricity, however hydrogen in a gaseous state, even when compressed is only really suitable for pipeline or truck transport due to low energy density. For international shipping of hydrogen in large quantities, a carrier method is required to improve energy density and transportability. Rasool et al. [155] and Wang et al. [156] have both conducted detailed cost evaluation of potential hydrogen carriers among mature technologies for international export shipping of Australian green hydrogen; liquefied hydrogen ($LH_2$), compressed hydrogen ($CH_2$), ammonia ($NH_3$), methanol (MeOH) and methane, potentially as green e-LNG (liquefied methane synthesised from hydrogen produced by electrolysis using renewable electricity). CSIRO [143] points to $LH_2$ and $NH_3$ as the most viable, while in AEMO's hydrogen superpower scenario [152], $NH_3$ is selected as the base case hydrogen carrier, being, according to AEMO's assessment, the lowest cost and most widely deployed at the present time.

From the customer side, METI [36] (Japan) also uses $NH_3$ as their base case hydrogen carrier. In this context, it is useful to understand the properties of these two potential methods of hydrogen transport by ship, compared with LNG, which are set out in Table 4-2. Although the calorific value of $LH_2$ is well above that of LNG and $NH_3$, due to a much lower density, the energy density of $LH_2$ is the lowest of all. The greatest technical challenge is in the liquefaction temperature, which for $LH_2$ is considerably lower than LNG, while for $NH_3$ it is much higher.

*Table 4-2 - Properties of LNG, $LH_2$ and NH3 Compared* [157], [158]

| Fuel | Calorific value MJ/kg (LHV) | Density kg/m$^3$ | Energy density MJ/m$^3$ | Temperature (Liquid state) |
|---|---|---|---|---|
| LNG | 45 | 450 | 20,250 | -162°C |
| $LH_2$ | 120 | 71 | 8,520 | -283°C |
| $NH_3$ | 19 | 680 | 12,920 | -33°C |

$LH_2$ production, transport and storage is not new, however this has been primarily domestic production for industrial uses. There is still considerable room for research and development in scaling up $LH_2$ production and improving efficiency of processes for large scale production as an energy transport vector for international shipping. Ship transport of $LH_2$ is a new technology, the first ocean going $LH_2$ carrier "Suiso Frontier" [149] began operation in 2021 as a part of the Japan – Australia HESC project. As can be expected with any demonstration technology scale-up, $LH_2$ shipping trials have not been without technical challenges, including a brief uncontrolled hydrogen flame-out event on board [159].

Conversely, $NH_3$ exports and shipping are already well-established with 65 $NH_3$ tanker vessels transporting 19.8Mt of $NH_3$ exports worldwide in 2021 [160]. For immediate industrial deployment of international trade of hydrogen by ocean freight at large scale, $NH_3$ appears the most feasible carrier at the present time.

Whichever vector is used, the energy density deficit compared to LNG will necessitate an increase in shipping activity if direct energy replacement of LNG is considered. For every one ship of LNG, 2.4 shiploads of $LH_2$ or 1.6 shiploads of $NH_3$ of equivalent volume would be required to deliver the same energy.

A generalised domestic energy balance for a country exporting green hydrogen is presented in Figure 4-2, including transformations to various transport vectors.

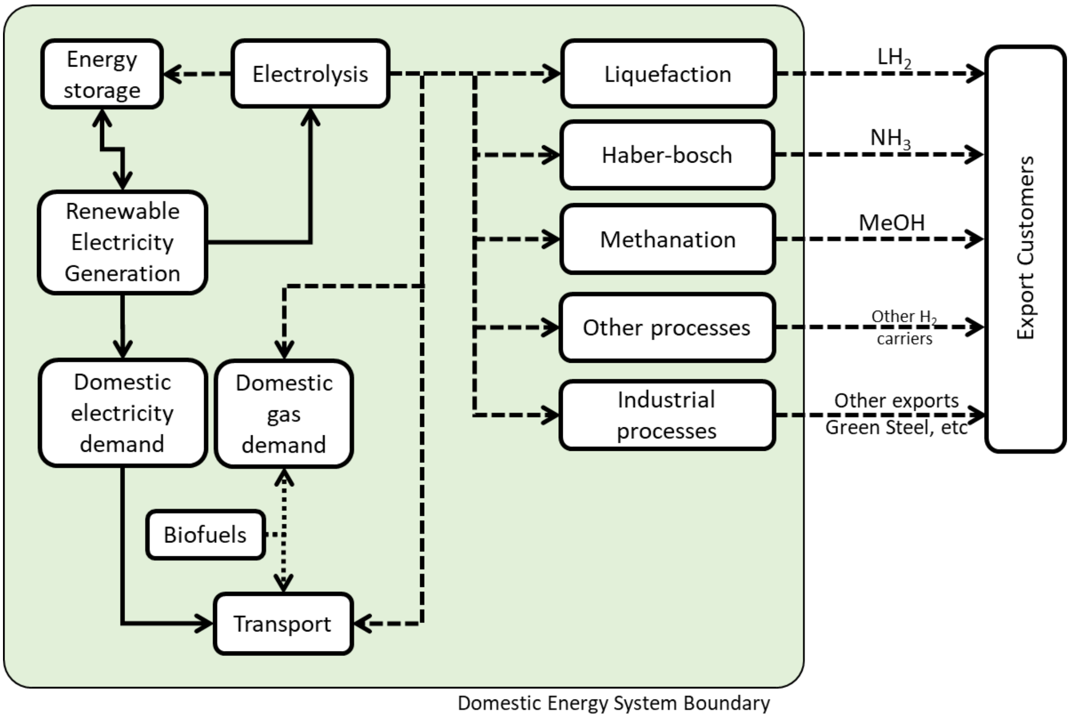



*Figure 4-2 - Domestic Energy System with Hydrogen Exports in the Hydrogen Export 2050 Scenario*

### 4.1.4 Hydrogen Export Literature Review

A number of papers have been published recently taking a country specific approach in examining the prospect of zero-$CO_2$ hydrogen production and exports, including Rasool et al. [155] and Wang et al. [156] who each examine the cost profile of different hydrogen carrier methods for export from Australia, Gallardo et al. [161] with a techno-economic analysis of the case for export from Chile using low cost solar electricity in the Atacama Desert region, Burdack et al. [162] with a similar techno-economic analysis of potential green hydrogen exports from Colombia. Kavavand et al. [163] provide a similar analysis for the case of green hydrogen and $NH_3$ exports from Iran using wind and solar electricity, while Galvan et al. [164] propose a plan for green hydrogen exports from South America, adding up to 20% electricity demand in conjunction with an electricity generation transition to renewable sources. Armijo and Philibert [165] present a case study of green hydrogen and $NH_3$ production in Chile and Argentina, initially supplying local needs then expanding to export operations, Khan & Al-Ghamdi [166] examine the potential benefits and challenges for hydrogen exports from Gulf Cooperation Council member states and Bhandari [167] provides a study of potential for green hydrogen production in Niger. Hjeij et al. [168] develops an index for rating the hydrogen export competitiveness of countries and Downie [169] has developed a high-level framework for geopolitical leverage of states exporting renewable electricity including through media such as green hydrogen. With regards to exporter-side domestic impacts, one of the few studies [170] develops the idea of domestic implications for export-oriented hydrogen producers in terms of water availability and land use in low-income countries including Morocco, Mexico and South Africa. The idea of a domestic hydrogen market operating in synergistic conjunction with hydrogen export operations is discussed in a few papers [165], [168] while the idea of a domestic hydrogen market acting as an incubator for an export industry takes a major place in the main Australian hydrogen strategy narrative as set out in AEMO [152], CSIRO [154], COAG [144] and ARENA [147] reports. However, the potential for hydrogen exports to dominate and adversely impact the exporters' domestic hydrogen market is absent. Further references to energy security, impacts on domestic energy markets generally and distortion of local electricity pricing in these papers examining the hydrogen export case is lacking. Any mentions of energy security refer only to importing countries [162], [169], [171].

The current academic and policy body of knowledge on hydrogen exports thus reflects the typical focus in which energy security is primarily a concern for energy import dependent countries[31]. This confirms the gap in existing work on the topic of hydrogen exports and importance of this work to develop a framework for domestic energy security specific to the emergence of large-scale green hydrogen exports to contribute to filling this gap.

### 4.1.5 Methodology and Structure

Having established the research need, the methodology study and structure of this paper are set out as follows. In this chapter the CSIRO "Hydrogen Export" scenario [154] is taken as a plausible case for a fully developed green hydrogen export industry and use it as the reference against which to develop this framework. Section 4.2 expands on what the hydrogen export scenario means domestically for Australia's energy system, and also validate that scenario against major trading partners hydrogen strategies. In section 4.3, comparative resource cases for factors applicable to green hydrogen export, including a review of literature on the “resource curse” or “paradox of plenty” phenomenon is examined and tested if those conditions might apply to hydrogen exports. In addition, I have reviewed other research done on the known domestic energy system impacts from exporting industries with strong links to the domestic energy system; LNG and aluminium, and filter these existing frameworks for potentially comparable factors and effects, considering the extent to which these energy intensive export-focussed sectors are embedded in Australia’s domestic energy system.

In section 4.4 some of the energy-exporter focussed tools presented in chapters 2 and 3 are used to evaluate exporter economic vulnerability and domestic energy security before (2019) and after (2050) the realisation of the hydrogen export scenario. In section 4.5 present the compiled conceptual framework for domestic energy system impacts of green hydrogen exports developed in this study is presented, and chapter conclusions and policy recommendations are contained in section 4.6.

### 4.1.6 Limitations of This Study

This study is limited to the domestic energy system and related internal economic effects of a country becoming a major hydrogen exporter. This study specifically focusses on “green” hydrogen, produced by electrolysis from renewable electricity and does not address fossil fuel-derived hydrogen as the share of the later in the global market for decarbonised energy is expected to decline, and from a producer perspective the linkages to the domestic energy system are expected to be negligible as hydrogen producers also move away from fossil fuel-based electricity generation domestically. While the extent of renewable energy-generation required to reach the extent of hydrogen production identified in various studies is assessed at a high level, this assessment is provided for context, and analysis of the construction program required and potential challenges to achieving it are excluded from this study.

## 4.2 What would being a Hydrogen Exports Superpower look like for Australia?

### 4.2.1 Electricity Generation Requirements

“Hydrogen superpower” appeared as a forecast scenario in AEMO’s “2021 Inputs Assumptions and Scenarios Report” for Australia’s National Electricity Market (NEM) [152], in which “NEM-connected renewable energy exports via hydrogen become a significant part of Australia’s economy”. The hydrogen superpower scenario has been updated and expanded in AEMO’s latest Integrated System Plan (ISP) issued in June 2022 [172]. CSIRO and Climateworks prepared a detailed modelling report [154] for AEMO as an input to the next ISP update, which covers all of

Australia not just the NEM states (Queensland, New South Wales, Victoria, Tasmania and South Australia). COAG's 2019 report "Australia's National Hydrogen Strategy" [144] sets out a similar, highly ambitious scenario titled "Hydrogen – Energy of the Future", with modelling inputs provided by consulting firm Deloitte [153]. Key data of these various hydrogen exporting scenarios are summarised in Table 4-3.

*Table 4-3 - Australia Green Hydrogen Export Scenarios*

| Scenario and Parameter | 2030 | 2040 | 2050 |
|---|---|---|---|
| COAG (2019) "Hydrogen – Energy of the Future" scenario[144], [153] | | | |
| Green $H_2$ produced (Australia) | 0.5Mt (60PJ) | - | 18Mt (2,160PJ) |
| Electricity for Green $H_2$ production (Australia) | 19TWh | - | 912TWh |
| AEMO (July 2021) "Hydrogen Superpower" scenario[152] (all figures NEM only) | | | |
| Total Green $H_2$ produced (domestic + export) | 1.0Mt (120PJ) | 5.0Mt (600PJ) | 15.0Mt (1,800PJ) |
| Green $H_2$ exported | 0.6Mt (73PJ) | 3.4Mt (408PJ) | 12.3Mt (1,474PJ) |
| Total electricity demand including Green $H_2$ production | - | 614TWh | - |
| Electricity for Green $H_2$ production (% of total electricity demand) | 57TWh | 285TWh (46.4%) | 795TWh |
| Electricity for Green $H_2$ exports (% of total electricity demand) | 41TWh | 221TWh (36.0%) | 774TWh |
| AEMO (June 2022) "Hydrogen Superpower" scenario[172] (all figures NEM only) | | | |
| Total Green $H_2$ produced (domestic + export) | 0.9Mt (107PJ) | - | 17.0Mt (2,038PJ) |
| Green $H_2$ exported | 0.7Mt (84PJ) | - | 11.5Mt (1,376PJ) |
| Total electricity demand including Green $H_2$ production | 294TWh | - | 1,278TWh |
| Electricity for Green $H_2$ production (% of total electricity demand) | 51TWh (17.3%) | - | 900TWh (70.4%) |
| Electricity for Green $H_2$ exports (% of total electricity demand) | 49TWh (16.7%) | - | 768TWh (60.1%) |
| CSIRO & Climateworks for AEMO (Dec 2022) "Hydrogen Export" scenario[154] | | | |
| Total Green $H_2$ produced (domestic + export) | 1.9Mt (233PJ) | 6.3Mt (757PJ) | 20.2Mt (2,426PJ) |
| Green $H_2$ exported | 1.7MT (204PJ) | 5.4Mt (648PJ) | 17.4Mt (2,088PJ) |
| Total electricity demand including Green $H_2$ production | 455TWh | 790TWh | 1,550TWh |
| Electricity for Green $H_2$ production (% of total electricity demand) | 112TWh (24.6%) | 339TWh (42.9%) | 1,008TWh (65.0%) |
| Electricity for Green $H_2$ exports (% of total electricity demand) | 98TWh (21.6%) | 290TWh (36.7%) | 867TWh (55.9%) |

There is a however reasonable convergence in the scale of the 2050 case from each source report. Of these scenarios, the most recent and most comprehensive (covering all Australia, and with 10-year steps) is the “Hydrogen Export” scenario prepared by CSIRO and Climateworks [154] for AEMO, which is adopted in this chapter as the reference case for further analysis in this work.

