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Framework for Assessment of the Economic Vulnerability of Energy-Resource-Exporting Countries

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Abstract: 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 paper presents an assessment framework and quantitative scorecard for evaluating the economic vulnerability of countries with significant energy exports. The background research of various related conceptual frameworks distils useful insights from energy security, corporate risks, and general economic vulnerability. Carbon exposure, largely missing from related work, 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 five major global energy exporters with comparative analysis between countries and over time.

Keywords: energy resource exports; exporter vulnerability; carbon risk; energy security

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1. Introduction

The global distribution of energy resources is rarely geographically aligned with concentrations of human population and energy consumption. The global distribution of oil reserves clearly demonstrates this, with 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 GDP [2]. Within large countries, energy resources are often transported over long distances (such as gas) or converted to another form (coal to electricity) near the production site for ease of transportation to demand centres. Domestic energy self-sufficiency is widely considered to be desirable [3] 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 [4], South Korea [5], the European Union [6]) is well developed. In response to increasing demand from energy import-dependent 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 [7]. 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. The purpose of this paper is to contribute to this balance.

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 [8]. The vulnerability of energy exporters to the so-called resource curse [9] 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 [10], production reliability [11], or geo-political choke-points [3] 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. In this paper we will specifically concentrate 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 [12], 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% [12]) 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 [7]) 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 [13], 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 [14]. 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 [15].

Following this introduction, this paper is composed of four main sections; Section 2 presents a review of related frameworks and methodologies. Section 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 4 develops the novel conceptual framework by defining a scorecard of specific assessment metrics and their related quantitative evaluation methods. Section 5 applies the assessment metrics with economic data to produce a time-based scorecard for five selected energy-exporting countries. Conclusions to the research presented in this paper are summarised in Section 6.

2. Review of Related Frameworks and Methodologies

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 [15,16].

Papers by Dike [16], Bhattacharyya and Blake [15] and Kanchana, McLellan and Unesaki [17], 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 and 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 follows:

$$\mathrm{REED} = \mathrm{X} \times \mathrm{M} \times \mathrm{D} \times \mathrm{E}$$

where:

$$\mathrm{X} = \text{Export dependence, Energy Exports (EE)/Total Exports (tot\_exports)}$$

$$\mathrm{M} = \text{Monopsony factor, } (x_{\text{country }1})^2 + (x_{\text{country }2})^2 + \ldots + (x_{\text{country }n})^2$$

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

$$\mathrm{D} = \text{rating based on distance between capitals of the exporter and importer}$$

(if <1500 km, D = 1, if >1500 and <4000 km, D = 2, if >4000 km, D = 3)

$$\mathrm{E} = \text{export economic impact, value of oil and gas exports/exporter GDP}$$

Bhattacharyya and Blake 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. 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 1.

Table 1. Indicators for Energy Trading Exposure.

Indicators for Energy Trading Exposure (Kanchana et al.)	
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 [18]
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. is apparently unique in considering multiple fuels from the exporter perspective, although index assessments are segregated by fuel.

Without getting drawn into the resource curse dialectic of broader economic consequences of energy exports and instead staying focused on issues of the energy system and export revenues, quite a number of papers reviewed address specific country or regional examples of the interaction between domestic energy security and energy resource exports for net energy exporters [19–23]. As observed by Novikau [20] "Conceptualization and operationalization of energy security for energy-exporting countries are relatively complex because these countries always both produce and consume energy resources." and as such, much of the body of academic literature focusses on the complexities of specific cases with a range of interesting and valuable findings. However, none were found to propose a generally applicable assessment framework for vulnerability to loss of export revenues, which is the objective of this paper.

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 Development Policy and Analysis Division, Committee for Development Policy [24] was developed [25] in response to the need expressed by the UN General Assembly for a tool along with other indicators including GNI (Gross National Income) [26] and HAI (Human Assets Index) [27] 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 paper. The EVI was implemented in 2000 and has been revised multiple times. The latest version [28] 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 1. Various authors including Guillaumont [25,29–31], Briguglio [32,33] and Cariolle [28] have applied the basic EVI framework to case studies of developing countries, with variations and additions including comparing vulnerability to shocks and recovery resilience.

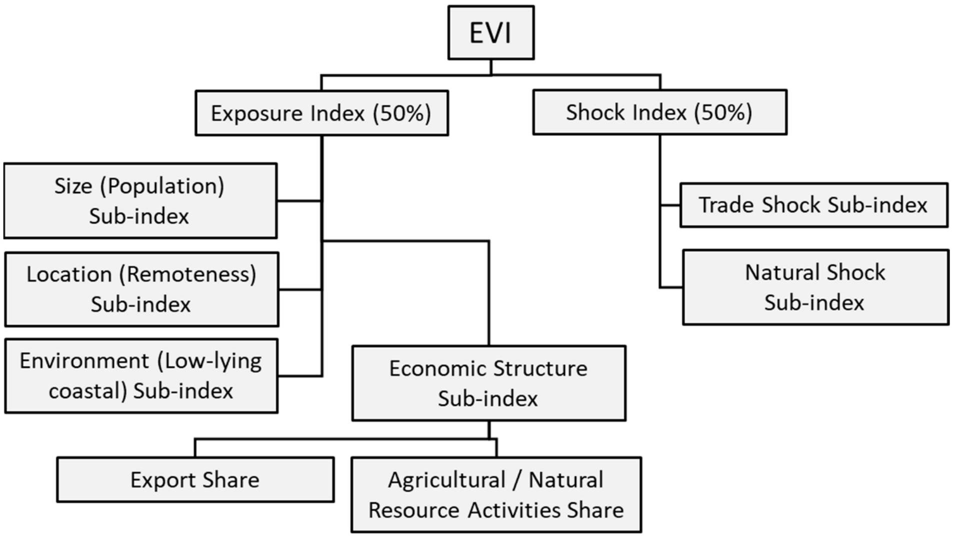


Figure 1. Structure of the UN Economic Vulnerability Index.

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, we can nonetheless gain some useful insights 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. We must likewise 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.

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.

