Energy Security Indicators

EnergiaTurva

Work Package 1

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Abstract

This report provides a comprehensive review of global energy security indicators, tracing the evolution of the concept from early supply-focused definitions to today's multidimensional frameworks. As noted in the document, *"energy security (ES) lacks a universal definition because of its multidimensional character"* and modern approaches increasingly integrate environmental, social, technological, and political factors. The study synthesizes major evaluation methods, including supply-oriented metrics, composite indices, and advanced statistical techniques such as PCA, highlighting how indicator sets have expanded from a handful of variables to more than 300 in recent literature. Emphasis is placed on the Global Energy Security Index developed by Azzuni and Breyer, which incorporates 15 dimensions, 50 parameters, and 76 indicators to address gaps in transparency, weighting, and global comparability. The report also reviews sector-specific frameworks, such as agricultural energy security, and discusses methodological challenges in data collection and normalization. Overall, the analysis demonstrates that energy security is an inherently complex, interconnected concept requiring holistic, quantitative, and adaptable assessment tools to support national and international policy planning. As the document states, *"the above dimensions are interrelated and are not completely independent,"* underscoring the need for integrated evaluation approaches.

Keywords

Energy Security Indicators

Contents

1. Introduction

Energy security research is limited before 2001 but has since become a major topic because energy underpins economic growth, society and modern life (Azzuni and Breyer, 2020). Since energy affects nearly every aspect of daily functioning, strengthening energy security is seen as a core societal goal, supporting both national stability and individual well-being. Energy security (ES) has become a critical international issue for countries around the world and a central factor shaping the economic growth (EG) of nations and regions, global standing, and overall development (Winzer, 2012).

2. Energy security Indicators on Global level

Energy security (ES) lacks a universal definition because of its multi-dimensional character. The broader concept of energy security, expanding beyond supply to include sustainability, environmental impact, and social stability, emerged as researchers and policymakers recognized that modern energy systems must address more than availability alone. The widely accepted "4A" framework defines it through availability, accessibility, affordability, and acceptability, four interrelated dimensions that interact rather than operate independently (APERC, 2007). Studies note that by the late 1990s, the idea that energy security should incorporate safety of energy use and environmental sustainability was already gaining traction, and this trend continued into the 2000s as global concerns about climate change and social resilience grew (Li et al, 2019).

Common energy-security assessment methods show two main approaches (Radovanović et al., 2016), namely:

1. **Supply-oriented**, which focuses on short-term security of energy procurement and transport but excludes social and environmental factors;
2. **Composite indices**, which combine multiple indicators with weighting to reflect their different impacts and urgency levels.

2.1 Global Energy Security Index and its Application on National Level

Radovanović et al. (2016) developed a new energy security indicator called to capture long-term sustainability. They tested it across 28 EU countries from 1990–2012, assessing the influence of six key factors on energy security. The proposed "Energy Security Index" differs by explicitly incorporating both environmental and social dimensions.

2.1.1 Evaluation of three ES dimensions (SESD, SEUD, SPED) (Wang and Zhou, 2017)

Wang and Zhou (2017) presented an energy-security evaluation method that integrates subjective and objective weighting (SOWA) and a balance score matrix (BSM) to assess how well countries manage trade-offs across three competing ES dimensions, namely

i) Security of Energy Supply–Delivery dimension (SESD): the major factors of energy availability and infrastructure.
ii) Safety of Energy Utilization dimension (SEUD): fair access to energy services and environmentally sustainable energy use
iii) Stability of the Political-Economic Environment dimension (SPED): reflects a country's political and socioeconomic strength and how these factors influence energy policy and investment.

The results showed that most countries struggle to build a well-balanced, secure energy system. The framework helps quickly identify weaknesses across ES dimensions and provides targeted recommendations for improving national performance. clustering countries into categories.

2.1.2 **Comparison of literatures on energy security evaluation (Li et al, 2019).**

Energy security has shifted from a single-focus idea to a multi-dimensional concept. It now includes availability, infrastructure, prices, social and economic impacts, technology, environment, governance, and efficiency. Research has mainly centred on major energy-consuming regions such as China, the United States, and the European Union.