The “Hydrogen Export” scenario proposes additional renewable electricity generation dedicated to green hydrogen production for exports of 98TWh in 2030, 290TWh in 2040 and 867TWh in 2050, by which time over half (55.9%) of Australia’s electricity production (1,550TWh) is dedicated to producing green hydrogen for export. Considering Australia’s electricity generation in 2019 was 264TWh (including distributed and behind the meter generation such as rooftop solar) [137], this clearly constitutes a significant industrial undertaking, when combined with the replacement of fossil fuel generation (212TWh in 2019, 80.3% of total), excluding domestic electricity consumption increase from increased electrification in industry and society, and underlying economic growth.

Figures for hydrogen production for export are variously stated in megatons (Mt) and petajoules (PJ). Production of gaseous hydrogen is also at times measured in $Nm^3$. Comparisons with LNG production require conversion to common LNG trade units of billions of cubic metres (BCM) or MBtu (millions of British Thermal Units. To assist in ease of conversion between hydrogen units and comparison with LNG, this research has also created a simple unit conversion tool, included in Appendix B – Green Hydrogen Unit Conversion Tool. This tool also shows required electricity consumption and equivalent production of green ammonia based on hydrogen quantity input.

Table 4-4 and Figure 4-3 set out an indicative example based on this “Hydrogen Export” scenario of the extent of new renewable electricity generation required solely for hydrogen production. This example assumes the mix of renewables as 40% onshore wind, 40% solar and 20% offshore wind. Energy storage in the form of batteries and pumped hydro would also need to be deployed however these are not shown since even though they function as generators on the discharge cycle, they are not net electricity generators and do not add energy to the system, only storing it for later release. The capacity factors for each technology are taken from Aurecon’s 2020 report for AEMO [173].

*Table 4-4 - New Generation Required Solely for Hydrogen Production for Export*

| Parameter | Unit | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Hydrogen production | PJ | 204 | 648 | 2,088 |
| Electricity Generation | TWh | 98 | 290 | 867 |
| Onshore Wind | | | | |
| Share of export green $H_2$ generation | % | 40% | 40% | 40% |
| Share of export green $H_2$ generation | TWh | 39 | 116 | 347 |
| Capacity factor | % | 43.0% | 46.0% | 46.0% |
| Installed capacity required | GW | 10.4 | 28.8 | 86.1 |
| Offshore Wind | | | | |
| Share of export green $H_2$ generation | % | 20% | 20% | 20% |
| Share of export green $H_2$ generation | TWh | 20 | 58 | 173 |
| Capacity factor | % | 51.0% | 57.0% | 57.0% |
| Installed capacity required | GW | 4.4 | 11.6 | 34.7 |
| Solar | | | | |
| Share of export green $H_2$ generation | % | 40% | 40% | 40% |
| Share of export green $H_2$ generation | TWh | 39 | 116 | 347 |
| Capacity factor | % | 30.5% | 31.0% | 31.0% |
| Installed capacity required | GW | 14.7 | 42.8 | 127.7 |

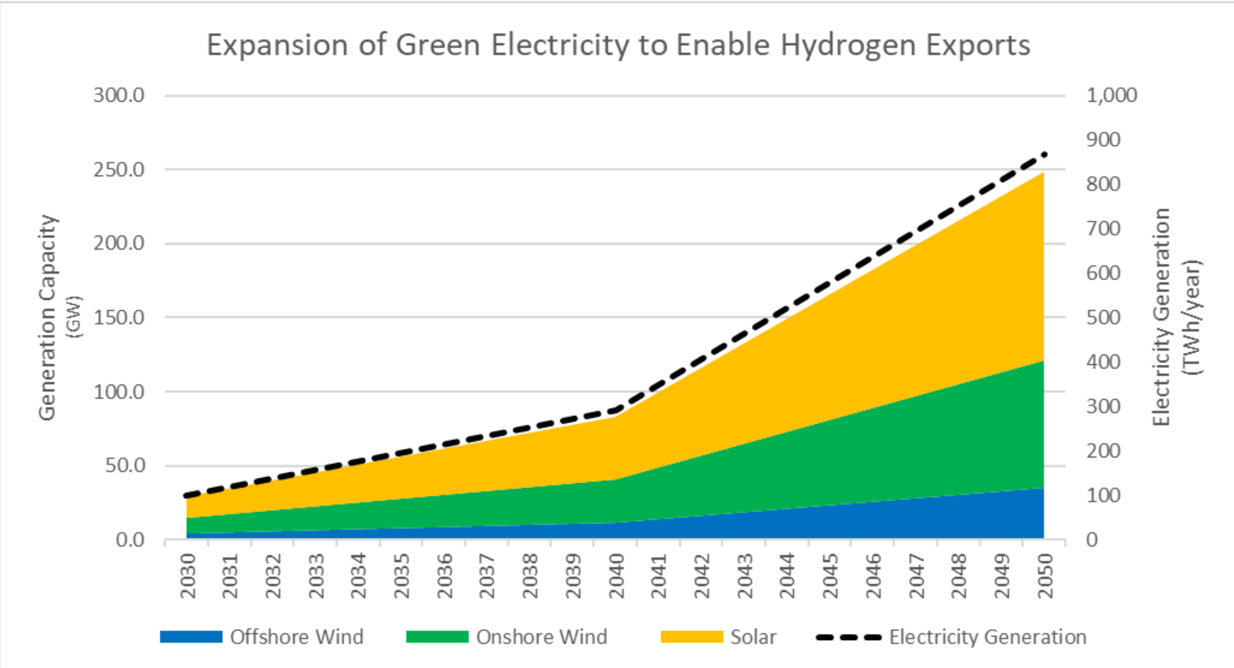



*Figure 4-3 - Expansion of Green Electricity Required Solely for Hydrogen Production for Export*

The following construction program will be required to achieve these new generation capacity figures, solely dedicated to green hydrogen production:

2020-2030

- 2 to 3 new wind farms per year of 200MW per site.
- The first two 2GW offshore wind farms begin operation by 2030.
- 3 to 4 new solar farms per year of 400MWp per site.

2030-2040

- 9 new wind farms per year of 200MW each year.
- A new 2GW offshore wind farm every 3 years.
- 7 new solar farms per year of 400MWp per site.

2040-2050

- 29 new wind farms per year of 200MW each year.
- A new 2GW offshore wind farm every 14 months.
- 14 new solar farms every 18 months of 400MWp per site.

### 4.2.2 Hydrogen Export Quantity Validation with Major Trading Partners

The Hydrogen Export reference scenario anticipates 2,088PJ (17.4Mt) of hydrogen exports by 2050. The reasonableness of this figure (or not) can be validated by considering the announced hydrogen strategies of Japan and South Korea, two of Australia's major LNG customers. According to the Ministry of Trade, Economy and Industry, Japan plans to import 3Mt of zero-carbon hydrogen by 2030, increasing to 20Mt by 2050 [36]. South Korea plans to reach 1.96Mt of green hydrogen imports by 2030 [174], assuming the same growth rate as Japan, they would reach 13.1Mt by 2050.

The potential share of Japan's and South Korea's hydrogen import market that Australia can reasonably achieve is estimated based on Australia's current share of their LNG imports, since green hydrogen (in whichever carrier form) will increasingly be used to replace LNG imports [36] as a primary energy source in power generation and for industrial use. Australia's share of LNG supply [175] to Japan and South Korea is shown in Table 4-5.

Japan and South Korea were Australia's number 2 and number 3 LNG export customers in 2021, taking 34.1% and 12.3% of total LNG exports respectively. China was Australia's number 1 LNG export customer, taking 39.4% of Australia's total LNG exports, however here this work concentrates on Japan and Korea due to their clearly articulated and ambitious hydrogen strategies which are also largely reliant on imports.

*Table 4-5 - Australia's LNG trade to Japan and South Korea (2021)* [175]

| 2021 LNG trade | Japan | South Korea |
|---|---|---|
| Total LNG imports from all sources (Mt) | 74.35 | 46.92 |
| LNG imports from Australia (Mt) | 26.77 | 9.69 |
| Share of LNG from Australia | 36% | 21% |
| Share of Australia's LNG exports | 34.1% | 12.3% |

If the Japan and South Korea were to maintain the same share of supply from Australia for hydrogen as is currently the case for LNG, then Australia's exports of green hydrogen (in whatever carrier form) would be 7.2Mt to Japan and 2.7Mt respectively, and a total of 9.9Mt by 2050. If a similar proportionality is assumed again to 2021 LNG trade of which 53.6% is to other energy import dependent countries (China, Singapore, etc), then a total of 21.3Mt of hydrogen exports is estimated. In this context, the scale of CSIRO's Hydrogen Export scenario seems reasonably aligned with potential importer demand.

#### 4.2.3 Hydrogen Export Price Validation with Major Trading Partners

The Japanese government's expectations for hydrogen price reduction are set out by METI [36]; 30 JPY /$Nm^3$ by 2030 and not more than 20 JPY/$Nm^3$ by 2050 (approx. 20 USD/GJ and 13 USD/GJ respectively, using the JPY/USD exchange rate of 140.12 as at 24/5/2023). For context, Japanese average LNG price (delivered to the destination port) in January 2023 was approximately 17 USD/GJ[176], in September 2019 (before the major disruptions to global energy markets of the Russia – Ukraine war and the COVID-19 pandemic), it was approximately 11 USD/GJ[177].
From the supply side, in Advisian's report for the Australian Government's Clean Energy Finance Corporation (CEFC), the cost of hydrogen CIF Japan in 2050 is forecast to fall to approximately 25 USD/GJ[178]. The gap of 2050 price delivered to Japan between the Japanese government and Australian sources is considerable and further work will be necessary to achieve a convergence by reducing capital costs, technical efficiencies and operating costs of renewable electricity generation, hydrogen production, conversion processes to carriers, and end use technologies, to enable the required development of this sector.

#### 4.2.4 Operating Mode Considerations

When considering the operation of electrolysers, COAG [144] suggests the coupling of hydrogen production for export with electrical grid operations control in a kind of demand-management role for balancing excess renewables and frequency control. While this is possible from a technical perspective, Advisian [178] points out that export-oriented hydrogen production projects will seek to maximise their capacity factor to reduce production cost per unit hydrogen for capital investment in plant and suggested a hydrogen electrolyser capacity factor figure of at least 75%. CSIRO [143] enumerates 2018-based LCOH in Australian dollars per kilogram of hydrogen for various capacity factor cases, shown in Table 4-6, converted to USD. Although the magnitude of these figures does not include cost reduction from scale-up and technological development in the decades ahead, the relative difference based on capacity factor is not expected to change substantially.

*Table 4-6 - LCOH (2018) at the Electrolyser for Various Capacity Factor Cases* [143]

| Case | Capacity Factor | LCOH (USD/kg) |
|---|---|---|
| Grid connected renewables | 85% | 4 |
| Dedicated renewables | 35% | 7 |
| Excess renewable generation | 10% | 17 |

The case for “dedicated renewables” assumes using co-located wind and solar, while the “excess renewables” case assumes hydrogen generation optimised to only use otherwise curtailed excess grid-connected renewable electricity generation (mainly solar day-time peaks).

The conclusion drawn here is that any export-oriented hydrogen production plants will most likely operate at maximum capacity factor to ensure the most efficient use of invested capital and will not have an economic interest to provide grid balancing of variations in renewable generation, unless otherwise incentivised through specific policies. Optimisation for much lower capacity operation of hydrogen electrolysers for grid balancing is an entirely different function and hence a different business case for investment altogether and would only be viable if revenue received from that role compensates for lost revenue from higher capacity factor operation for maximum hydrogen production.

## 4.3 Comparative Resources

As established in section 4.1.4, there is a gap in existing literature on hydrogen exports regarding the domestic implications on the exporting country. In this section a brief comparative examination is made of the resource curse hypothesis, LNG exports, and aluminium exports to establish some aspects of a conceptual framework for the domestic economic and energy system impacts of a future large-scale green hydrogen export industry.

### 4.3.1 Resource Curse Framework: Applicability to Hydrogen Exports?

There is a considerable body of literature examining the potential for extraction and export of natural resources to yield negative economic results. This section references the common features of the “resource curse” framework and examine each one to determine whether exports of hydrogen could be considered to be worse, better, or the same. The aim is to establish a comparative framework for resource curse risk compared to fossil fuels and mineral resources to which the framework has historically been applied. This work does not attempt to provide a full literature review of the resource curse hypothesis, which would be extensive, but rather two representative papers have been selected as the reference point for comparison. Badeeb et al. [179] conducted a wide-ranging critical literature review of the resource curse hypothesis and compiled the various causal factors, while Leonard et al. [180] develop a framework for the application of the resource curse hypothesis to renewable energy.