2.3. 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 paper has identified a number of useful and relevant papers on energy security and assessment methods [3,18,34–60]. Three papers in particular have been selected for analysis here; Sovacool and Mukherjee [47], Kruyt [52] and Martchamdol [53]. These papers each 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.

Sovacool and Mukherjee [47] present a comprehensive and wide-ranging review of critical factors for energy security drawn from both in-depth engagement with stakeholders (interviews, surveys and a focused workshop), and a review of energy security literature. Of particular interest for the research topic of this paper is the extensive list of simple indicators and metrics of that Sovacool and Mukherjee and have compiled, which is distilled into five dimensions grouping together twenty components, shown in Table 2.

Table 2. Energy Security Dimensions and Components (Sovacool and Mukherjee).

Dimension	Component
Availability	1. Security of supply and production 2. Dependency 3. Diversification
Affordability	4. Price stability 5. Access and equity 6. Decentralization 7. Affordability (low prices)
Technology development	8. Innovation and research 9. Safety and reliability 10. Resilience and adaptive capacity 11. Efficiency and energy intensity 12. Investment and employment
Sustainability	13. Land use 14. Water 15. Climate change 16. Air pollution
Regulation and governance	17. Governance 18. Trade and regional interconnectivity 19. Competition and markets 20. Knowledge and access to information

Sovacool and Mukherjee's paper sets out in detail the full list of 320 simple indicators and 52 complex indicators that feed up to the components and dimensions shown in Table 2. The extent of this indicators list highlights the utility of detailed evaluation indicators for deep-dive analysis in addition to visibility of high-level dimensions of energy security, a number of which are reflected later in this paper as applicable to an exporter vulnerability framework. Sovacool and Mukherjee's method of engaging in a detailed qualitative consultation process with numerous stakeholders with interest in energy security appears to open up broader insights in addition to specific empirical analysis that many research papers concentrate on.

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 3 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.

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.

Table 3. Energy Security Indicators (Kruyt).

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 and 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

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 4. 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.

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. In this paper, we have supplemented these findings with authoritative work on energy security from a Japanese perspective. Murakami et al. [3] 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 [56], the Japanese Ministry of Economy Trade and Industry (METI) applied the same seven indicators, with slight naming differences, reproduced in Table 5.

Frondel and Schmidt [60] 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.

Table 4. Energy Security Indicators (Martchamdol and Kumar).

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 × $/kWh elec price ÷ $ GDP per capita
Residential energy per household	PJ final energy residential use ÷ total number of households

Table 5. Energy Security Indicators (Murakami).

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 designated 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

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 paper. 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 6 summarises the vulnerability factors distilled from the perspective of energy producer corporations internal risk management reporting.

Table 6. Energy Producer Common Vulnerability Factors.

Risk Factor	Peabody [61,62]	Rio Tinto [63,64]	Total [10,11]	Shell [65,66]
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.

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.

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 [67] 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.

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. In demand centres, temporary disruptions may be seasonal.

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 7), operated by JERA (formerly Tokyo Electric Power Company) and Tokyo Gas, with a total LNG storage capacity of 2,830,500 t. In 2017, a total of 34,780,000 t of LNG was imported into Tokyo Bay [68,69]. This storage capacity represents approximately one month (29.7 days to be precise) of 2017 Tokyo Bay LNG imports.

From the diversified LNG supply sources shown in Table 8, 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 7. Tokyo Bay Area LNG Storage Terminals and Capacity.

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
Higashi-Ogishima Thermal Power Station LNG Terminal	243,000
Futsuu Thermal Power Station LNG Terminal	499,500
Total	2,830,500

Table 8. Sources of LNG received in Tokyo Bay and shipping time.

Supplier Country [68,69]	% of Tokyo Bay Share	Export Terminal	Days Shipping to Tokyo Bay [70]
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 Laffan	31
	Weighted average delivery time		16.4
Others	7.0%		

Coal fired power plants dependent on imported fuel follow a similar fuel buffering strategy, usually at individual power plant sites. The Hitachinaka Thermal Power Station (2 × 1000 MW), north of Tokyo, was visited by the author and plant management interviewed regarding fuel storage strategy. The plant has a 400,000 t stockpile adjacent to the plant, which is supplied primarily from the Warkworth mine in Australia, exporting out of the Port of Newcastle. At the plant's coal burn rate of 14.8 kt/day, this buffer storage is equivalent to 25 days operation. Considering the typical shipping time from the Port of Newcastle is 19.4 days [70], 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.

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.

3.3. Nuclear Power and Uranium Exports

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 efficiency of transportation. However, yellowcake contributes only around 40–45% [71,72] to the total cost of nuclear fuel, which in turn contributes 14–17% [71,72] to the total cost of nuclear electricity when modern high efficiency centrifuge enrichment is used, as set out in Table 9.

Table 9. Nuclear fuel cycle cost breakdown.

Process	Proportion of Total [71,72]
Uranium mining	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 [73]. 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 yellow cake and thermal coal were quite comparable, at USD71 and USD107 per tonne, respectively [74]. 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 31,020 MWh/t of yellowcake uranium oxide compared to 3.1 MWh/t for coal [75,76]. From an energy exporter's perspective, fuel supplied to an energy customer to provide 1.0 TWh of electricity could either earn USD 2289 from 32 t of uranium exports or USD 34,240,000 from 320,000 t 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 export of uranium 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 resource 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 paper.

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 paper, we have taken a strategic approach to exporter vulnerability and focus on factors quantifiable from energy units as the intrinsic value of energy resources, rather focusing 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 Section 2 of this paper. The screening process is structured as show in Figure 2.