Li et al. (2019) and Radovanovic et al. (2016) claimed that common evaluation methods include about ten widely used composite indexes, as follows

1. *Herfindahl–Hirschman Index* (Brezina et al., 2014): is a supply-oriented method that clarifies the degree of the dependence on a particular supplier. It can be used as an indirect indicator for energy security of a country.
2. *Shannon–Wiener Index* (Phdungsip, 2015; Omayio and Mzungu, 2019).
3. *Supply/Demand Index* for Long-term Security of supply (Scheepers et al., 2007; Vazquez et al., 2002; Haas et al., 2025): is a composite indicator that comprises a number of individual indicators and considers the characteristics of demand, supply and transport.
4. *Oil Vulnerability Index* (Gupta, 2008; Eshita, 2008): considers certain economic indica- tors, import dependence and political stability, in a range of values between 1 and 100.
5. *Vulnerability Index* (Von Hippel, 2011; Svidler, 2023): is a composite indicator that considers five different indicators on a scale of values between 1 and 100: i) energy intensity, ii) energy import dependency, iii) ratio of energy-related carbon emissions to Total Primary Energy Supply (TPES - calculated for whole nation-states and globally iv) electricity supply vulnerability and v) non diversity in transport fuels.
6. *Risky External Energy Supply* (Blyt et al., 2004; Musteala, 2013): considers only evaluation of diversification of energy generating products transport safety.
7. *Socioeconomic Energy Risk* (Flanagan et al., 2011; Bompard et al., 2017): is a composite index that considers: i) energy sources diversification, ii) energy resources availability, iii) feasibility, iv) energy intensity, v) energy transport, vi) energy dependence, vii) political stability, viii) market liquidity and Gross domestic product (GDP).
8. *U.S. Energy Security Risk Index* (US chamber of Commerce (2019): is a complex composite index based on 83 individual indicators evaluating i) geopolitical indicators, ii) economic development, iii) environmental concerns and reliability
9. *IEA's MOSES* (Measuring Short-term Energy Security (IEA, 2011, Jewell, 2011): It uses 35 supply-focused indicators covering short-term robustness (resource and infrastructure adequacy), sovereignty (exposure to foreign threats) and resilience (capacity to manage disruptions).
10. *International Energy Security Index*[1] (Badea et al., 2011): The most important parameters considered i) global fuel resources, ii) fuel import, ii) energy expenditure, iii) energy prices and market volatility, iv) energy intensity, v) energy transport and environmental concerns
11. *Global Energy Architecture Performance Index* (WEF, 2017).

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[1] International Index of Energy Security Risk, 2015 Ed. Washington DC: US Chamber of commerce; 2015.

The above dimensions are interrelated and are not completely independent, but are basically included in the four dimensions, namely supply stability, use safety, technical reliability and social and environmental sustainability. Li et al. (2019) applied **principal component analysis (PCA)** to condense many correlated energy-security indicators into a few uncorrelated components that capture most of the data's variance. This reduced redundancy and highlighted the main statistical dimensions shaping G20 energy security. Using historical trends and PCA-derived weights, they evaluated how each indicator influenced G20 countries over 24 years.

Li et al. (2019) also used a **SWOT analysis** to identify each country's strengths, weaknesses, opportunities, and threats in energy security. Below some related articles article are shown:

- Security of external energy supply (Le Coq and Paltseva, 2009).
- Supply and demand indices and their welfare implications (Lusk and Tonsor, 2021).
- EU Joint Research Centre's Energy Security Index,
- World Economic Forum's Energy Architecture Performance Index (EAPI) (WEF, 2017)
- A Long-Term and Global Energy Security Performance Evaluation Model (Wu and Yu, 2024)
- Energy & Climate Security Risk Index[2]

Yu et al. (2022) highlight that simple indicators capture only a narrow aspect of energy security, while composite ones incorporate a broader range of considerations. They argue that recent studies usually is around 20–30. A larger number of indicators, however, makes an index more complex and harder to compare because data collection becomes more difficult. According to wide variation exists in how energy-security (ES) indicators and indices are defined, with ES dimensions ranging from 1 to 20 and indicators from 1 to 320.