Hydrogen may be treated as a natural resource being ultimately derived from solar, wind and hydro energy, however it also has characteristics of a manufacturing industry with high levels of capital investment in each stage of production, and as the resource is essentially inexhaustible there is potentially no “post-resource” phase. In practical terms, there are of course limitations. For example, the required critical materials needed for green hydrogen supply chain technologies including renewable electricity generation, energy storage and electrolysis(e.g., lithium, graphite, platinum, rare-earth metals)[181] or the limits to land and other inputs. The investment cycle and the potential for insufficient long-term investment could also be considered as a potential resource-ending cause.

The causal factors from each have been extracted into Table 37 below, and applied an assessment of how each factor would apply to hydrogen exports and a simple rating system as follows:

- 0 the factor is not applicable to hydrogen exports
- 1 the factor is applicable to hydrogen exports, but the impact is mitigated compared to the classic resource curse
- 2 the factor is applicable to hydrogen exports the same as with the classic resource curse
- 3 the factor is applicable to hydrogen exports with a more severe impact than for the classic resource curse

*Table 4-7 - Resource Curse Causal Factors and Expected Relevance to Green Hydrogen Exports*

| Causes | Reference | Relevance to hydrogen | Rating |
|---|---|---|---|
| 1. Extracted not produced (high capital investment and low labour input) | Badeeb [179]<br>Leonard [180] | A. Although renewable, the energy source for green hydrogen depends on high capital investment in wind and solar and electrolysis, with relatively little labour required, similar to LNG production.<br>B. Foreign investment and foreign debt may be required, offshoring of profits and control.<br>C. Limited opportunities for local employment in manufacturing of specialised equipment. | 2<br>2<br>2 |
| 2. Price volatility | Badeeb [179]<br>Leonard [180] | A. Green hydrogen is an energy commodity comparable to fossil fuels in market price mechanisms. | 2 |
| 3. Limited resource | Badeeb [179] | A. Unlimited resource of renewable electricity.<br>B. Limitations to availability of critical minerals required for renewable electricity and electrolysers [182], [183]<br>C. Potential water scarcity can be addressed by treatment of wastewater or desalination of seawater which require additional capital equipment but adds negligible energy requirements (0.14% and 0.05% respectively) [184] | 0<br>1<br>1 |
| 4. "Dutch disease" currency exchange rate and labour pull effects | Badeeb [179]<br>Leonard [180] | A. Increase in export revenues affecting exchange rate and causing domestic manufacturing to become less export-competitive and thus shrink the sector. This may be mitigated by potentially indefinite production (no crash at the end of resource deposit life)and permanent realignment of the economy (see issues in 4.D, 9.A, 13.A).<br>B. Diversion of talent from other sectors (labour pull) into renewable / hydrogen construction projects away from other sectors due to higher salaries, similar to effects seen on fossil fuel projects | 1<br>2 |
| 5. Economic mismanagement | Badeeb [179] | A. Hydrogen exporting countries are potentially just as susceptible to economic mismanagement in the same manner as the classic resource curse hypothesis suggests. | 2 |
| 6. Rent seeking | Badeeb [179] | A. Equitable distribution of green hydrogen export windfall revenues within a country or concentration of benefits by elites does not appear to change for hydrogen compared to fossil fuels or minerals. | 2 |
| 7. Corruption and institutional quality | Badeeb [179] | A. Hydrogen exporting countries are potentially just as susceptible to corruption and issues of institutional quality in the same manner as the classic resource curse hypothesis suggests. | 2 |
| 8. Damage to the natural environment | Leonard [180] | A. Renewable energy installations (particularly solar) will require significant land coverage, for as long as hydrogen production continues, affecting local ecology. Since wind and solar resources are less concentrated than deposits of fossil fuels, a larger land area is affected in producing electricity for green hydrogen than for fossil fuels.<br>B. Since hydrogen production is not limited by finite resource life, operations may continue perpetually and there is potentially no future planned date for site rehabilitation and restoration.<br>C. Renewable electricity generation and hydrogen production would have less (negligible) potential for contamination of ground water (CSG issue) [131], water table dropping (coal mining issue)[185] | 3<br>3<br>0 |

| Causes | Reference | Relevance to hydrogen | Rating |
|---|---|---|---|
| 9. Diversion of investments away from human capital | Leonard [180] | A. Skilled and higher paid renewable energy construction jobs would attract workers from other sectors, unchanged compared to fossil fuels or mineral extraction. | 2 |
| 10. Diversion of land | Leonard [180] | A. As per 8.A, more land will be diverted per PJ exported for green hydrogen compared to fossil fuels | 3 |
| 11. Economic dependence | Leonard [180] | A. If any one sector of the economy (oil/gas/minerals extraction or green hydrogen) grew proportionally too large, there is the potential for economic dependence and vulnerability. As with fossil fuels, this effect is highly dependent on the size and diversity of the rest of the economy, which may be reduced by "Dutch Disease" effects. | 2 |
| 12. Technology / expertise dependence | Leonard [180] | A. As a nascent industry there are a relatively small number of gatekeepers of key renewable energy and hydrogen production technologies upon which producing countries will be dependent. By comparison, mineral / fossil fuel extraction technology and expertise are well established worldwide. | 3 |
| 13. Income inequality | Leonard [180] | A. Skilled and higher paid renewable energy construction jobs would attract workers from other sectors, while other sectors suffer the effects of "Dutch Disease", similar to fossil fuel extraction activity. | 2 |

As can be seen summarised in Table 37, most of the established causal factors in the resource curse hypothesis are applicable to green hydrogen production and exports. Those related to land use and technology dependence are rated higher than traditional extractive export industries, while those related to limitations to ongoing production are rated lower. Factors of governance and equitable distribution of benefits, economic management, and institutional quality are likely to be largely unchanged for green hydrogen compared to non-renewable resource extractive activities, however such factors are also strongly related to pre-existing conditions in the exporting country.

The ratings in Table 4-7 indicate a tendency for resource curse effects of a similar extent to mineral or fossil fuel extraction export activities. The factors listed are intended to be a representative list to provide an indication of the relevance of the resource curse hypothesis to export-scale green hydrogen production, which would benefit from further detailed analysis.

### 4.3.2 LNG Exports Framework: Lessons for Hydrogen?

The similarities of LNG and hydrogen exports (whether as $NH_3$ or $LH_2$) are clear from an energy user perspective; hydrogen can be directly blended with natural gas in existing natural gas networks [186], [187], and increasingly LNG-fired gas turbines are capable of partial or full conversion to hydrogen firing [188], [189]. These similarities on the user side lead us to consider similarities on the production side and in particular how the reference case for Australia's transition from a gas producer for solely domestic consumption to a major global LNG exporter might provide insights for potential domestic energy system impacts from the transition to a major hydrogen exporting superpower.

#### 4.3.2.1 Competition between domestic use and export for gas, and possibly hydrogen?

Simshauser and Nelson [190] discussed potential impacts on the domestic gas supply system shortly before the commencement of LNG export operations from Queensland the following year (2016), and their analysis has proven remarkably accurate, forecasting unserved load immediately on commencement of LNG exports (domestic demand exceeds supply). Notwithstanding the pre-existing balance in supply and demand and extensive export-oriented development of coal seam gas (CSG) production wells, the introduction of an export pathway immediately enabled diversion of domestic gas supply to higher paying LNG export customers, exacerbated by insufficient new CSG supply for the step change in demand from LNG export facilities [191]. Even domestic industrial gas customers willing to pay international net-back LNG prices struggled to obtain long terms contracts for gas supply due to the dominance of LNG export demand.

Turning our attention to the emerging domestic and export-oriented green hydrogen market the CSIRO's HyResource reference website [192] provides a comprehensive list of hydrogen projects under development in Australia. This list has been filtered for proposed commercial scale projects (excluding those for research and demonstration) for the production of green hydrogen, and Appendix 1 shows those projects proposing either production for domestic use, export, or both. Of the 56 green hydrogen projects listed, 25 (45%) are designated for solely domestic supply of green hydrogen in its various carrier forms, 13 (23%) are explicitly for export only, while 18 projects (32%) have intentions to export and provide local supply. The domestic only projects tend to be much smaller scale than the export-oriented projects.

The potential parallels with the commencement of LNG exports in Queensland are clear; once export facilities are in place, local hydrogen users will be in direct competition with international customers for supply, and pricing will be linked to international markets. There would be potential for "unserved load", or local investments in hydrogen utilisation becoming stranded assets without access to a supply of hydrogen that their original business case was based on before local hydrogen supply pricing became linked to export markets.

On this basis it is clear that approximately one-third of the green hydrogen projects under development in Australia will potentially have locally developed hydrogen using infrastructure that will sooner or later become export-exposed in a similar manner to the LNG export start-up. This represents a material risk to the business case of any such domestic project unless instruments such as fixed price long term supply contracts, or regulated domestic supply reservations are implemented. While it may appear preferable from a social licence perspective, the inclusion of domestic offtakes in a project that will become predominantly export-oriented is a clear energy security risk, unless regulatory instruments are applied to protect domestic users.

#### 4.3.2.2 Competition between domestic use and export-oriented electrolysers for electricity?

In addition to the direct effects from Queensland LNG export start-up on eastern Australia's domestic gas system, chapter 3 of this work also established the secondary effects experienced in the electricity system considering pre-LNG CSG ramp gas as a generation fuel. In the case of future green hydrogen production for export, the linkage to the NEM is much more direct, for two reasons:

First, unlike LNG exports that are concentrated in central Queensland with influence in the electricity system flowing on indirectly to other states, under the hydrogen export scenario green hydrogen exporting plants are potentially located in each NEM state, directly impacting each of the interconnected state grids.

Second, according to the CSIRO hydrogen export 2050 scenario 882TWh will be used for green hydrogen production for export out of a total electrical consumption of 1,570TWh, hence 56% of all NEM electricity will be taken for production of internationally traded green hydrogen. By comparison in 2019 only 10.8% of NEM state electricity is sourced from gas in LNG export exposed networks.

Consequently, the potential for international green hydrogen pricing to set the highest price for NEM electricity offtake is considerably more pronounced than it already is with LNG exports.

#### 4.3.3 Aluminium Exports Framework: Lessons for Hydrogen?

This section examines the aluminium production and export industry for potential similarities to contribute to our conceptual framework for green hydrogen export impacts on the domestic energy system. As an internationally traded commodity with significant production input of electricity, aluminium is a comparable resource to export-scale green hydrogen.

##### 4.3.3.1 Significance of electricity in aluminium smelting

The two key inputs into the smelting of aluminium are alumina and electricity, accounting for 29% and 21% of input costs respectively [193]and for this reason aluminium is sometimes referred to as “congealed electricity” [194] or “solid electricity” [195] because of the concentration of electrical energy required for smelting. Aluminium production from mined ore (bauxite) to raw ingots is substantially more energy intensive (212GJ/t) than for the manufacturing of steel from iron ore (23GJ/t) [196], although it is the final stage of smelting, which contributes 25% of that energy input as electricity (approximately 15MWh/t).

Historically, the 1970s oil shocks led to considerable relocation of aluminium smelting to countries with domestic low-cost electricity generation. For example, Japan’s domestic aluminium smelting industry peaked at 1.12Million tonnes in 1974 (world #2) [197], until being impacted heavily by the effects of the 1970s oil shocks, since Japan’s electricity generation at the time was 71% reliant [116] on imported oil and oil products for fuel. Japan’s sole remaining aluminium smelter still in operation, Nippon Light Metal Co. Ltd., Kambara Complex [198] only survives because its electricity supply is almost entirely from its privately owned hydro power stations which have protected the plant from electricity price increases due to imported fossil fuels. Just as Japanese aluminium smelter production was declining, the Boyne Smelter in Queensland, the Tomago Smelter in New South Wales and the Portland Smelter in Victoria were being constructed in the late 1970s and early 1980s in eastern Australia, attracted by access to low-cost electricity from local coal reserves [193].

#### 4.3.3.2 Aluminium as a Means of Exporting Low-Cost Electricity

In 2021, Australia produced 1.56Mt of aluminium, of which 1.43Mt (91.7%) was exported, 1.41Mt (98%) of those exports as unprocessed ingots [199]. In the same year Australia imported 0.41Mt of aluminium, 0.33Mt (82%) of which was in semi-fabricated forms such as extrusions, wire, sheet, plate and foil [199].

Due to the high energy intensity of aluminium, approximately 15% of Australia's electricity production is used in aluminium smelting [193]. Based on the abovementioned figure of 15MWh/t for electricity used in aluminium production, this exported portion of production consumed 21.45TWh. For comparison, this would equate to 133PJ of LNG exported to be consumed in modern combined cycle gas turbine power stations of 58% efficiency generating electricity for aluminium smelting. Considering the electricity density of aluminium, aluminium production and export can be seen as a form of exporting low-cost electricity to countries that do not smelt their own aluminium due to higher energy prices.