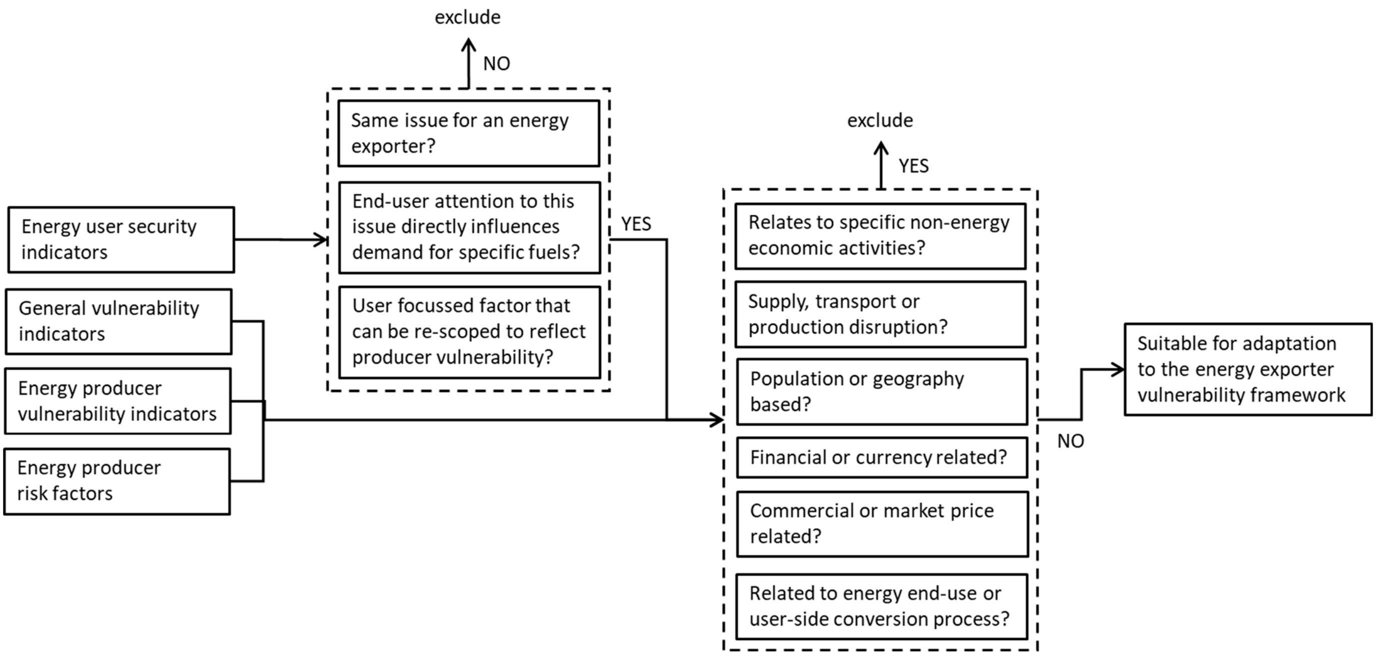


Figure 2. Screening Process for Selection of Energy Exporter Vulnerability Factors.

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.

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 [77–79] 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 [80–83]. In this paper the rating system of the Climate Change Performance Index (CCPI) [80] 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.

3.6. Diversity Indices

3.6.1. Comparison of HHI and SWI

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

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 and Rai [84], 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.

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 [18], Murakami [3], Wu and Rai [84], and Stirling [85,86].

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. [58], however this method is the most arbitrary of all and requires referential scaling to be applied.

In the case of customer diversity, Murakami [3] 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 [18] weighting approach to the HHI for energy suppliers includes both the World Governance Indicators [87,88] for governance issues and domestic societal outcomes, as well as country credit risk rating by the Economist Intelligence Unit. Kruyt [52] 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.

In this paper we propose 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.

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 10. Since many factors are related, in accordance with the factor selection principles set out in Section 3.4, related factors have been combined to establish a concise, workable list for the purpose of case study assessment. As set out in Section 3.4, factors sourced from energy security have been adapted to suit the energy exporter perspective.

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;

Internal vulnerability factor metrics:

M4—Energy exports significance to GDP;
M5—Production to Resource Ratio;
M6—Carbon intensity of energy export blend.

The selection of a total of 6 metrics with 3 each for internal and external vulnerabilities is made primarily to ensure that all relevant factors are included and also to provide balance between internal and external factors, while avoiding thematic overlaps between metrics and provides a scorecard that does not present so much data that it loses its effectiveness as an aggregated analysis tool.

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. In addition, combined indices are also developed in this paper and applied for the case studies for high-level comparison between countries.

Table 10. Comprehensive List of Potential Factors for Exporter Energy Economic Vulnerability.

Factor	Dike [16]	Bhattacharyya [15]	Kanchana [17]	UN EVI [28]	Sovacool and Mukherjee [47]	Kruyt [52]	Martchamadol [53]	Murakami [3]	Frondel [3,60]	Producer Corp [10,11,61–66]	Action	Integrated into Metric #
Energy exports as a share of total exports	✓										Include	M4
Customer diversity	✓		✓		✓					✓	Include	M3
Distance to customer	✓										Exclude	
Total exports as a share of GDP	✓		✓	✓							Include	M4
Energy price		✓				✓					Exclude	
Energy export to energy production ratio		✓	✓								Include	M5
Ratio of exports to domestic use		✓									Include	M1
Domestic energy intensity		✓					✓				Exclude	
Share of net energy imports to primary energy mix			✓			✓	✓				Include	M1
Share of energy import expenditures to GDP			✓			✓					Include	M4
Political stability of major energy trade partners			✓			✓			✓	✓	Exclude	
Openness to global energy trade			✓								Exclude	
Diversity of primary energy mix			✓			✓		✓	✓	✓	Include	M2
Reserves to production ratio			✓			✓	✓			✓	Include	M5
Dependency/energy self-sufficiency rate			✓		✓			✓	✓		Include	M1
Population				✓						✓	Exclude	
Location (remoteness)				✓							Exclude	
Environment (low lying coastal)				✓							Exclude	
Agric/Nat Resource share of GDP				✓							Include	M4
Trade shock risk				✓							Exclude	
Natural shock risk				✓							Exclude	
Access and equity to energy supply					✓						Exclude	
Affordability of energy supplies					✓						Exclude	
Costumer side sustainability issues					✓						Include	M6
Regulation and governance issues					✓						Exclude	
Resource estimates						✓				✓	Include	M5
Supplier diversity					✓	✓		✓	✓		Include	M3
Supply source geographical diversity											Exclude	
Share of zero carbon fuels (vulnerability to climate change policies)					✓	✓	✓				Include	M6