2.1.3 A comprehensive quantitative framework for ES (Azzuni and Breyer, 2017)

Azzuni and Breyer (2020) stated that the debate over the appropriate level of energy security has elicited numerous and varied answers, by e.g. (Azzuni and Breyer, 2017; Kanchana and Unesaki, 2014: Kumar, 2016; Lu et al., 2014: Phdungsilp et al., 2015). Every answer reflects the analytical frameworks, definitions, and dimensions used to evaluate energy security. They introduced an energy security index consisting of 15 dimensions and their associated parameters Azzuni and Breyer (2017). It was designed to overcome the following research gaps identified in previous studies:

1. Energy security is too multifaceted to be adequately represented by the current set of dimensions and parameters;
2. The methodology behind constructing the energy security index lacks transparency;
3. A lack of robust data or exclusive use of the suggested numerical indicators;
4. The index has been tested narrowly, either on a single geographic area or for a brief period of time;
5. All dimensions and parameters in the index are weighted equally, regardless of their relative importance;
6. The results are not translated into meaningful policy recommendations to improve energy security.

[2] https://ces.csd.eu/

Azzuni and Breyer (2020) emphasize the need for methods that reflect the multidimensional nature of energy security while also enabling objective, numerical assessment. They propose a comprehensive quantitative framework for an energy security index that is globally comparable yet adaptable to national contexts, covering all key dimensions of energy security. Their results show each country's overall performance and scores across 15 dimensions, including:

1. *Availability:* is a fundamental dimension of energy security. It concerns three parameters.
   - Existence of energy resources (e.g. oil, gas)
   - Access to energy sources (secure infrastructure, transport and technology needed to convert energy sources into energy services)
   - Existence of consumers or industrial use (demand perspective)

   Globally, energy resources, especially renewables, are abundant enough to meet long-term demand, although their geographic distribution is uneven. To build a sustainable future, universal access to energy (especially electricity) is essential for meeting individual needs. As population and development grow, demand is expected to keep rising, ensuring long-term 'security of demand'.

   Threats and risks: Threats to availability largely stem from limited access, which depends on infrastructure that remains vulnerable and can constrain overall energy security. Abundance can also create risks such as the resource curse (abundant energy resources tempt those in power to use them for personal gain. Other states may even try to seize control of valuable resources, leading to conflict) or Dutch disease (occurs when resource exports drive up a country's currency, reducing competitiveness and causing deindustrialization). Ultimately, availability is not about global scarcity but about how societies manage resources, access, and infrastructure.

   Indicators: Several numerical indicators can be used, such as the reserve-to-production ratio (Kruyt et al., 2009, Jansen, 2009), reserves per capita (Narula and Reddy, 2016), total resource estimates (Martchamadol and Kumar, 2012) or total energy resources per capita (Sovacool, 2011a). However, most of these metrics are tied to fossil-fuel systems and become less meaningful in a renewable-based future. Measures like final energy consumption per capita (Kanchana and Unesaki, 2015) are more relevant going forward. Ultimately, abundant global energy resources shift the question from scarcity to how humanity chooses to manage them.
2. *Diversity;* is a core element of energy security. Main parameters are
   - diversity of fuels (energy carriers)
   - diversity of sources
   - diversity of means to make the energy available to end-users ((technologies, transportation)
   - diversity of consumers (e.g., markets and sectors).

   Security comes from variety. A system with multiple fuels, sources, technologies, transport routes, and consumer markets is far more resilient because failures in one area can be absorbed by others. However, diversity must be balanced with cost, compatibility, and environmental impacts. Renewable energy generally strengthens diversity.

Threats and risks: Total self-sufficiency does not guarantee energy security, nor is dependence inherently a threat. The core dilemma is that full independence reduces diversity and increases vulnerability to accidents, strikes, or unforeseen environmental impacts. Moreover, many components of the energy system still need to be imported. An optimal, well-balanced energy mix is the preferable approach.

Indicators: Common indicators used to assess diversity's contribution to energy security include the mix of energy sources in total primary energy supply, electricity generation and transport (Jewell et al., 2014), the Herfindahl–Hirschman (HH) Index adjusted for political risk (Narula and

Reddy, 2016), energy trade relative to GDP, import dependency (Haghighi, 2007); the Shannon–Wiener Index (Phdungsip, 2015); and the share of renewables in the energy system (Jansen, 2009).