#### 4.3.3.3 Aluminium producer interactions with the domestic electricity system

**Effects on electricity pricing**

The development of Bayswater Power Station in New South Wales is closely connected with the development of the Tomago smelter, as was the Loy Yang A Power Station in Victoria and the Portland Smelter [200], [201]. In both cases, state governments led with construction of additional coal-fired generation capacity to enable the development of the smelters which a shorter construction time than the power station but whose power they require to operate and agreed to discounted long term electricity supply contracts for smelters to attract investment and industrial development[193]. These and other smelters operating in Australia have subsequently used their market power as a major existing incumbent industrial employer and electricity user to obtain further price reductions significantly below market electricity supply prices, with the threat of ceasing operations and transferring production to other locations with a lower cost of electricity. This pattern is found to occur worldwide [193]. When generators are privately owned, this loss is mitigated by increasing the price of electricity charged to other users. When generators are state-owned, the loss is subsidised from government funds. In either case, multinational aluminium corporations are consistently subsidised by the host community.

**Grid stability**

Aluminium smelters are technically and commercially optimised to run continuously at full output. In situations of extreme demand and insufficient electricity supply, aluminium smelters can be disconnected from the grid to restore system balance and prevent blackouts [202], however the damage to smelting equipment can be severe for even a few hours of lost electricity supply, so an aluminium smelter would not be considered as an interruptible industrial load in terms of grid operations and such an operation would only be performed in extreme circumstances of imminent grid blackout. The operation of aluminium smelters does provide a measure of grid stability due to their continuous stable operation and significant load, although this is only an incidental benefit.

#### 4.3.3.4 Aluminium Smelting and Applicable Factors to a Hydrogen Exporting Framework

Australia's aluminium smelting industry can therefore be seen to have some similarity with green hydrogen in its electrical intensity of production and primary export focus. Table 4-8 lists various specific commercial and technical impacts of aluminium smelting operations on the domestic electricity system and considers their application to green hydrogen production to contribute to the framework for analysing the domestic impacts of a green hydrogen industry.

*Table 4-8 - Aluminium Smelting Domestic Impacts and Applicability to a Future Green Hydrogen Export Industry*

| Aluminium industry domestic impacts | Reference | Green Hydrogen application |
|---|---|---|
| 1. Electricity price<br>Aluminium production located globally based on lowest cost of electricity.<br>Investors threaten relocation offshore to leverage electricity price reductions / subsidies. | Oil shock effects driving Japan's smelter shut down, growth in Australia's industry in 1980s [197], [199]<br>Electricity supply contract renegotiation in Australia [193] | A. Lowest cost of green electricity will be a primary driver for location of projects.<br>B. Potential for hydrogen producers relocate production for lower $/MWh, greater risk than for aluminium as technology development continues to reduce green electricity costs for newer installations. |
| 2. Capacity Factor<br>Smelters are commercially optimised for continuous operation at full output | Smelters operate baseload, and are willing to accept take-or-pay electricity contracts[193] | Highest capacity factor operations provide the best return for invested capital in hydrogen production. Grid electricity is preferred over dedicated renewable generation.[173] |
| 3. Grid Interaction<br>Smelters are technically optimised for continuous full capacity operation | Aluminium production assets are severely affected by electricity supply. [203] interruptions | Electrolysers are much less sensitive to electricity supply disruptions than smelters and can operated as interruptible loads in case of supply demand imbalance on the grid.[143] |

### 4.4 Evaluation of the Hydrogen Superpower scenario

Using the evaluation tools established in chapter 2 for energy exporter vulnerability and chapter 3 for domestic energy security, the present (pre-pandemic 2019) state of Australia's energy system and energy exporting economy is subsequently compared with the hydrogen export scenario set out in section 4.2.

#### 4.4.1 Energy Exporter Economic Vulnerability Metrics

The economic vulnerability of energy exports can be evaluated using the six metrics set out in Section 2.4, as follows:

External vulnerability factor metrics

M1 - Customer Energy Import Dependence

M2 - Customer Energy Mix Diversity

M3 - Export Customer Diversification Weighted by Carbon Emissions Reduction Rating

Internal vulnerability factor metrics

M4 - Energy Exports Significance to GDP

M5 - Resource to Production Ratio

M6 - Carbon Emissions Intensity of Energy Export Blend

Our objective in this section is to compare the current status (pre-pandemic 2019 data reference point) with the future case of a fully implemented hydrogen exporting superpower scenario by 2050 as has been examined in section 4.2. In each case, forecasts for 2050 fossil fuel exports are reduced to zero as oil and gas are considered largely depleted except for some gas for domestic use and coal is no longer tradeable in any meaningful quantity, consistent with the IEA Net Zero by 2050 scenario[204]. Green hydrogen (in its various carrier forms) is by 2050 Australia's primary energy export.

The evaluation of metrics M1-M6 for 2050 is based on an assumed forecast case as follows, based to the extent possible on currently policy settings for the 2050 time horizon.

From 2019 to 2050, a single change in the top 5 export customers is assumed;  Japan, China, India, South Korea and Taiwan in 2019, with Singapore replacing Taiwan at #5. In the case of Japan, South Korea and Taiwan, their aggressive decarbonisation plans [36], [205], [206] are assumed to be achieved and in each case petroleum imports are ceased by 2050, being replaced by almost complete electrification of energy use. In Japan's case, the present 14% renewables and 9%

nuclear contribution to electricity generation increases to 38% renewables and 22% nuclear, ensuring 60% domestic energy supply. In South Korea, the current share of 30% nuclear is maintained and renewables expand to 20% of total energy supply are assumed, allowing 50% energy self-reliance. For Taiwan, the aggressive decarbonisation strategy based on offshore wind and solar is assumed to achieved 70% energy self-reliance, hence their reduction in imports from Australia and removal from the top 5 export customers. The energy self-reliance of India and China increases in line with nuclear and renewable energy development trends, reducing by 50% dependence on imported energy. Singapore, added as #5 in 2050 is assumed to increase its very small local renewable generation by a factor of 10, but still remains 96% dependent on energy imports, 60% of which is assumed as being supplied from Australian renewable electricity (green hydrogen / direct cable).

#### 4.4.1.1 M1 – Customer Energy Import Dependence

The energy import dependence ratio of each export customer is multiplied by the share of energy exports to that customer, and then the total is divided by the exporter's total energy exports. Share of energy imports to the total primary energy supply is a recognised indicator for energy security [28], [30] and import dependent countries will have a tendency to reduce their share of energy imports to improve domestic energy security. As a result, a high level of customer import dependence represents a vulnerability for the exporter, while a lower score indicates the mix of customers is less dependent on energy exports hence less likely to try to reduce their import dependence further, thus a less vulnerable situation for an exporter.

*Equation 4-1 - M1 – Customer Energy Import Dependence*

$$M1 = \frac{Q_A \times ({}^{E}/_{TPES})_A + Q_B \times ({}^{E}/_{TPES})_B + \cdots + Q_n \times ({}^{E}/_{TPES})_n}{Q_{total\ exports}}$$

Where Q = quantity of energy exports to country A, B, n, or the total energy export (in PJ)

E = energy imports by country A, B, n (in PJ)

TPES = total primary energy supply of country A, B, n (in PJ)

Metric calculation results are shown in Table 4-9.

*Table 4-9 - M1 – Customer Energy Import Dependence (Australia) 2019 and 2050*

| | 2019 | 2050 |
|---|---|---|
| M1 | 0.744 | 0.413 |

The significant reduction in M1 seen in Equation 4-1 is driven primarily by the actions of the largest export customer Japan (46% of Australia's energy exports) realising their decarbonisation strategy which includes increasing the share of domestic renewable electricity generation from 14% in 2019 to 38% by 2050 and increasing nuclear power generation from 9% to 22% over the same time period [36]. A similar change is also modelled for South Korea (3rd largest export customer with 13% of Australia's energy exports) based on their policies to hold nuclear generation at 30% and increase domestic renewables from 2% to 20% [174]. As a result, by 2050 both Japan and Korea are considerably less likely to further reduce energy imports hence Australia's export vulnerability is reduced.

#### 4.4.1.2 M2 - Customer Energy Mix Diversity

Diversity of energy sources is a widely recognised indicator for energy security [8], [28], with a greater diversity providing greater energy security. Energy importers can be expected to pursue actions to diversify their energy mix, and reduce imports of existing fuels in their primary energy mix. Hence, a lower customer energy mix diversity represents a higher vulnerability to loss of export revenue. The Herfindahl-Hirschman Index (HHI) index, which is widely used to assess energy mix diversity [28], is applied here to quantify the energy mix diversity of individual export customers. Thus, for the current evaluation, a higher score represents less customer energy mix diversity and higher vulnerability for the exporter.

The exporter's total export portfolio position weighted by export energy share of each customer is thus calculated by the following equation;

*Equation 4-2 - M2 - Customer Energy Mix Diversity*

$$M2 = \frac{(Q \times HHI_{TPES})_A + (Q \times HHI_{TPES})_B + \cdots + (Q \times HHI_{TPES})_n}{Q_{total\ energy\ exports}}$$

Where Q = quantity (in PJ) of energy exports to country 1, 2, …, n, or the total energy export quantity

$HHI_{TPES}$= HHI diversity index for total primary energy supply for country 1, 2, n

$= (x_{coal})^2 + (x_{gas})^2 + (x_{oil})^2 + (x_{nuclear})^2 + (x_{hydro})^2 + (x_{wind})^2 + (x_{solar})^2 + (x_{biomass})^2 + (x_{geothermal})^2$

$X_{fuel\ type\ A}$= consumption of fuel type A / TPES

The calculation result for M2, shown in Equation 4-2 is strongly influenced by Japan's long term decarbonisation strategy for 2050 [36], being Australia's primary energy export customer as noted earlier. Japan's strategy sees reduced fossil fuel use and increased shares of nuclear, geothermal, biomass, solar, onshore wind and offshore wind, with an increase in their energy mix diversity shown by a reduction in $HHI_{TPES}$, from 0.273 to 0.226. South Korea's own energy strategy which includes increase total renewables including onshore and offshore wind, solar and biomass from 2% to 30% increases their energy mix diversity as shown by a reduction I HHITPES from 0.320 to 0.182, although the overall effect on M2 is less since South Korea's overall share of Australia's energy exports is only 13%, compared to Japan's 46% share. An exception is Singapore, with little domestic renewable energy potential, where reducing fossil fuels makes the country more concentrated in externally sourced energy relying on imported green hydrogen and a direct electricity cable connection. The overall weighted diversity index result for M2 is an increase in customer energy mix diversity hence reduced exporter vulnerability. Since green hydrogen is largely seen to replace coal and LNG consumption, the direct effect from green hydrogen exports on the change in M2 from 2019 to 2050 is negligible.

*Table 4-10 - M2 - Customer Energy Mix Diversity (Australia) 2019 and 2050*

| | 2019 | 2050 |
|---|---|---|
| M2 | 0.329 | 0.228 |

#### 4.4.1.3 M3 - Export Customer Diversification Weighted by Carbon Emissions Reduction Rating

Exporter vulnerability is reduced as diversity of energy export customers is increased, with a greater number of smaller customers affording greater protection against loss of exports to any one customer [48], [49]. The same approach is applied on the importer side with respect to diversity of suppliers as a measure of energy security [8], [28] . The HHI index is applied to quantify export customer diversification. In the current international energy supply market (2019 case), the index is adjusted by the use of a factor representing each export customer's actions to reduce $CO_2$ emissions, where stronger commitments cause greater vulnerability to current fossil fuel exports.

*Equation 4-3 - M3 - Export Customer Diversification Weighted by Carbon Emissions Reduction Rating*

$$M3 = [CER \times (X_{FF})^2 + (100 - CER) \times (X_{ZCF})^2]_{country\ 1} + \cdots \\ + [CER \times (X_{FF})^2 + (100 - CER) \times (X_{ZCF})^2]_{country\ n}$$

Where;

CER = the export customer country's $CO_2$ emissions reduction rating index (0-100), adopted from the Climate Change Performance Index [93]

$x_{FF}$ = fossil fuels exported to country 1, 2, n, as a fraction of total energy (PJ) exports.

$x_{ZCF}$ = zero carbon fuels exported to country 1, 2, n, as a fraction of total energy (PJ) exports.

For this metric, greater diversity of customers yields a lower score, which is desirable for the exporter to reduce vulnerability that would be associated with having only one or two large customers. The Climate Change Performance Index (CCPI) [93]) used as input to the CER, rates poor performance with a low score. For the exporter, countries with a high CER score represent heightened vulnerability to future fossil fuel exports. For zero-carbon fuels, the CER weighting factor is applied in reverse (100-CER), since commitment to $CO_2$ emissions of export customers for zero carbon fuels will reduce vulnerability to export concentration to those customers. Using this approach that differentiates between fossil fuels and zero carbon fuels, we are able to dynamically assess vulnerability with this metric as a country's energy export mix transitions away from fossil fuels, along with changing importer $CO_2$ emissions reduction commitments.

In 2050, we assume Australia has largely ceased exporting fossil fuels, with those exports replaced by green hydrogen, and fossil fuels are only exported to countries with limited if any emissions reduction policies. Accordingly, fossil fuel exports to Japan, South Korea and Singapore (Australia's 1st, 3rd and 5th largest energy exports customers respectively) are completely replaced by green hydrogen which has the effect of flipping the weighting factor of each country to 100-CER. This is the primary driver for the reduction in M3 shown in Equation 4-3.

*Table 4-11 - M3 - Export Customer Diversification (Australia) 2019 and 2050*

| | 2019 | 2050 |
|---|---|---|
| M3 | 10.171 | 5.595 |

The result is a significantly reduced vulnerability to Australia as it transitions to green hydrogen exports in line with customer policy settings and import demand.