Table 10. *Cont.*

Factor	Dike [16]	Bhattacharyya [15]	Kanchana [17]	UN EVI [28]	Sovacool and Mukherjee [47]	Kruyt [52]	Martchamadol [53]	Murakami [3]	Frondel [3,60]	Producer Corp [10,11,61–66]	Action	Integrated into Metric #
Market liquidity (ratio of own demand to market availability)						✓					Exclude	
Energy intensity per capita						✓	✓				Exclude	
Energy intensity per GDP						✓	✓	✓			Include	M4
GDP per capita						✓					Exclude	
Loss in Transmission							✓				Exclude	
Loss in Transformation							✓				Exclude	
CO_2 emissions per capita							✓				Exclude	
CO_2 emissions per GDP					✓		✓				Include	M3
Household access to electricity							✓				Exclude	
Share of income to pay for electricity							✓				Exclude	
Residential energy per household							✓				Exclude	
Reduction of risks at supply route choke points								✓			Exclude	
Reliability of the domestic power system						✓		✓			Exclude	
Resilience to supply disruptions								✓			Exclude	
Law/regulation changes in operational site countries										✓	Exclude	
Community disputes near operational sites										✓	Exclude	
Customer greenhouse gas emissions reduction policies					✓					✓	Include	M3
Natural disasters and weather disrupt production										✓	Exclude	
Transport availability and infrastructure difficulties										✓	Exclude	
Equipment failure and production reliability										✓	Exclude	
Commercial risks										✓	Exclude	
Financial risks/price stability					✓					✓	Exclude	
Terrorist attack										✓	Exclude	
Influence of pandemics										✓	Exclude	
Demand for electricity										✓	Include	M1
Ongoing technological innovation					✓					✓	Exclude	
Operational health, safety and environmental issues					✓					✓	Exclude	
Physical effects of climate change on operations										✓	Exclude	

3.9. Scaling of Metrics in the Scorecard

In order to bring the scores for disparate indicators with quite different rating systems and numerical ranges to a common scale for ease of comparison and trending, normalisation of values is required. Tongsopit et al. [59], Gupta [18], Kanchana et al. [17], in their work related to quantifying energy security or exporter vulnerability, each apply the min-max method of linear transformation to normalise data and bring all indicators to a common scale. Others, such as Martchamadol and Kumar [53] 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 this paper's assessment methodology 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 data-set, 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 as follows:

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

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".

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.

External Vulnerability Factors (1–3).

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.

$$M1_{\text{country A}} = E_{\text{ country A}} / TPES_{\text{ country A}}$$

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.

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

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 five export customers, the energy share of up to five export customers is assessed to ensure customer diversity is sufficiently captured.

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 follows;

$$M2 = \frac{(Q \times HHITPES)\ country\ 1 + (Q \times HHITPES)\ country\ 2 + \ldots + (Q \times HHITPES)\ country\ n}{Qenergy.exports}$$

where:

Q = quantity (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

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 five export customers, the energy share of up to five 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 we have elected to take the TPES approach to ensure inter-regional comparability 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.

4.3. Export Customer Diversification

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.

$$M3 = CER_{country\ 1} \times (x_{country\ 1})^2 + CER_{country\ 2} \times (x_{country\ 2})^2 + \ldots + CER_{country\ n} \times (x_{country\ n})^2$$

where:

CER = a country's CO_2 emissions reduction rating index.

x = share of energy (PJ) exported for export customer country, 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 [80]) 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.

Internal Vulnerability Factors (4–6).

4.4. Energy Exports Significance to GDP

This metric is a simple ratio of revenue from energy exports divided by total GDP.

$$M4 = (R_{gas\ exports} + R_{oil\ exports} + R_{coal\ exports})/GDP$$

where:

R = revenue;

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.

4.5. Production to Resource 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 [89,90]. 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.

$$M5 = (100 - RPR_{aggregated})/100$$

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 $\geq$ 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.

$$\text{RPRaggregated} = \frac{\text{RPRaggregated} = [\,\text{Scoal} \times (\text{Qcoal}/\text{Pcoal}) + \text{Sgas}(\text{Qgas}/\text{Pgas}) + \text{Soil} \times (\text{Qoil}/\text{Poil})\,]}{\text{X}}$$

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 production to resource 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 [1,91] is used. Production data for coal, oil and gas is obtained from the IEA [7].

4.6. Carbon 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 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 [77] including reference data from European [78] and Japanese [79] sources for CO_2 emissions per unit mass of each fuel, multiplied by standard energy density conversion factors.

$$\text{M6} = \frac{[\,(\text{Scoal} \times \text{fcoal}) + (\text{Sgas} \times \text{fgas}) + (\text{Soil} \times \text{foil}) + (\text{Szcf} \times \text{fzcf})\,]}{\text{X}}$$

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 11.

Table 11. Fossil Fuel Emissions Factors.

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 density and high moisture content and is hence excluded here from the coal type 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 [77] 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.

5. Case Studies

The assessment framework is applied to case studies of five energy-exporting countries, Australia, Canada, Indonesia, Norway and Russia. Countries selected for case studies are exporters of multiple fuels, since this paper is particularly focused 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. The authors will be pleased to share the calculation and source data in excel format used to establish the scores reported below upon request from interest parties.

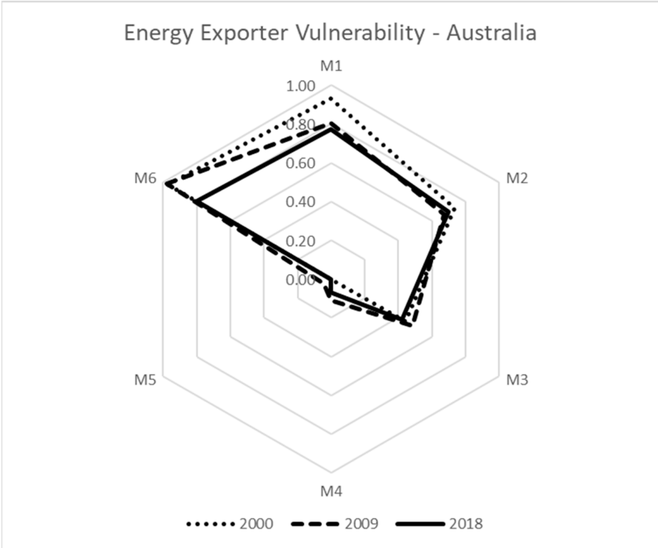
5.1. Australia

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

Table 12. Economic and energy export key data (Australia).