3. *Cost:* The cost dimension is often reduced to affordability, but it includes several factors.
   - Energy price (consumers, producers, pricing system/subsidies, energy poverty, peak oil, and stability/volatility)
   - Cost of energy security in terms of supply disruption
   - Investments that are needed to make systems more secure

   Ultimately, renewables offer a more stable, long-term, cost-effective path for strengthening energy security. The full cost of energy security must be evaluated across all dimensions, not just the price of disruptions.

   Threats and risks: Among the cost-related threats, price volatility is a major risk because rapid shifts make it difficult to assess failure probabilities. Energy poverty is another concern, as it can fuel internal unrest.

   Indicators: Jun et al. (2009) attempted to create a cost index but had to narrow their definition, leaving many factors unaccounted for. Other useful indicators include capital stock renewal costs, GDP impact per percent change in energy prices (Koronov, 2014), price volatility (Narula and Rerry, 2016), market costs of energy in €/MWh (Franki and Viškovi, 2015) carbon-price–related costs (Jansen, 2009), and the value of lost load (VoLL) (Rutherford et al., 2007).
4. *Technology and Efficiency:* Technology strongly shapes energy security. It has direct or indirect relationships to three dimensions
   - New technology advancement. New technologies for producing, transporting, storing, and converting energy expand available options and improve system resilience.
   - Energy system efficiency. Efficiency improvements also strengthen security by reducing energy needs, especially when paired with a shift to renewables, which eliminates large losses from fossil and nuclear systems.
   - Energy intensity, the amount of energy required to produce one unit of GDP.
   - Energy conservation

     Threats and risks: However, technological progress can also introduce risks, such as nuclear proliferation or rebound effects, so its benefits must be evaluated carefully.

     Indicators: Quantifying technological and efficiency improvements is challenging, but several indicators are used. These include R&D spending (Sovacool, 2013), the share of equipment past its service life (Koronov, 2014), electricity distribution losses (Sovacool, 2013), and, most commonly, energy intensity (Erdal et al., 2025; Gnansounou, (2011).
5. *Location:* Studies on energy security vary widely in scope (from local to global, urban to rural, and national to international) depending on the specific objectives of each inquiry. Energy security extends beyond national boundaries and must also be understood as a regional concern. Policymakers tend to focus primarily on national energy security. As a result, a broad range of parameters must be considered.
   - Energy system boundaries: for identifying the control area under study and the area affected by the system.
   - Location of energy source: Energy resources can undermine energy security depending on where they are located. Their accessibility also varies leading to different costs of extraction and supply.

- Density factor (centralized/decentralized): Density can help or harm energy security. Concentrated systems are efficient but vulnerable targets, while decentralized renewable systems face fewer risks and offer stronger overall security.
- Land use: Deforestation, land degradation, and waste storage show how energy production harms land and communities. Conflicts also arise from nuclear waste sites and NIMBY attitudes, as people oppose energy facilities near them, due to risks, misinformation, or uneven benefits. The LULUCF Regulation will introduce a new accounting system in 2026, giving each Member State a four-year emissions-removals budget for 2026–2029 to guide progress toward its 2030 target. Until the end of 2025, countries must still meet the "no-debit" rule, ensuring sectoral emissions do not exceed removals. According to the new Land Use, Land-use Change and Forestry (LULUCF) Regulation (EU, 2023: COM, 2024), new rules will apply from 2026 regarding emissions and removals. Reporting covers carbon pools in biomass, dead organic matter, and soils, as well as land-use changes such as deforestation or conversion of grassland. Forests provide most removals, while cropland and land-use change generate most emissions. Wetlands will be added as a reporting category in 2026.
- Globalization: Global energy interconnection can improve security, but it complicates control across national borders. Some research shows that decentralized renewable systems can function without global energy trade, reducing related risks.
- Population settlement and distribution: People used to settle near energy sources, but today energy is transported to population centres. This long-distance interconnection increases energy-security risks.
- The geography of the location: Strategic chokepoints like the Strait of Hormuz (20% of the global crude oil trade) and the Strait of Malacca (where 80% of Japan and Korean oil passes and 30% of shipped oil around the world) heighten disruption risks due to dense traffic and limited route options. Concentrated fossil-fuel infrastructure also increases vulnerability, as large power stations have complex failures and are harder to repair.
- Industrial intensity: Energy-intensive industries are highly vulnerable to disruptions, so spreading them across regions or countries lowers economic risk and improves energy security.