#### 4.4.1.4 M4 - Energy exports significance to GDP

The basic indicator of a country's vulnerability to the dominance of any one economic activity is captured in this metric, which is widely applied in general economic vulnerability of developing countries [54], as well as in the case of oil exporters [48] and similarly the cost of energy imports as a fraction of GDP which is a widely applied energy security metric [28]. While an increase in revenue from energy exports is generally desirable, it also has the effect of increasing a country's economic vulnerability if the share of energy export revenue to GDP is increased.

*Equation 4-4 - M4 - Energy exports significance to GDP*

$$M4 = \frac{R_{fuel\ A} + R_{fuel\ B} + \cdots + R_{fuel\ n}}{GDP}$$

where; R = revenue

GDP = gross domestic product

The composition and results for M4 are shown in Table 4-12, all units are in billions of USD, converted from Australia dollars at AUD1.00 = USD0.65 (the prevailing exchange rate at the time of writing). Although the value of energy exports will increase by 20.6% from 2019 to 2050 with green hydrogen revenue entirely replacing fossil fuel exports, M4 will decline from 2019 to 2050 under the hydrogen export superpower scenario. This is in part due to the cessation of coal, oil and LNG exports; however it is more strongly influenced by the growth of Australia's domestic services economy.

*Table 4-12 – M4 - Energy Export Significance to GDP Metric Including the 2050 Hydrogen Exports Scenario*

| Year | 2019 (USD Billion) | 2050 (USD Billion) |
|---|---|---|
| GDP[207] | 1490 | 5300 |
| Coal export revenue[208] | 14.7 | 0.0 |
| LNG export revenue[209] | 30.9 | 0.0 |
| Oil export revenue[209] | 8.3 | 0.0 |
| Hydrogen export revenue[153] | 0.0 | 65.0 |
| Total energy export revenue | 53.9 | 65.0 |
| M4 | 0.036 | 0.012 |

#### 4.4.1.5 M5 - Resource to Production Ratio

[208] An energy exporter’s vulnerability to achieve sustainable income from resource exports is heavily dependent on the remaining life of resource deposits. This is a particular concern for countries producing and exporting fossil fuels. However, some countries deposits of some resources (black coal in Australia for example) are so vast that the actual related vulnerability is negligible, hence the resource to production ratio input figure is capped at 100 years to return a vulnerability score of zero.

*Equation 4-5 – M5 - Resource to Production Ratio (Metric Calculation)*

$$M5 = \frac{100 - RPR_{aggregated}}{100}$$

Where;

RPR = the resource to production ratio for each energy resource type (years), with an upper limit to RPR of 100. i.e., for RPR≥100; M5 = 0.

*Equation 4-6 - Aggregated Raw Resource to Production Ratio*

$$RPR_{aggregated} = \frac{S_{coal} \times (Q_{coal}/P_{coal}) + S_{gas} \times (Q_{gas}/P_{gas}) + S_{oil} \times (Q_{oil}/P_{oil}) + S_{greenH2} \times 100}{X}$$

Where;

$RPR_{aggregated}$ = Resource to production ratio (aggregated)

Q = total demonstrated resource of each energy resource type, in petajoules

P = annual production rate of energy resource type, in petajoules per year

S = export quantity from each energy type, in petajoules per year

X = total export quantity from all energy types, in petajoules per year

The aggregate RPR is the RPR of each resource weighted by its share of total energy exports (in PJ). By using total demonstrated (including sub-economic) resources estimates instead of economically recoverable reserves, the results return a strategic insight and are insulated from short term price volatility and technology changes. Since the production of green hydrogen is sustainable indefinitely and not dependent on the exploitation of a finite resource, the ratio of Q/P is not relevant and instead the maximum allowable figure of 100 is applied. As Australia's export energy transition progresses and share of fossil fuels diminishes while the share of green hydrogen increases, $RPR_{aggregated}$ tends toward 100 and the score for M5 (representing exporter vulnerability) tends toward zero.

Inputs and results for B are shown in Table 4-13. In 2019, the weighted calculation of M5 returns a figure of 0.0 due to the overwhelming presence of coal exports (72% of all energy exports by energy value), along with 95% of all resources. Since hydrogen is derived from renewable electricity the resource is unlimited, hence M5 again scores 0.0. Data for gas and oil resource estimates is sourced from the Australian Petroleum Production and Exploration Association (APPEA), coal resource estimates are sourced from Geoscience Australia (GA) [208]

*Table 4-13 – M5 – Resource to Production Ratio Metric Including the 2050 Hydrogen Exports Scenario*

| Year | 2019 | 2050 | Reference |
|---|---|---|---|
| Resource | | | |
| Gas | 86,399 | 0 | APPEA [209] |
| Oil | 13,749 | 0 | APPEA [209] |
| Coal | 1,959,417 | 1,798,446 | GA [208] |
| Hydrogen | 0 | very high | CSIRO [154] |
| Production | | | |
| Gas | 4,938 | 0 | APPEA [209] |
| Oil | 719 | 0 | APPEA [209] |
| Coal | 12,596 | 0 | GA [208] |
| Hydrogen | 0 | 2,088 | CSIRO [154] |
| M5 | 0.0 | 0.0 | |

The results show that a transition from exporting fossil fuels from limited life deposits to exporting green hydrogen provides significant benefits for the export in reducing their vulnerability to the loss of export revenue due to resource depletion, although the effect for Australia is obscured by in coal resources in excess of 100 years of production.

#### 4.4.1.6 M6 – Carbon Intensity of Energy Export Blend

As Energy import dependent countries worldwide pursue their own decarbonisation, exporter dependence on fossil fuel exports is an important vulnerability. Fuels with higher $CO_2$ emissions intensity are at greater risk of demand reduction and loss of markets sooner. The weighted $CO_2$ emissions intensity of the exporter's energy exports blend is therefore a measure of vulnerability to loss of export revenue. Increasing shares of zero carbon fuels such as green hydrogen reduce an exporter's exposure to loss of revenue from customer side energy transition away from fossil fuels.

*Equation 4-7 - M6 – Carbon Intensity of Energy Export Blend*

$$M6 = \frac{(S_{coal} \times f_{coal}) + (S_{gas} \times f_{gas}) + (S_{oil} \times f_{oil}) + (S_{zero\ carbon\ fuels} \times f_{zero\ carbon\ fuels})}{X}$$

where S = export quantity from each energy type, in PJ

X = total export quantity from all energy types, in PJ

f = $CO_2$ emissions adjustment factor for each energy type, as per Table 2-11.

*Table 4-14 - Fossil Fuel Emissions Factors*

| Energy type | Emissions factor (t CO2/TJ) | "f" CO2 emissions adjustment factor |
|---|---|---|
| Coal | 96.3 | 1.00 |
| Crude Oil | 73.3 | 0.76 |
| Natural gas | 56.1 | 0.58 |
| Green hydrogen | 0.0 | 0.00 |

The composition and result for M6 is shown in Table 4-14. Australia's current highly vulnerable position of high carbon intensity of energy exports is replaced by effectively 100% from green hydrogen, hence a score for M6 of 0.0 in 2050. The policy implication for Australia is that an early transition away from exporting fossil fuels as an early mover to supply emerging green hydrogen markets in Japan and Korea as set out earlier in this paper, considerably reduces exporter vulnerability.

Table 4-15 - M6 - Carbon Intensity of Energy Exports Including the 2050 Hydrogen Exports Scenario

| Year | 2019 | 2050 |
|---|---|---|
| Gas exports (PJ) | 3,686 | 0 |
| Oil exports (PJ) | 518 | 0 |
| Coal exports (PJ) | 10,629 | 0 |
| Hydrogen exports (PJ) | 0 | 2,088 |
| Total exports (PJ) | 14,833 | 2,088 |
| M6 | 0.86 | 0.00 |

#### 4.4.1.7 Export Vulnerability Metrics Scaled and Compared

A scaling and normalisation method is applied, consistent with the approach for these metrics in chapter 2 of this work, and the comparison is shown in Figure 4-4. The upper values for each metric are normalised to 1.0, except for M5 which scored 0.0 for both 2019 and 2050. Overall, it is clear that the energy transition away from fossil fuels and toward domestic zero carbon generation sources supplemented by exportable green hydrogen has a positive impact in every metric, on the condition that the exporter, in this case Australia, adapts their energy exports to meet the demand for zero carbon energy.

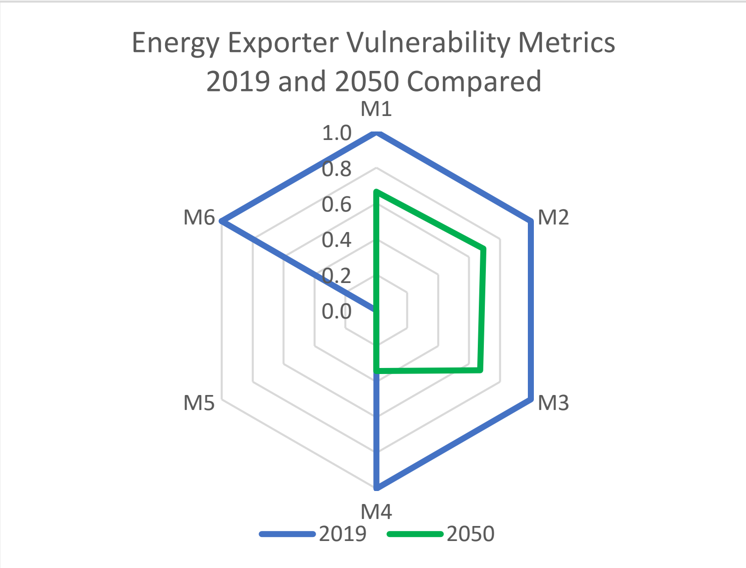



Figure 4-4 - Energy Exporter vulnerability Metrics 2019 and 2050 Compared

Table 4-16 - Energy Exporter vulnerability Metrics 2019 and 2050 Compared (Data for Figure 36)

| | 2019 | 2050 | 2019 | 2050 |
|---|---|---|---|---|
| | raw scores | | normalised and scaled | |
| M1 | 0.621 | 0.413 | 1.000 | 0.665 |
| M2 | 0.329 | 0.228 | 1.000 | 0.693 |
| M3 | 8.314 | 5.595 | 1.000 | 0.673 |
| M4 | 0.045 | 0.015 | 1.000 | 0.340 |
| M5 | 0.000 | 0.000 | 0.000 | 0.000 |
| M6 | 0.859 | 0.000 | 1.000 | 0.000 |

### 4.4.2 Energy Exporter Domestic Energy Security Metrics

The exporter-energy security impacts of the hydrogen exports superpower scenario examined in this chapter are evaluated using the two new metrics set out [185]. For these two metrics, the possible range of scores is 0.0 to 1.0, and a higher score means higher domestic energy security (higher is more desirable).

#### 4.4.2.1 Ex.PESS – Exporter's Primary Energy Self-Sufficiency

Energy security theory widely holds that higher primary energy self-sufficiency is a desirable objective [8], [28]. In the case of energy exporters, the calculation method of primary energy self-sufficiency needs some additional consideration to avoid an incorrectly favourable result weighted by energy production dedicated to exports that do not contribute to domestic supply, hence input figures for domestic energy self-sufficiency for each energy type are capped at 100%.

*Equation 4-8 - Ex.PESS – Exporter's Primary Energy Self-Sufficiency*

$$Ex.PESS = \frac{(TES \times DSS)_{electricity} + (TES \times DSS)_{oil} + (TES \times DSS)_{gas} + (TES \times DSS)_{greenH2}}{TPES}$$

Where;

Ex.PESS = Exporter Primary Energy Self Sufficiency

TES = total energy supply in each category

DSS = domestic supply self-sufficiency, capped at 100%, being the maximum rate of production that can be applied for domestic use.

TPES = total primary energy supply (sum of all TES categories; electricity, oil, gas and green hydrogen).

In the 2050 hydrogen export superpower scenario [154], hydrogen is introduced as a new energy source, being entirely generated from domestic renewable electricity. The use of imported oil and oil products, principally as transport fuels is expected to be ceased before 2050, since under this scenario new internal combustion engine vehicles will not be available beyond 2035. Any use of imported fossil fuels (primarily diesel) in electricity generation is also replaced with various local renewables and hydrogen. Australia thus becomes 100% self-sufficient in energy sources for its domestic electricity supply. Domestic gas is almost entirely converted to biogas, hydrogen blending and synthetic methane from green hydrogen. The inputs and calculation result for Ex.PESS in 2019 and 2050 for the hydrogen export superpower scenario are shown in Table 4-17.

The policy implication for Australia of a major transition to a green hydrogen export superpower by 2050 in this metric is the benefit of displacing imported oil used in 2019 primarily as a transport fuel and also a small portion for power generation with abundant locally produced renewable electricity and green hydrogen, thus enhancing Australia's energy security.

*Table 4-17 - Exporter's Primary Energy Self-Sufficiency Including the 2050 Hydrogen Exports Scenario*

| | 2019 | | 2050 | |
|---|---|---|---|---|
| | TES | % DOM | TES | % DOM |
| Oil | 2,307 | 31.4% | 0 | - |
| Electricity source | 2,404 | 98.6% | 5,652 | 100.0% |
| Gas | 922 | 100.0% | 790 | 100.0% |
| Hydrogen | 0 | - | 2,088 | 100.0% |
| Ex.PESS (aggregate) | | 0.71 | | 1.00 |

#### 4.4.2.2 Ex.DES – Exporter Domestic Energy System Exposure to Export Impacts

When an energy exporter's domestic energy system is linked to export activities, energy security can be impacted through the influence of international market forces on pricing and demand. This metric quantifies the extent to which an energy exporter's domestic energy system is exposed to these export impacts.