	2000	2009	2018
GDP (Bil USD 2021$)	415.2	927.8	1432.9
Total exports (Bil USD 2021$)	64.5	164.0	263.0
Gas exports (PJ)	388	756	3402
Oil exports (PJ)	811	583	458
Coal exports (PJ)	5084	7078	10,333
Total energy exports (PJ)	6283	8416	14,193

As seen in Figure 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 (production to resource 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—Production to Resource Ratio
M6—Carbon intensity of energy export blend

Figure 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.

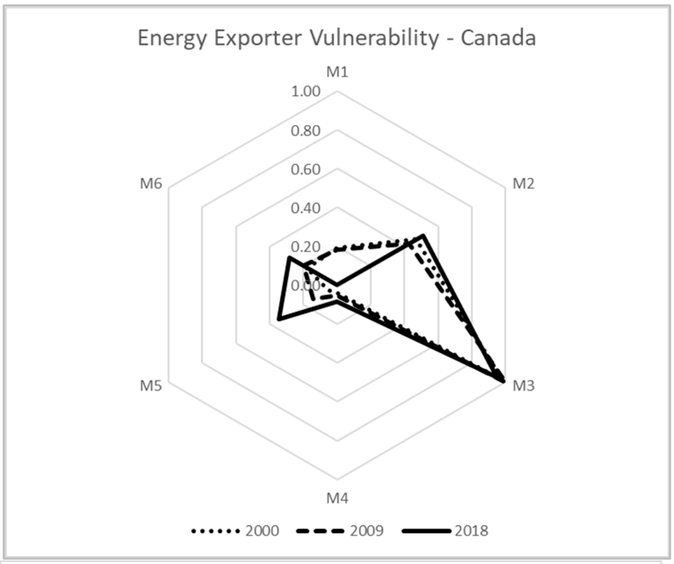
5.2. Canada

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

Table 13. Economic and energy export key data (Canada).

	2000	2009	2018
GDP (Bil USD 2021$)	744.6	1376.5	1721.8
Total exports (Bil USD 2021$)	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	11,853

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 profile domestic energy profile, as seen in Figure 4. As seen by a very low score for M5, Canada's production to resource ratio is very low 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.



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

Figure 4. Energy Exporter Vulnerability Scorecard (Canada).

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.

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.

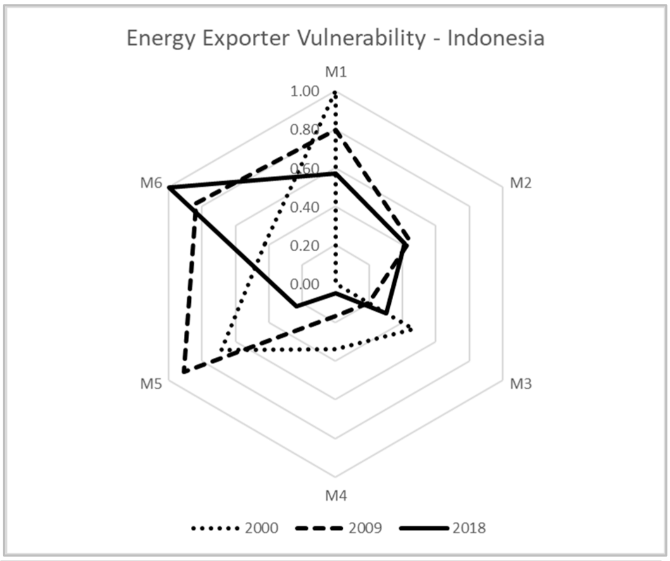
5.3. Indonesia

Indonesia's key energy exporter data over the period studied is shown in Table 14.

Table 14. Economic and energy export key data (Indonesia).

	2000	2009	2018
GDP (Bil USD 2021$)	165.0	539.6	1042.0
Total exports (Bil USD 2021$)	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	11,459

Figure 5 shows 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—Production to Resource Ratio
M6—Carbon intensity of energy export blend

Figure 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 (production to resource 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.

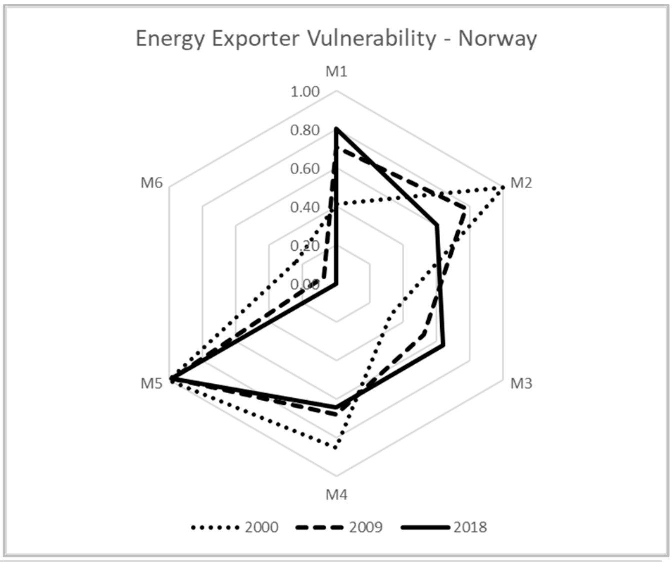
5.4. Norway

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

Table 15. Economic and energy export key data (Norway).

	2000	2009	2018
GDP (Bil USD 2021$)	171.2	386.2	437.0
Total exports (Bil USD 2021$)	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 Figure 6), 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—Production to Resource Ratio
M6—Carbon intensity of energy export blend

Figure 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 (production to resource 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.