Threats and risks: The threat of disruption is higher in smaller areas. Thus, high traffic density and less diverse rout options with more military deployment reduce energy security. On the other side, during World War II, America managed to find plenty of different routes to supply Europe with energy through the wideness of the Atlantic Ocean. Further and apart from the military consideration, dense energy industry is a threat to energy security, 97% of mankind's industrial production comes from fossil fuel. Larger power stations tend to have complex failure modes, more difficult repairs and higher unit costs of spare parts. The last parameter is industrial intensity. Energy intensive industries are vulnerable to energy disruption. Therefore, redistributing energy intensive industries within a country or to other countries reduces the risk to the economy and increases energy security.

Indicators: Many indexes can be used to evaluate the location's effect on the energy security such as nuclear waste per m2, environmental footprint of energy facilities or the distance for energy delivery from suppliers to consumers (Le Coq and Paltseva, 2009).

6. *Timeframe:* This dimension concerns how energy security is viewed over time. Should it be assessed in the short term (a year or less) or over very long horizons (centuries)? Short-term issues tend to interest private stakeholders and policymakers, while long-term concerns matter more to analysts and strategic decisionmakers. Yet today's energy choices have long-lasting effects on

how energy will be produced, stored, and used. Because the future energy system will differ from today's, long-term security depends on managing present risks. Sovacool (2011b) identifies three time-related parameters:

- Timeline. whether we look forward or backward: where to see the current energy system in relation to the timeline. Looking backward helps explain how the current system emerged; looking forward helps anticipate future needs.
- Length of event, how long an event takes to cause an impact: Slow, sustained pressures (like rising import prices) affect the system differently than sudden shocks.
- Length of effect (struggle or impact). Some impacts persist long after the triggering event, for example, the 1973 oil embargo led to the creation of the International Energy Agency (IEA), whose influence continues.

Using the wrong timeframe can distort analysis. Because energy investments are long-lived, consumers must stay engaged to prevent declining security.
Threats and risks: Threats require both short-term responses (such as emergency stock coordination) and long-term strategies (diversification, flexibility, efficiency). *Indicators:* for choosing an appropriate timeframe may include life-expectancy index (Ürge-Vorsatz et al., 2012), technology cycle (WEC, 2008), or timely bilateral agreements.

7. *Resilience:* Resilience in energy systems is the ability to keep functioning during and after disruptions. It means maintaining the same core services, structure, and performance even when shocks occur. A resilient system has diverse energy sources, so if one fails, others can replace it. It can switch between suppliers, fuels, technologies, and even customers. Resilience also depends on emergency stockpiles (like batteries, hydro reservoirs, or oil storage), spare capacity, and infrastructure that can quickly shift to alternative fuels or equipment. Producers need backup capacity to increase output when demand spikes.
   Threats and risks: There are two forms of resilience: Passive (withstands shocks and returns to normal) and active (adapts, learns, and improves after disturbances). *Indicators:* Several indicators can be used to assess resilience, including emergency stockpiles, capacity margins, backup production and storage, national emergency plans, the Resilience Capacity Index (RCI), and metrics such as the ratio of total primary energy supply to GDP.
8. *Environment:* The environment is a key dimension of energy security. It involves five main factors:
   - *Energy resources, rate of exploitation, and location shape after exploitation:* Resources must not be exploited faster than they regenerate; overuse harms ecosystems and reduces long-term security. Human activity already exceeds Earth's capacity, contributing to the Anthropocene. Many energy resources are hazardous and degrade land, climate, and food production.
   - *Extraction and transportation methods***:** Energy extraction and transport should avoid environmental damage. Examples include oil spills, bird deaths from turbines or concentrated solar power (CSP), radioactive waste from nuclear power, and pollution from fracking.
   - *Outcome of the energy usage - environmental impacts of energy use:* Energy systems produce CO_2, greenhouse gases, air pollution, heavy metals, water contamination, acid rain, and ozone-depleting emissions. Lower environmental harm increases energy security. Ecological footprint measures the pressure of human consumption.
   - *Effect from climate conditions and climate change on the energy security:* Climate change affects energy systems through storms, floods, sea-level rise, and resource disruption. While some effects may be beneficial (e.g., reduced heating demand, new sea routes), negative impacts overwhelmingly dominate, threatening infrastructure, societies, and stability.