*Equation 4-9 - Ex.DES – Exporter Domestic Energy System Exposure to Export Impacts*

$$Ex.DES \;=\; \frac{\left(Ex.DES_{gas} \times TES_{gas}\right) + \left(Ex.DES_{electricity} \times TES_{electricity}\right) \,+ \left(Ex.DES_{greenH2} \times TES_{greenH2}\right)}{TES_{gas} + TES_{electricity} + TES_{greenH2}}$$

Where;

$Ex.DES_{(energy\ type)}$ : 1 minus the ratio of domestic energy supply of that energy type that is physically linked to an export market

$TES_{(energy\ type)}$ : total energy supply of the given energy type

We show the composition and calculation results for Ex.DES in 2019 (historical data) and 2050 (forecast scenario) in Table 4-18. Due to the widespread deployment of export-focussed electrolysers connected to the electricity grid in each state, 100% of grid electricity becomes physically linked to an export pathway, and hence heavily exposed to pricing and demand from international markets since by 2050, 867TWh (55.9%) of Australia's electricity production of 1,550TWh is taken by green hydrogen production for export. The extent of 2050 hydrogen supply that is connected to export-oriented hydrogen production facilities is difficult to forecast at this time; we have reviewed and filtered CSIRO's HyResource database [192] for planned hydrogen producing projects (see Appendix 1) and established that of the 43 projects planned to supply the domestic market, 18 of them (42%) are associated with an export-oriented facility, hence we have therefore applied the figure of 42% as the share of domestic hydrogen supply that is physically export-exposed. The policy implication for Australia is a reduction in energy security as the domestic energy system becomes entirely export-linked and majority export-focussed, only mitigated by domestic-focussed gas projects with no LNG export linkage and local hydrogen production. The export-linkage of the electricity system has the potential to cause domestic electricity pricing to become set not by domestic supply-demand forces, but by international demand for green hydrogen, unless protective policy measures are put in place.

*Table 4-18 - Exporter Domestic Energy System Exposure to Export Impacts Including the 2050 Hydrogen Exports Scenario*

| | 2019 | 2050 |
|---|---|---|
| Gas (domestic use) (PJ) | 922 | 790 |
| Electricity (domestic use) (PJ) | 950 | 5,652 |
| Hydrogen (domestic use) (PJ) | 0 | 338 |
| Ex.DES (gas) | 0.37 | 1.00 |
| Ex.DES (elec) | 0.59 | 0.00 |
| Ex.DES (hydrogen) | 0.00 | 0.42 |
| Ex.DES (aggregate) | 0.48 | 0.14 |

#### 4.4.2.3 Exporter Energy Security Metrics Compared

The results for Ex.PESS and Ex.DES are compiled in Table 4-19. The result is mixed for domestic energy security in 2050 under the hydrogen export superpower scenario; while primary energy self-sufficiency reaches the maximum possible value of 1.00 with the cessation of power generation using imported diesel fuel, the electricity network has become largely export linked through large scale export-oriented grid connected electrolysers, causing Ex.DES to fall significantly.

*Table 4-19 Exporter Energy Security Metrics 2019 - 2050 Compared*

| | 2019 | 2050 |
|---|---|---|
| Ex.PESS | 0.71 | 1.00 |
| Ex.DES | 0.48 | 0.14 |

### 4.5 Framework Summary

The elements of conceptual framework for domestic impacts from the green hydrogen export superpower scenario established in this chapter are summarised in Figure 4-5 and shown linked to the applicable stage of the energy system value chain. By associating each framework element to a phase in the green hydrogen production and export supply chain, the direct application of each is further clarified.

As set out in Section 2, the extent of renewable electricity generation required to supply hydrogen production is of such a large scale that policymakers, regulators, project developers and community stakeholders will benefit from an increased awareness of factors related to the renewable electricity phase as an input to optimise projects and mitigate negative outcomes for related communities. Elements of the framework related to domestic energy demand are essential considerations for grid operators, regulators, governments, and other major industrial electricity users who will potentially be in competition with hydrogen export customers for electricity supply. Elements of the framework related to the green hydrogen exports phase are most applicable to state and national government policy makers and related advisors and think-tanks to the extent that establishing a robust and relevant policy framework reflecting these elements of domestic vulnerability sets clear expectations for an emerging industry of the investment conditions that are sustainable for the producing country and state.

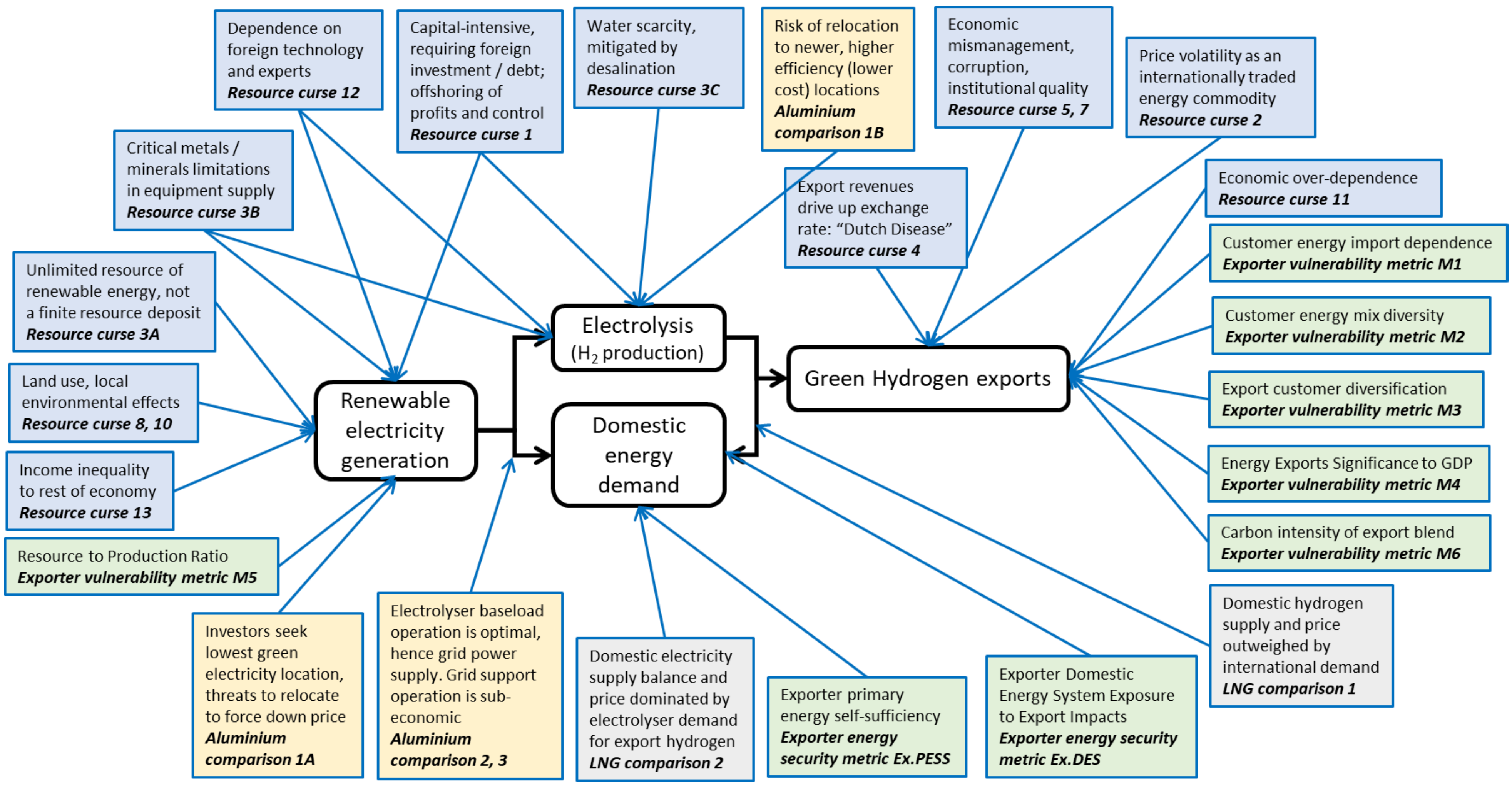



*Figure 4-5 - Conceptual Framework for Domestic Impacts of the Green Hydrogen Export Superpower Scenario*

## 4.6 Conclusions

In this chapter a conceptual framework has been developed for understanding the domestic energy system implications to a prospective green hydrogen exporter such as Australia.

Further, it has been established that the Hydrogen Export scenario proposed by CSIRO and Climateworks for AEMO in their 2022 report [154] is broadly consistent in terms of export quantity with projected demand expressed by potential import customers Japan and South Korea, although there is still some way to go in technological development in both production and end use equipment before convergence on the buyer's and the seller's price is reached.

From the analysis of frameworks for resource curse hypothesis, LNG exports and aluminium exports in the preceding sections, a conceptual framework for domestic implications and energy security risks is compiled and shown in Figure 4-5.

Our initial examination of relevance of the resource curse hypothesis has provided indications of many similarities with extractive resource export industries while also revealing some differences. Further research and analysis on this topic is recommended to establish a more comprehensive understanding of potential resource curse risks to emerging hydrogen exporters to enable preventative action in policies and development planning. From the comparison with the LNG export framework, it has been shown in this chapter that a high export price for hydrogen can result in domestic hydrogen supply being diverted to export markets and driving up the domestic electricity price. From the comparison with the aluminium export frameworks, it has been shown in this chapter that a low export price for hydrogen can result in established hydrogen producers threatening to relocate production to another country if the electricity price paid is not reduced, requiring cross-subsidy from other customers accepting increased prices, or in the form of government subsidies.

Table 4-20 shows together the quantitative evaluation of Australia's energy export economic vulnerability and domestic energy security, comparing 2019 as the base case with the 2050 hydrogen export scenario.

*Table 4-20 - Summary of Change in Exporter Internal Vulnerability and Domestic Energy Security from 2019 to 2050 (Hydrogen Export Scenario)*

| | 2019 | 2050 | Comment |
|---|---|---|---|
| Exporter Internal Vulnerability | | | |
| M1 | 0.744 | 0.413 | Less vulnerable (improved) |
| M2 | 0.329 | 0.228 | Less vulnerable (improved) |
| M3 | 10.171 | 5.595 | Less vulnerable (improved) |
| M4 | 0.036 | 0.012 | Less vulnerable (improved) |
| M5 | 0.00 | 0.00 | Unchanged (negligible vulnerability) |
| M6 | 0.860 | 0.00 | Less vulnerable (improved) |
| Exporter Domestic Energy Security | | | |
| Ex.PESS | 0.71 | 1.00 | More secure (improved) |
| Ex.DES | 0.48 | 0.14 | Less secure (deteriorated) |

As seen in Table 4-20, exporter vulnerability due to importer efforts to reduce import dependence (M1) and to diversify energy sources (M2) is reduced by switching to green hydrogen exports from 2019 to 2050 since it is found that by 2050 these actions will already have been implemented by importing countries as they increase the extent and diversity of domestic zero-carbon energy sources. Exporter vulnerability due to carbon risk in export fuels (M3) is dramatically reduced since fossil fuel exports to countries taking action to decarbonise are replaced by green hydrogen imports. Vulnerability is expected to have decreased due to a lower ratio of energy exports to GDP (M4), even though both increase, since GDP is forecast to increase at a faster rate, although this result may not necessarily be widely applicable to other countries, depending on their economic structure. Vulnerability in terms of resource to production ratio (M5) is unchanged for Australia at a level of negligible exposure, exchanging over 300 years of coal reserves in 2019 for unlimited renewable energy supply hydrogen exports. However, for current fuel fossil exporters with less than 100 years of known resources, or none at all, a transition to green hydrogen exports using unlimited renewable electricity could provide a material reduction in vulnerability. A current fossil fuel exporter's vulnerability due to carbon exposure (M6) is found to be substantially reduced by reducing or eliminating fossil fuel export in favour of green hydrogen.

Further, we have found that primary energy self-sufficiency as measured by Ex.PESS is increased as all energy needs are met in 2050 from domestic renewable energy, providing an improvement in the exporting country's energy security situation. However, the exporter's domestic energy system exposure to international market effects (as measured by Ex.DES) is found to significantly increase, representing a deterioration of the exporting country's energy security situation in that dimension as the entire electricity grid and a significant part of domestic hydrogen supply is directly linked to export demand and pricing.

Amid the excitement surrounding the possibility of developing a new zero-carbon export industry in the form of green hydrogen, countries with excess renewable energy potential capable of supporting large scale green hydrogen production should carefully consider the domestic implications, as established in this study, to design development plans and policies to appropriately maximise the benefits from this new export industry while limiting the risk of negative impacts to domestic customers and domestic energy security.

# Chapter 5 - Conclusions and Further Work

## 5.1 Need for This Research

This research was initiated with a wide-ranging literature review on energy security and international energy trade, which revealed a dominant focus on countries dependent on energy imports and very limited treatment of the particular vulnerabilities of energy exporters. These unaddressed vulnerabilities of energy exporting countries established in this research can be arranged into main categories;

- economic vulnerability of a country due to its reliance on energy resource export revenues
- impacts on the domestic energy system due to energy resource export activities.