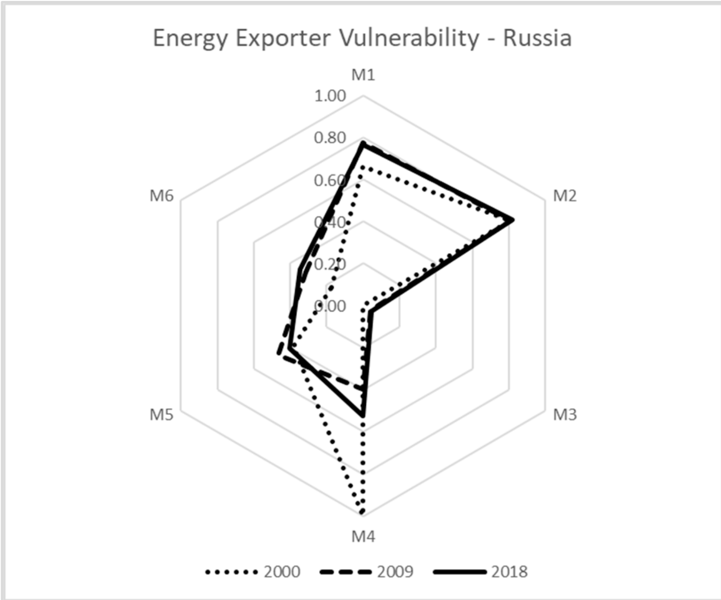
5.5. Russia

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

Table 16. Economic and energy export key data (Russia).

	2000	2009	2018
GDP (Bil USD 2021$)	195.9	1223.0	1687.0
Total exports (Bil USD 2021$)	101.0	285.0	430.0
Gas exports (PJ)	6556	5873	8434
Oil exports (PJ)	8309	14,707	16,403
Coal exports (PJ)	1067	2875	5576
Total energy exports	15,932	23,455	30,413

Figure 7 shows that Russia has exceptionally low vulnerability scores for M3 (export customer diversification) and M5 (production to resource 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. The M5 score reflects the massive natural resources 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.



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

Figure 7. Energy Exporter Vulnerability Scorecard (Russia).

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.

5.6. Metric Comparisons between Countries

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

Over the time period 2000–2018 Figure 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 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 slight decrease stems from an initial increase in exports to Japan, overtaken by 2018 to exports to China and India.

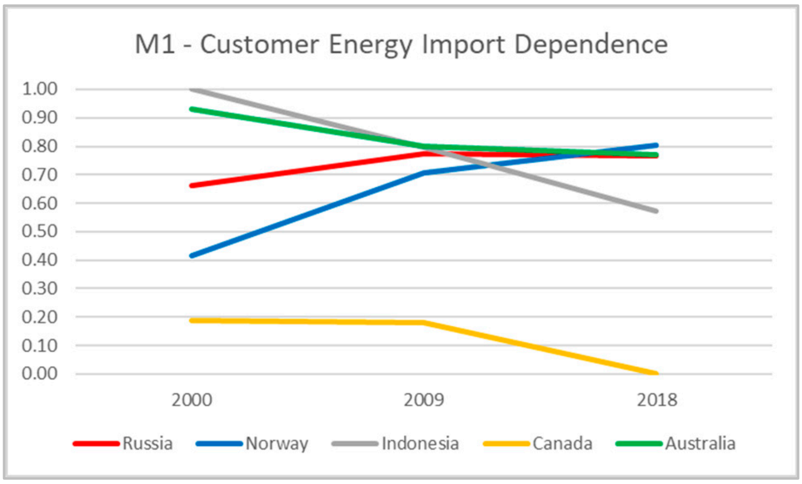


Figure 8. Customer Energy Import Dependence (M1).

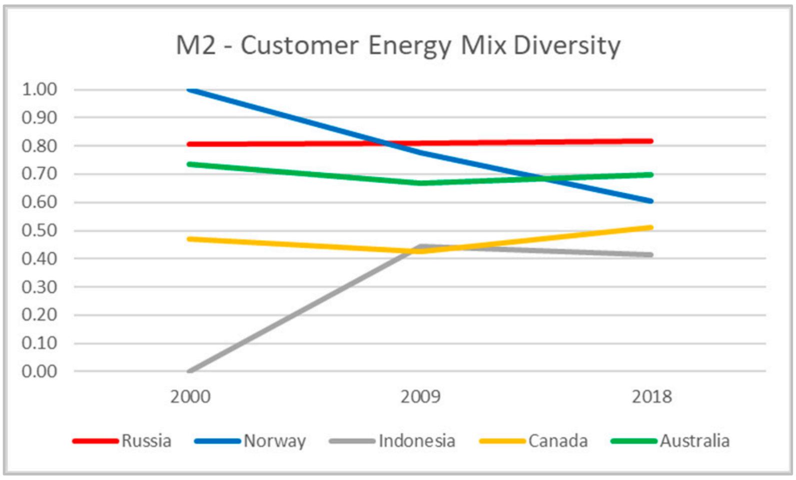


Figure 9. Customer Energy Mix Diversity (M2).

In Figure 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 USA exports 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 worse carbon emissions reduction rating than the UK.

Over the period studied, Figure 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.

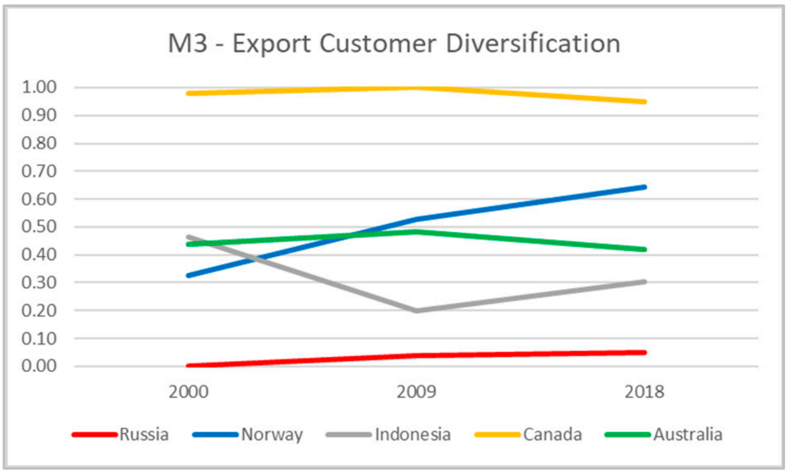


Figure 10. Export Customer Diversification (M3).