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- *Energy–water nexus (interdependence between water and energy):* Energy production needs water, and water supply needs energy. A secure system balances both. Research explores solutions like renewable-powered desalination.

Threats and risks: Environmental threats include climate change, poor adaptation, and ignoring the environment–energy link. Since all energy production affects nature, the environmental dimension must be part of energy security.

Indicators: Many indicators can be used to assess the environmental dimension of energy security. These include generation of energy related radioactive waste, lifecycle carbon emissions, or water withdrawals per kWh (Sovacool, 2011a), water stress (WEC, 2013), CO^2 emissions per capita (Phdungsilp, 2015) and carbon intensity, i.e., CO^2 production per kWh consumed (Badea et al., 2011; Grigoroudis et al., 2015).

9. *Health:* Energy security is closely tied to human health. The health dimension has two main parts*:*
   - *How health affects the energy system:* Healthy workers in energy production and transport are more productive, miss fewer workdays, and reduce healthcare costs, making the energy system more efficient and secure. Healthy consumers also use energy more effectively, and healthier societies can invest more in sustainable technologies that strengthen energy security.
   - *How the energy system affects health of individual and the society*: Energy systems can harm workers, consumers, and society. Workers face risks from nuclear radiation, coal mining diseases, toxic emissions, and accidents. Consumers exposed to fossil-fuel pollution suffer from respiratory problems and long-term illnesses. Society is affected by pollution, radioactive waste, and major accidents like Chernobyl and Fukushima. Globally, current energy systems contribute to over 5% of health problems and millions of deaths each year, weakening social stability and energy security.

   Threats and risks: The main threat is the low awareness of how health and energy security are connected, leading to inaction. Without addressing climate change, 30–170 million more people may face malnutrition by 2080; while solving it could save billions in healthcare costs. Many researchers point to renewable energy as the key solution.

   Indicators in this dimension are health spending per capita with the United Nation Human Development Index (WEC, 2008), the infant mortality rate (IMR) (Reddy, 2015) or emission per capita (Epstein et al., 2011; Buonocore, 2016).
10. *Culture:* Culture is an important part of energy security because it shapes how people produce, distribute, and consume energy. Cultural factors influence decisions such as accepting new energy laws, supporting renewable projects, or prioritizing certain consumers. Energy poverty, political movements, and materialistic values can all affect how energy systems function. Energy conditions also shape culture. The dimensions are
    - How cultures affect energy security: Human factors shape energy production, transfer, and consumption. Energy poverty can push harmful production, cultural events like the 1917 revolution can halt output, and nationalization affects security. Materialistic cultures may prioritize industry over the poor, while consumption varies by values, age, and social justice. Younger populations tend to support more sustainable, secure energy use. Cultural acceptance of new laws that enhance energy security (e.g., CO^2 tax),
    - How energy conditions can shape or change cultural behaviour: Resource discoveries, shortages, or disruptions can change social behavior, create conflict, or shift consumption habits. Wealthier societies generally achieve energy security more easily, while demographic trends (like younger populations) tend to support more sustainable energy use.

Threats and risks: The main threat in this dimension is psychological manipulation, especially through media that distorts facts.
Indicators: A common indicator used to describe cultural conditions is the Human Development Index (HDI) (Erdal. 2015).

11. *Literacy:* Knowledge and access to information are essential for energy security. Energy literacy requires that information is available, appealing enough for people to engage with, and used to support secure energy practices.
    - *Availability of information*: High-quality, accessible information and structured education programs help consumers and workers understand how energy systems function and how to use them efficiently.
    - *Presentation and spread of information:* Information must be communicated in ways that motivate learning. Government support, R&D funding, ecolabels, and programs like Japan's Top-Runner help people make informed choices.
    - *Use of information:* Educated individuals and trained workers contribute to a more secure energy system.