The first point can be considered as a paired concept on the other side of the supplier-consumer relationship with importer-side energy security concerns. The second point sits conceptually within the scope of conventional energy security.

In addition, in the context of increasing global efforts to mitigate anthropogenic climate change, there is a particular gap in knowledge of how countries with major fossil fuel energy resource export will be impacted by the global energy transition to a zero-$CO_2$ emissions future, in relation to;

- present economic vulnerability due to the carbon risk inherent in fossil fuel exports
- future impacts on the domestic energy system of replacing fossil fuel exports with green hydrogen

The aim of the research presented in this thesis has thus been to contribute to filling knowledge gap on energy exporter vulnerability, now and in a net-zero $CO_2$ emissions future. This aim has been achieved through establishing a comprehensive conceptual framework for energy exporter vulnerability, by designing a suite of quantitative assessment indicators adapted to energy exporter conditions, and then by apply both of these two the central case study of Australia's energy export industry.

## 5.2 Conceptual Framework

In response to the clearly identified need set out in section 5.1, this research has established a novel comprehensive framework of the unique vulnerabilities experienced by countries engaged in exporting energy resources. This framework is composed of 3 elements, as follows:

1. Economic vulnerabilities of an energy exporting country stemming from their energy export activities. This has been developed using similar and related frameworks including:
    a. Oil exporter risks
    b. General economic vulnerability
    c. Energy security of domestic energy supply
    d. Energy producer companies own business risk assessment
2. Domestic energy security impacts created by energy export activities. This has been developed in the following way:
    a. Review of conventional energy security frameworks, factors and indicators, and assessment of each for relevance to the domestic energy system of countries with net energy exports.

    b. A systems approach to review each of the potential variations of domestic / export energy system configuration for any additional impacts unique to energy exporter that are not covered by importer-focussed energy security frameworks.
3. Domestic energy system impacts of large-scale green hydrogen exports. This framework has been developed using comparative resource frameworks including:
    a. Resource curse hypothesis, typically applied to non-renewable extractive resource exports, with individual factors reviewed for applicability to green hydrogen
    b. Aluminium production for export, with similarities being an electricity-intensive and globally traded resource export
    c. Gas production for export as LNG, with links to the domestic gas supply system

Together, these framework elements shed significant additional light on the unique vulnerabilities now experienced by energy exporters, and how those vulnerabilities will transform along with the global energy transition.

### 5.3 Quantitative Assessment Tools

The research work to establish the conceptual frameworks set out in Section 5.2 has led to the detailed work of designing new quantitative indicators for novel aspects of the framework elements not otherwise represented in literature. The suite of quantitative assessment tools developed in this research consists of the following:

| Metric | Description |
|---|---|
| Exporter Economic Vulnerability | |
| M1 | Customer energy import dependence |
| M2 | Customer energy mix diversity |
| M3 | Export customer diversification weighted by carbon emissions reduction rating |
| M4 | Energy exports significance to GDP |
| M5 | Resource to production ratio |
| M6 | Carbon emission intensity of the export blend |
| Exporter Domestic Energy Security | |
| Ex.PESS | Primary energy self-sufficiency suited to the complex features of energy systems of producer-exporters |
| Ex.DES | Domestic energy system exposure to impacts from export activities and international market linkages |

Metrics M3 and M6 have been specifically designed to evaluate exporter inherent carbon risk, from an external and internal perspective respectively.

In Chapter 2 the energy exporter economic vulnerability metrics developed are applied to the central case study of this work, Australia, showing historical trends for each metric, and comparison with a mix of comparable major energy exporters; Canada, Indonesia, Norway and Russia.  In Chapter 3 the exporter domestic energy security metrics are applied to case studies of Australia and historically trended.

Together, these 8 indicators constitute a useful addition to conventional energy security assessment indicators, fulfilling the aim of this research to fill the exporter-side knowledge gap.

### 5.4 Findings - What Energy Exporters Can Expect from the Global Energy Transition

The quantitative tools summarised in section 5.3 are applied to the reference case of Australia, and results are shown in Table 5-1, Figure 5-1, Table 5-2 and Figure 5-2.

*Table 5-1 - Energy Exporter Vulnerability Assessment (Australia) Past, Present and Green Future*

| | 2000 | 2019 | 2050 | 2000 | 2019 | 2050 |
|---|---|---|---|---|---|---|
| | raw scores | | | scaled and normalised | | |
| M1 | 0.702 | 0.620 | 0.413 | 1.00 | 0.88 | 0.59 |
| M2 | 0.337 | 0.328 | 0.228 | 1.00 | 0.97 | 0.68 |
| M3 | 8.602 | 8.314 | 5.595 | 1.00 | 0.97 | 0.65 |
| M4 | 0.031 | 0.045 | 0.015 | 0.68 | 1.00 | 0.34 |
| M5 | 0.000 | 0.000 | 0.000 | 0.00 | 0.00 | 0.00 |
| M6 | 0.909 | 0.859 | 0.000 | 1.00 | 0.95 | 0.00 |

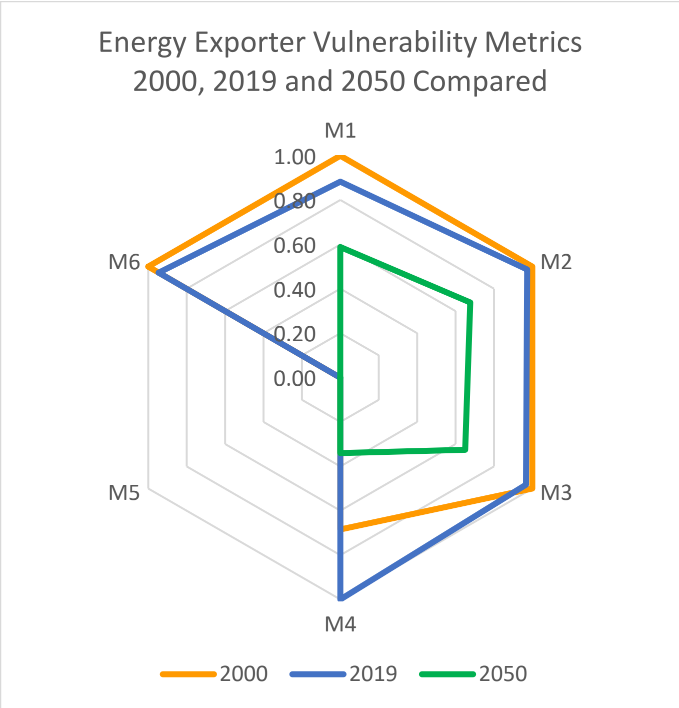



*Figure 5-1 - Energy Exporter Vulnerability Assessment (Australia) Past, Present and Green Future*

Over the period 2000-2019, the following trends are observed from the energy exporter economic vulnerability metric results:

- a moderate reduction in vulnerability in M1 (customer energy import dependence) due to an increased share of exports to China which is less dependent on exports than the prior customer mix.
- a slight reduction in vulnerability in M6 (carbon emissions intensity of the energy export blend) as the share of LNG exports has increased compared to coal.
- a considerable reduction in vulnerability in M4 (energy exports significance to GDP), as the overall Australian economy has grown at a faster rate than that of energy exports.
- negligible change in M2 (customer energy mix diversity) and M3 (export customer diversification weighted by carbon emissions reduction rating).
- no change in zero vulnerability assessed for M5 (resource to production ratio).

The assessment using these metrics is extended to the 2050 scenario of large-scale exports of green hydrogen replacing fossil fuel exports, showing:

- significant reductions of vulnerability in all metrics
- still no change in zero vulnerability assessed for M5 (resource to production ratio), as Australia's reliance on multiple hundreds of years of coal resources is replaced by unlimited renewable energy for green hydrogen production.
- zero vulnerability assessed for M6 (carbon emissions intensity of the energy export blend) as Australia's energy exports are by that time fully de-carbonised.

*Table 5-2 - Energy Exporter Domestic Energy Security Assessment (Australia) Past, Present and Green Future*

| | 2013 | 2019 | 2030 |
|---|---|---|---|
| Ex.PESS | 0.75 | 0.71 | 1.00 |
| Ex.DES | 0.84 | 0.48 | 0.14 |

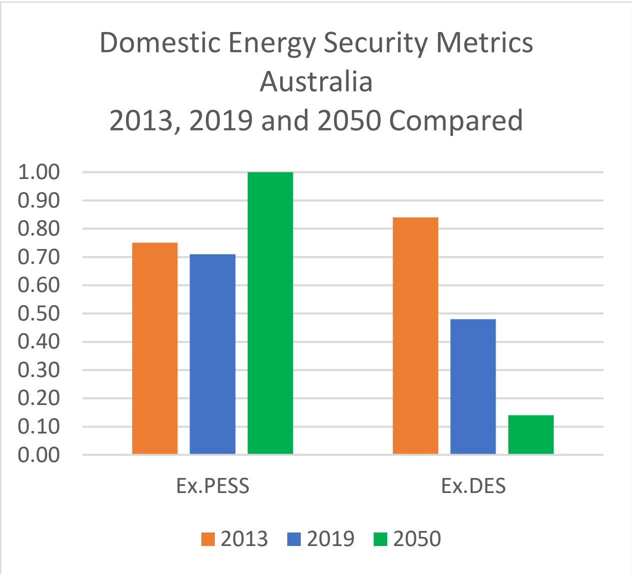



*Figure 5-2 - Energy Exporter Domestic Energy Security Assessment (Australia) Past, Present and Green Future*

Over the period 2013-2019, the following trends are observed from the metrics for the exporter's domestic energy system energy security:

- Ex.PESS measure of energy security was reduced slightly due to a greater reliance on imported oil as local production decreases and demand increases.
- Ex.DES measure of energy security was reduced due to the commencement of LNG exports from three new LNG terminals in Queensland.

The assessment using these metrics is extended to the 2050 scenario of large-scale exports of green hydrogen replacing fossil fuel exports, showing:

- Ex.PESS will rises to the maximum score for complete domestic energy self-sufficiency as imported oil is entirely replaced by domestically generated renewable electricity and green hydrogen for transport and remote power generation.

- Ex.DES will fall significantly denoting a worsening energy security rating in this metric, as a result of each state's electricity supply system becoming export-exposed due to widespread construction of export-oriented electrolyser plants.

Overall, all metrics except one (export exposure of the domestic energy system) show a significant improvement (less vulnerable economically and more secure domestically) in the projected case of Australia's energy exports transition from fossil fuels to green hydrogen.

In any case, as Australia's current fossil fuel export customers pursue ambitious plans to decarbonise their domestic energy system, the question is not so much as whether to make the transition as an exporter from fossil fuels to green hydrogen in its various carrier forms, as it a matter of making the best of the necessary change and proactively capitalising on green hydrogen as a new, replacement energy export.

The applicability of these findings to other current fossil fuel exporters planning to re-orient their energy exports from the sunset industry of fossil fuels to green hydrogen can be tested by returning to the comprehensive conceptual framework developed in this work, and by calculating a country-specific rating for each of the 8 indicators developed through this research, in concert with existing energy security assessment tools and methods of assessing economic benefit.

### 5.5 Applications of this Research and Further Work

Countries with a significant portion of their economy reliant on exports of energy resources need a comprehensive framework and specific assessment tools to better understand their vulnerabilities as related to those exports. This research has contributed to enhancing energy exporters self-awareness at a conceptual framework level and at a detailed quantitative level.

The applications of this research for policy makers and energy industry participants are both immediate and forward-looking, as follows:

- Considering historical trends leading up to present performance, countries can determine if their economic vulnerability and energy security are improving, stable, or declining. This can be a valuable feedback process on energy related policy settings and industrial activity and provide guidance for future policies and investment decisions.
- Present-day fossil fuel exporting countries can comprehensively map out the potential effects on their own economic vulnerability from energy exports and impacts on the domestic energy system of embracing a new industry of green hydrogen exports. They can then design policies and guide industrial development for their country's optimal development through this major transition.

Opportunities for further research identified in this work include the following topics:

- A deeper study of the relevance of detailed aspects of the resource curse hypothesis to large-scale green hydrogen exports can be continued from the initial review provided in this work.

- As the extent of energy infrastructure construction (renewable electricity generation, transmission lines, hydrogen electrolysers and conversion plants for exportable carriers) required for the anticipated transition has been demonstrated in section 4.2.1, there immediately arise questions of shortages of critical minerals to manufacture the equipment required. Further research on potential supply shortages and alternative materials is proposed.
- The potential opportunities and benefits for reducing import customer energy demand by relocation of energy intensive activities closer to low-cost renewable energy resources, in a similar manner to the relocation of aluminium production from Japan to Australia as examined in section 4.3.3, such as green steel production, rather than transforming renewable electricity into hydrogen, then into a carrier, for shipping to a distant customer.