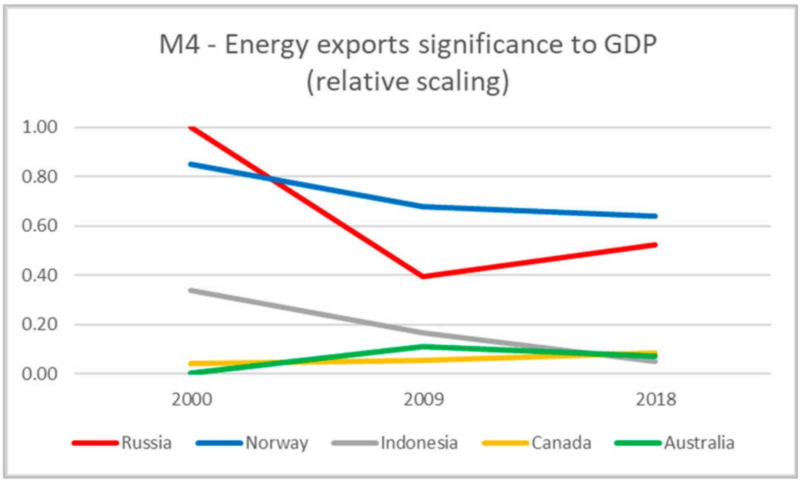


Figure 11. Energy Exports Significance to GDP (M4).

The clear messages from Figure 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.

According to the data for carbon intensity of each country's export blend shown in Figure 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.

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:

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

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

Table 17 and Figure 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.

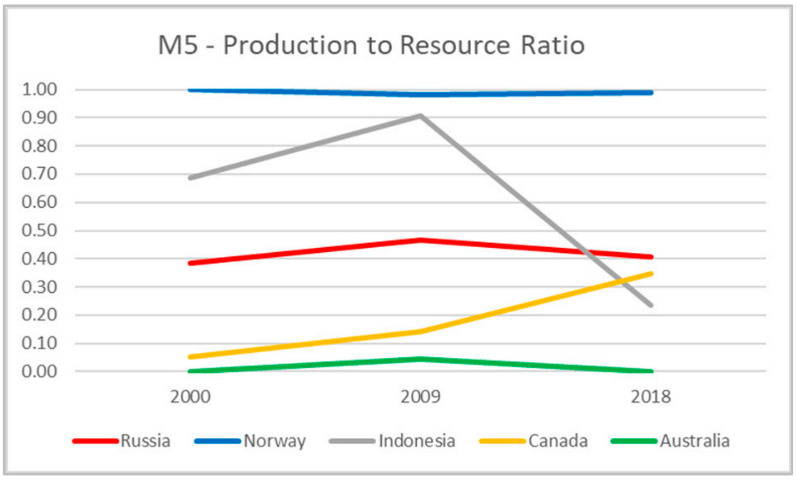


Figure 12. Production to Resource Ratio (M5).

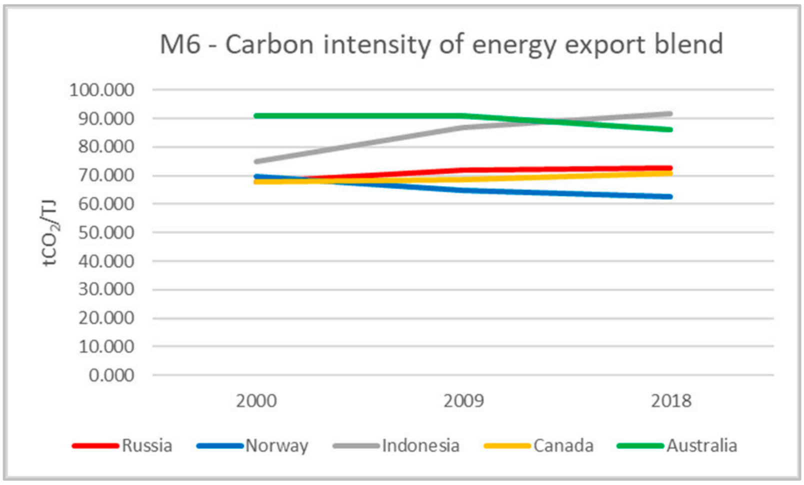


Figure 13. Carbon Intensity of Energy Export Blend (M6).

Table 17. M.Ext for Case Study Countries.

	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

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.

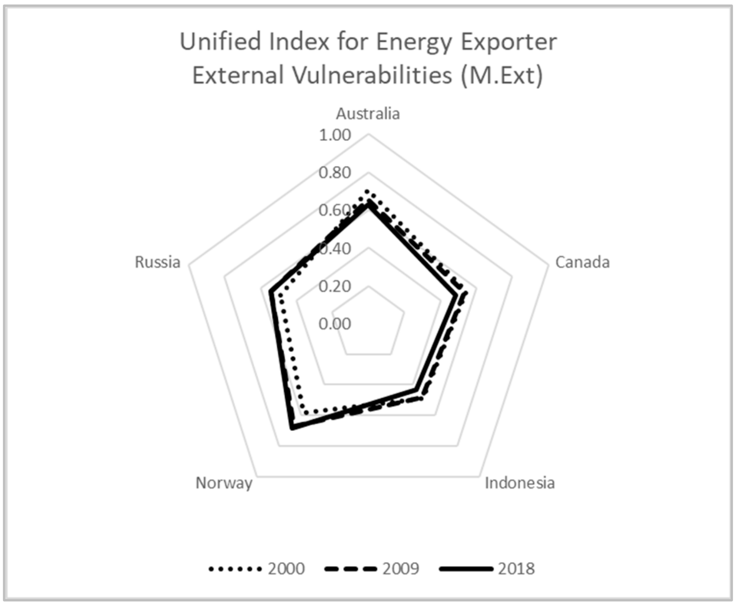


Figure 14. M.Ext for Case Study Countries.