    Threats and risks: Major threats include workforce shortages, lack of market information, and policy failures driven by lobbying or corruption.
    Indicators: Indicators for this dimension include public resistance to new energy projects (Sovacool, 2011a), innovation research investment (Yao and Chang, 2014), or the number of courses related to energy in schools.
12. *Employment:* The link between energy security and employment runs both ways. An insecure energy system (especially when prices rise above affordability) can increase unemployment, as seen in past disruptions that caused large job losses. Stable and secure energy systems, by contrast, support higher employment. Employment also influences energy security. More jobs mean higher incomes, stronger purchasing power, and more resources for maintaining and improving the energy system. Millions of people work in energy production and transport, and having skilled workers is essential.
    Threats and risks: Poor working conditions increase risks and weaken energy security.
    Indicators: A suitable index for this dimension is employment in the energy sector (Sovacool and Mukherjee, 2011 and Chang, 2014).
13. *Policy:* Politics and energy security are deeply connected. There are three important parameters of policy that are pivotal for energy security, namely:
    - Political systems, their stability, and their foreign relations strongly influence how securely a country can produce, trade, and use energy. Democratic systems tend to reflect citizens' interests, while dictatorships often ignore social needs, weakening energy security. International relations, sanctions, and treaties also shape a country's energy stability.
    - Regulations form the second parameter. Energy policy can lean toward free markets or strong government control. Each approach has benefits and risks: free markets may encourage efficiency but also harmful resource use, while heavy regulation can correct market failures but sometimes distort incentives. Subsidies (especially for fossil fuels) are a major issue, often undermining long-term energy security. Reforming them can yield large economic and environmental benefits.
    - Governance (how policies are implemented). Poor enforcement, corruption, or decisions made against public will can undermine energy security, as seen in cases like unwanted nuclear projects or illegal waste disposal.

Threats and risks: The main threats in the policy dimension come from political uncertainty, corruption, and lack of transparency. These weaken energy security in both dictatorships (where energy revenues fuel corruption) and democracies, where lobbying and elite interests can override public will. Even when citizens strongly support renewable energy, political systems may fail to act. A second major threat is the manipulation of public opinion. Energy security is sometimes used to justify policies or even military actions that serve elite interests, a process known as securitization. This distorts priorities and undermines balanced, long-term energy security.

Indicators: Relevant indicators for this dimension include subsidy levels, regulatory standards (Jansen, 2009), transparency indexes, political stability measures, the World Bank's Worldwide Governance Indicators (IEA, 2007), and energy-efficiency standards (Reddy, 2004).

14. *Military:* The military often uses power to pursue strategic objectives, and energy plays a critical role in its operations. Their relationship involves multiple complex factors that must be examined.
    - Energy resources for military purposes
    - Militarization refers to the growing use of military force to influence energy security. Military operations often target energy systems directly to achieve strategic outcomes, and energy supplies have become a major driver of military conflict.
    - Use of energy as a means in a military conflict to achieve political objectives. Today, using energy as a political weapon has limited impact. Sanctions that block purchases from specific energy producers are also considered forms of the energy weapon.

    Threats and risks: Key threats in the military dimension come from how armed forces use and influence energy systems. Modern militaries consume large amounts of energy, and military actions (especially involving nuclear or environmental damage) can reduce overall energy security. Militarization of energy security is another risk. Conflicts over resources, attacks on energy infrastructure, and competition for control of energy routes have driven many wars. Energy can also be used as a political tool, such as export restrictions or sanctions. Energy systems themselves can destabilize societies, triggering unrest, civil wars, or terrorism funded by energy revenues. Securitization (framing energy issues as existential threats) can justify extreme military actions that overlook other dimensions of security. Post-conflict damage, terrorism, and the high economic and social costs of military operations further undermine energy security.

    Indicators: Indicators for this dimension include energy consumption for military purposes (Smil, 2004). and military expenditures (Stern, 2010).