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# Appendix A – Green Hydrogen Development Projects (Australia)

Commercial scale green hydrogen development projects categorised by intended offtake (domestic, export or both).[192]

| Project | State | Domestic | Export |
|---|---|---|---|
| 1. Abel Energy Bell Bay | Tasmania | ✓ | ✓ |
| 2. Arrowsmith Hydrogen | Western Australia | ✓ | |
| 3. Australian Renewable Energy Hub (Pilbara) | Western Australia | ✓ | ✓ |
| 4. Bristol Spring Solar Hydrogen | Western Australia | ✓ | |
| 5. Cape Hardy Green Hydrogen | South Australia | | ✓ |
| 6. Central Queensland Hydrogen Energy | Queensland | ✓ | ✓ |
| 7. Collie Battery and Hydrogen Industrial Hub Project | Western Australia | ✓ | |
| 8. Darwin Green Liquid Hydrogen Export | Northern Territory | ✓ | ✓ |
| 9. Darwin H2 Hub | Northern Territory | | ✓ |
| 10. Desert Bloom Hydrogen | Northern Territory | ✓ | ✓ |
| 11. Altona Renewable Hydrogen Plant | Victoria | ✓ | |
| 12. Edify Green Hydrogen (Townsville) | Queensland | ✓ | ✓ |
| 13. Energys Renewable Hydrogen Production Facility | Victoria | ✓ | |
| 14. Fortescue Green Hydrogen and Ammonia Plant Bell Bay | Tasmania | ✓ | ✓ |
| 15. Swanbank Future Energy and Hydrogen Precinct | Queensland | ✓ | |
| 16. Fortescue Geelong Hydrogen Hub | Victoria | ✓ | ✓ |
| 17. Geraldton Export-scale Renewable Investment (GERI) | Western Australia | ✓ | ✓ |
| 18. Gibson Island Green Ammonia | Queensland | ✓ | |
| 19. Good Earth Green Hydrogen and Ammonia (Moree) | New South Wales | ✓ | |
| 20. Goondiwindi Hydrogen | Queensland | ✓ | |
| 21. Grange Resources Renewable Hydrogen (Port Latta) | Tasmania | ✓ | |
| 22. Great Southern (Georgetown) | Tasmania | ✓ | |
| 23. Origin Green Hydrogen Export | Queensland | ✓ | ✓ |
| 24. Green Springs (off-grid) | Northern Territory | ✓ | ✓ |
| 25. H2-Hub (Gladstone) | Queensland | ✓ | ✓ |
| 26. Woodside H2TAS | Tasmania | ✓ | ✓ |
| 27. Han-Ho H2 Hub | Queensland | | ✓ |
| 28. Hay Point Hydrogen Export | Queensland | | ✓ |
| 29. HIF Carbon Neutral eFuels Manufacturing Facility | Tasmania | ✓ | |
| 30. Hunter Energy Hub (AGL + Fortescue) | New South Wales | ✓ | ✓ |
| 31. Hunter Valley Hydrogen Hub (Origin + Orica) | New South Wales | ✓ | |
| 32. Hydrogen Brighton | Tasmania | ✓ | |
| 33. Hydrogen Launceston | Tasmania | ✓ | |
| 34. Hydrogen Park Murray Valley | Victoria | ✓ | |
| 35. Hydrogen Park South Australia | South Australia | ✓ | |

| Project | State | Domestic | Export |
|---|---|---|---|
| 36. Hydrogen Portland | Victoria | ✓ | ✓ |
| 37. HyEnergy | Western Australia | | ✓ |
| 38. Melbourne Hydrogen Hub | Victoria | ✓ | |
| 39. Murchison Hydrogen Renewables | Western Australia | | ✓ |
| 40. Neoen-ENEOS Export | South Australia | | ✓ |
| 41. Ord Hydrogen | Western Australia | ✓ | ✓ |
| 42. Origin ENEOS Gladstone | Queensland | | ✓ |
| 43. Origin Bell Bay Green Hydrogen and Ammonia | Tasmania | ✓ | ✓ |
| 44. Pacific Solar Gladstone Hydrogen | Queensland | | ✓ |
| 45. Port Bonython Hydrogen Hub | South Australia | | ✓ |
| 46. Port Pirie Green Hydrogen | South Australia | | ✓ |
| 47. Project Haber | Western Australia | ✓ | |
| 48. SM1 Port Augusta | South Australia | ✓ | |
| 49. South Australian Government Hydrogen Facility | South Australia | ✓ | |
| 50. Sumitomo Rio Tinto Green Hydrogen Yarwun | Queensland | ✓ | |
| 51. SunHQ Hydrogen Hub | Queensland | ✓ | |
| 52. Tiwi H2 | Northern Territory | | ✓ |
| 53. Torrens Island Green Hydrogen Hub | South Australia | ✓ | |
| 54. Western Green Energy Hub | Western Australia | | ✓ |
| 55. Whaleback Energy Park | Tasmania | ✓ | ✓ |
| 56. Yuri Renewable Hydrogen to Ammonia | Western Australia | ✓ | |

Total number of hydrogen producing projects shown in the CSIRO HyResource database[192] : 56
Domestic supply only : 25 projects (45%)
Export supply only : 13 projects (23%)
Both export and domestic supply : 18 projects (32%)

Projects supplying the domestic market : 43 (of which 18 (42%) are export-linked)

# Appendix B – Green Hydrogen Unit Conversion Tool

A screenshot of the conversion tool data table is shown below. The tool is based on a Microsoft excel spreadsheet format.

**Hydrogen Conversion Tool** Input into Yellow cells only

**Hydrogen**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PJ | 204 | GJ | 204,000,000 | MJ | 204,000,000,000 | Mt | 0.1775 | t | 177,500 | kg | 177,500,000 | Nm3 | 1,975,575,000 | MBtu | 20,176,364 | MWh(th) | 5,913,215 |
| GJ | 204,000,000 | MJ | 204,000,000,000 | Mt | 1.70 | t | 177,500 | kg | 177,500,000 | Nm3 | 1,975,575,000 | MBtu | 20,176,364 | MWh(th) | 5,913,215 | PJ | 21,288 |
| MJ | 204,000,000,000 | Mt | 1.70 | t | 1,700,992 | kg | 177,500,000 | Nm3 | 1,975,575,000 | MBtu | 20,176,364 | MWh(th) | 5,913,215 | PJ | 21,288 | GJ | 21,287,576 |
| Mt | 1.70 | t | 1,700,992.245 | kg | 1,700,992,245 | Nm3 | 1,975,575,000 | MBtu | 20,176,364 | MWh(th) | 5,913,215 | PJ | 21,288 | GJ | 21,287,575 | MJ | 21,287,575,596 |
| t | 1,700,992 | kg | 1,700,992,245 | Nm3 | 18,932,043,692 | MBtu | 20,176,364 | MWh(th) | 5,913,215 | PJ | 21,288 | GJ | 21,287,575 | MJ | 21,287,575,000 | Mt | 0.18 |
| kg | 1,700,992,245 | Nm3 | 18,932,043,692 | MBtu | 193,351,200 | MWh(th) | 5,913,215 | PJ | 21,288 | GJ | 21,287,575 | MJ | 21,287,575,000 | Mt | 0.18 | t | 177,500 |
| Nm3 | 18,932,043,692 | MBtu | 193,351,200 | MWh(th) | 56,666,667 | PJ | 21,288 | GJ | 21,287,575 | MJ | 21,287,575,000 | Mt | 0.18 | t | 177,500 | kg | 177,500,005 |
| MBtu | 193,351,200 | MWh(th) | 56,666,667 | PJ | 204,000 | GJ | 21,287,575 | MJ | 21,287,575,000 | Mt | 0.18 | t | 177,500 | kg | 177,500,000 | Nm3 | 1,975,575,055 |
| MWh(th) | 56,666,667 | PJ | 204,000 | GJ | 204,000,000 | MJ | 21,287,575,000 | Mt | 0.18 | t | 177,500 | kg | 177,500,000 | Nm3 | 1,975,575,000 | MBtu | 20,176,364 |
| BCM | 20 | BCM | 20 | BCM | 20 | BCM | 2 | BCM | 2 | BCM | 2 | BCM | 2 | BCM | 2 | BCM | 2 |

**Green Electricity Required (Gaseous H2)**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MWh/tH2 | 54.5 | MWh/tH2 | 54.5 | MWh/tH2 | 54.5 | MWh/tH2 | 54.5 | MWh/tH2 | 54.5 | MWh/tH2 | 54.5 | MWh/tH2 | 54.5 | MWh/tH2 | 54.5 | MWh/tH2 | 54.5 |
| MWh | 92,704,077 | MWh | 92,704,077 | MWh | 92,704,077 | MWh | 9,673,750 | MWh | 9,673,750 | MWh | 9,673,750 | MWh | 9,673,750 | MWh | 9,673,750 | MWh | 9,673,750 |
| GWh | 92,704.077 | GWh | 92,704.077 | GWh | 92,704.077 | GWh | 9,673.750 | GWh | 9,673.750 | GWh | 9,673.750 | GWh | 9,673.750 | GWh | 9,673.750 | GWh | 9,673.750 |
| TWh | 92.7 | TWh | 92.7 | TWh | 92.7 | TWh | 9.7 | TWh | 9.7 | TWh | 9.7 | TWh | 9.7 | TWh | 9.7 | TWh | 9.7 |

**Green Ammonia Equivalent Energy Basis**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t.NH3 | 10,967,741.94 | t.NH3 | 10,967,741.94 | t.NH3 | 10,967,741.94 | t.NH3 | 1,144,493.28 | t.NH3 | 1,144,493.28 | t.NH3 | 1,144,493.28 | t.NH3 | 1,144,493.28 | t.NH3 | 1,144,493.28 | t.NH3 | 1,144,493.31 |
| Mt.NH3 | 10,967.74 | Mt.NH3 | 10,967.74 | Mt.NH3 | 10,967.74 | Mt.NH3 | 1,144.49 | Mt.NH3 | 1,144.49 | Mt.NH3 | 1,144.49 | Mt.NH3 | 1,144.49 | Mt.NH3 | 1,144.49 | Mt.NH3 | 1,144.49 |

**Green Ammonia H2 to NH3 Molecule flow through**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t.NH3 | 9,580,506.78 | t.NH3 | 9,580,506.78 | t.NH3 | 9,580,506.78 | t.NH3 | 999,734.10 | t.NH3 | 999,734.10 | t.NH3 | 999,734.10 | t.NH3 | 999,734.10 | t.NH3 | 999,734.10 | t.NH3 | 999,734.13 |
| Mt.NH3 | 9.58 | Mt.NH3 | 9.58 | Mt.NH3 | 9.58 | Mt.NH3 | 1.000 | Mt.NH3 | 1.00 | Mt.NH3 | 1.00 | Mt.NH3 | 1.00 | Mt.NH3 | 1.00 | Mt.NH3 | 1.00 |
| | | | | | | | #REF! | | | | | | | | | | |

**Additional Electricity (Haber Bosch)**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MWh/tH2 | 3.0 | MWh/tH2 | 3.0 | MWh/tH2 | 3.0 | MWh/tH2 | 3.0 | MWh/tH2 | 3.0 | MWh/tH2 | 3.0 | MWh/tH2 | 3.0 | MWh/tH2 | 3.0 | MWh/tH2 | 3.0 |

**Green Ammonia Total Electricity**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MWh | 97,807,054.11 | MWh | 97,807,054.11 | MWh | 97,807,054.11 | MWh | 10,206,250.00 | MWh | 10,206,250.00 | MWh | 10,206,250.00 | MWh | 10,206,250.00 | MWh | 10,206,250.00 | MWh | 10,206,250.29 |
| GWh | 97,807.05 | GWh | 97,807.05 | GWh | 97,807.05 | GWh | 10,206.25 | GWh | 10,206.25 | GWh | 10,206.25 | GWh | 10,206.25 | GWh | 10,206.25 | GWh | 10,206.25 |
| TWh | 97.8 | TWh | 97.8 | TWh | 97.8 | TWh | 10.2 | TWh | 10.2 | TWh | 10.2 | TWh | 10.2 | TWh | 10.2 | TWh | 10.2 |

Hydrogen

| | |
|---|---|
| 119.93 | MJ/kg (LHV) |
| 141.86 | MJ/kg (HHV) |
| 1.18 | ratio HHV to LHV |

Green Ammonia Conversion

| | |
|---|---|
| 18.6 | MJ/kg (LHV) |
| 22.5 | MJ/kg (HHV) |
| 1.21 | ratio HHV to LHV |

Molecular Weight

| | |
|---|---|
| H2 | 2.0158 |
| NH3 | 17.0304 |
| 3H2 | 6.0474 |
| 2NH3 | 34.0608 |

# List of Publications

**Journal Papers**

1. Framework for Assessment of the Economic Vulnerability of Energy-Resource-Exporting Countries. Curtis, A.J., McLellan, B.C., Resources, 2023, 12, 27. https://doi.org/10.3390/resources12020027

2. Potential Domestic Energy System Vulnerabilities from Major Exports of Green Hydrogen: A Case Study of Australia. Curtis, A.J., McLellan, B.C., Energies, 2023, 16, 5881. https://doi.org/10.3390/en16165881

3. Exposing the Blind Spots in Domestic Energy Security of Major Energy Exporters. Curtis, A.J., McLellan, B.C., (under review)

**Conference Papers**

1. Towards A Conceptual Framework for Energy Economic Vulnerability of Energy Resource Exporting Nations. Curtis, A.J., McLellan, B.C., 33rd Energy Systems, Economic and Environment Conference, Tokyo, Japan, 2-3 February, 2017.

2. The Unique Characteristics of Energy Security for Energy Exporting Countries. Curtis, A.J., McLellan, B.C., 34th Energy Systems, Economic and Environment Conference, Tokyo, Japan, 25-26 January, 2018.