Table 18 and Figure 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 18. M.Int for Case Study Countries.

	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

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.

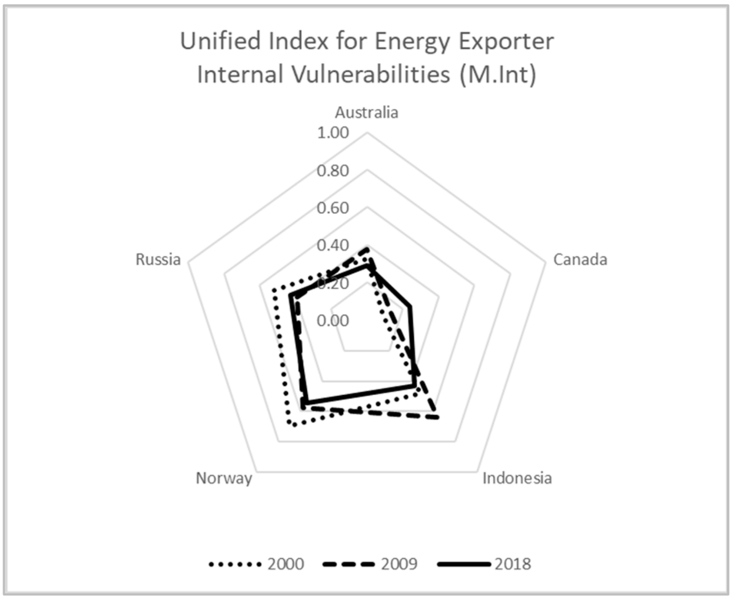


Figure 15. M.Int for Case Study Countries.

Finally, a single unified index for energy exporter economic vulnerability, M.V can be calculated by combining M.Ext and M.Int. 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.

$$M.V = [M.Ext \times eF] + M.Int$$

where;

Energy export exposure factor, eF = 1 + (E_E/E_P), shown in Table 19.
E_E = the country's combined energy resource exports in PJ
E_P = the country's total energy resource production in PJ

Table 19. Energy Export Exposure Factor (eF).

	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 paper.

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

Table 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

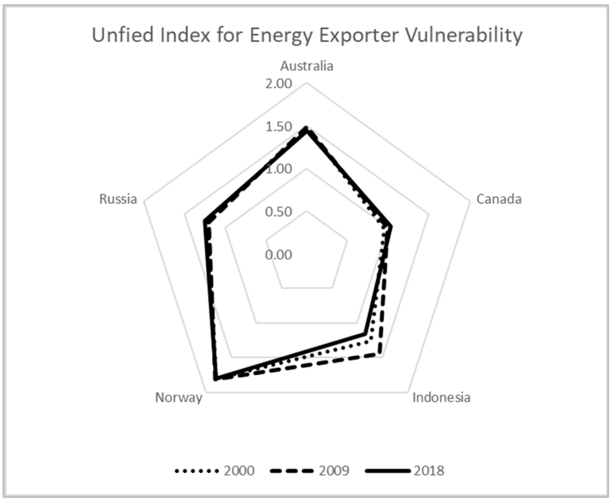


Figure 16. M.V for Case Study Countries.

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.

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. We have 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.

6.1. Limitations of the Framework

While attempting to provide a comprehensive method for quantitative assessment of energy resource exporter economic vulnerability, this study nonetheless recognises a few limitations and shortcomings in the proposed approach.

The proposed framework implicitly considers energy resource production as an export-oriented activity and does not address the interaction with a country's domestic energy system. For example, natural gas production may be shared in a physically interconnected system between domestic gas users, electricity generators, and export customers. Although the framework proposed here focusses on loss of export revenue as the primary economic concern of energy producers, the linkages of exports to the domestic energy system can potentially create additional economic vulnerabilities that are not addressed in this paper.

The proposed framework set out in this paper anticipate that countries dependent on energy imports will act rationally to optimise their domestic energy security. Specifically, metrics M1 (customer energy import dependence) and M2 (customer energy mix diversity) anticipate exporter vulnerability reflect this assumption. However, this may now necessarily be the case and an importing country may take the policy direction to optimise their energy supplies for lowest cost of supply rather than balanced with energy supply security. It is also conceivable that due to the extent of established energy supply infrastructure the cost to diversify the energy mix for electricity generation is not considered worth the benefit of increased energy security. A country may also prefer to rely on imported fuels rather than develop production of higher cost domestic resources. Any of these or similar considerations on the customer side would potentially reduce the effectiveness of some of the metrics in this framework in evaluating the exporter's vulnerability.

Finally, notwithstanding the detailed analysis presented in this paper, spill-over of non-energy related geopolitical issues into international trade in energy resources is a significant vulnerability for any energy exporter. The imposition of trade sanctions or trade embargoes, planned over-production to depress pricing, or even the disruptions caused by armed conflicts can all cause considerable disruption to both customer demand and the economic value of exports, thus representing vulnerabilities for exporters. Evaluation of geopolitical risk is however intentionally excluded from the scope of this paper.

6.2. Policy Recommendations

The assessment framework presented here is designed to contribute to the development and evaluation of economic policies and planning of energy production projects. It is proposed that at the very least any energy-exporting country can benchmark their performance across the six metrics with comparable countries, look for areas of comparative weakness, consider why others perform better and assess the potential applicability of other countries practices.

This paper presents an expanded understanding of energy exporter carbon risk by including two new assessment methods, metric M2 (export customer diversification, weighted by the customers CO_2 emissions reduction rating) and M6 (carbon intensity of the energy export blend).

The policy implication for all countries economically dependent on fossil fuel exports is clear; that the global energy transition to a net zero greenhouse gas emitting future is not a question of if it will affect export revenues, but when, and how quickly the change will occur. The metrics set out in the framework in this paper can guide policy makers to understand their level of dependence on fossil fuel export revenues, and how sharp that transition may be if not carefully managed while being under no illusions that energy transition is not only an energy user process, but will also cause monumental changes for energy exporters.

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