15. *Cyber Security:* Modern energy systems rely heavily on digital infrastructure, making cyber security a critical part of energy security. Because production, transmission, and consumption are controlled by networked digital systems, cyber failures or attacks can cause major physical and economic damage. Three factors are identified to be pivotal.
    - *Connectivity*: energy systems linked to the internet face growing cyberattack risks, which are often easier and safer for attackers than physical sabotage.
    - *Software vulnerability:* Supervisory control and data acquisition (SCADA) and industrial control systems can fail on their own or be disabled by viruses.
    - *IT skills:* strong cybersecurity expertise strengthens energy systems, while skilled attackers can exploit weaknesses.

    Threats and risks: Key threats include outdated grid components, insecure smart meters, low awareness of cyber risks, and underreported SCADA vulnerabilities.

    Indicators: Indexes for assessing cybersecurity include the frequency of cyberattacks on the system and the economic losses caused by those attacks.

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Haghjoo et al. (2024) highlight that the growing energy demand in agriculture makes ES a priority, yet no precise tool exists to measure it. Their study identified agricultural energy-security indicators through content analysis, expert validation, and field research. Four dimensions, namely accessibility, availability, utilization, and sustainability, emerged by surveying 160 farmers. In total 18 indicators were selected.

Badea et al. (2011) and Radovanović et al. (2017) oversimplified the concept of energy security by relying on just 8 and 6 indicators, respectively. Azzuni and Breyer (2020) overcome this issue by incorporating 15 dimensions, 50 parameters, and 76 indicators. Their research assesses energy security globally in contrast to previous studies focused on one country or region.

2.1.4 Calculation of 76 ES indicators (Azzuni and Breyer, 2020)

Each dimension consists of parameters with corresponding indicators, which are measured or calculated. All indicator values are subsequently normalized and standardized to percentages based on global reference values, ensuring the index is globally applicable. These percentage values are multiplied by their respective parameter weights. Parameters that positively influence the ES index retain their value, while those with a negative influence are transformed by subtracting the indicator value from 100%. The weighted parameters (Yj × Wj) are then summed to obtain each dimension's value (Xi). Finally, the dimensions are aggregated using their weights (Vi) to produce the overall ES index. Detailed methodological descriptions for each dimension and its parameters are provided below.

Equation (1) outlines the overall index, whereas Equation (2) specifies the calculation for each dimension

(1)

$$\text{Energy Security index } = \sum_{i=1}^{n} V_i \cdot X_i$$

Vi → weight of each dimension;
Xi → value of each dimension.

(2)

$$X_i = \sum_{j=1}^{m} W_j \cdot Y_j$$

Wj → weight of each parameter: Yj → value of each parameter. Yj is calculated using either one indicator or an average of several indicators.

Equation (3) is used when there is more than one indicator for any parameter.

(3)

$$Y_j = \frac{\sum_{n=1}^{o} I_{n.Y_j}}{n}$$

In → normalized indicator for parameter Yj;
O → the number of indicators.

All parameters within a dimension receive equal weights (Wj) due to insufficient data for differentiated weighting; the same applies to dimension weights (Vi) in the ES index. Future evidence could justify specific weights for dimensions (Xi) or parameters (Yj). Many previous studies also use equal weighting when constructing energy-security indices. Indicators are typically normalized using the max–min method (Eq. 4) when they are not already expressed as percentages.

(4)

$$I_{n.Yj} = \frac{I_a + I_{min}}{I_{max} - I_{min}} * 100\%$$

In.Yj → the normalised indicator;
Ia → the absolute value of the indicator;
Imin → the minimum value in the world for Ia;
Imax→ the maximum value in the world for Ia.

Sometimes indicators are normalized using a linear-regression optimal–worst method when their relationship to energy security is more complex. Equation (5) shows how this approach modifies the max–min method in Equation (4). This alternative normalization is applied only to indicators that require it.

(5)

$$I_{n.Yj} = \frac{I_a + I_{worst}}{I_{optimal} - I_{worst}} * 100\%$$

In.Yj → the normalised indicator;
Ia → the absolute value of the indicator;
Iworst → the worst value in the world for indicator Ia;
Ioptimal → the optimal value in the world for indicator Ia.

If data for certain indicators are missing, those indicators are left blank and do not affect the calculation of their parameter. However, if a parameter relies on only one missing indicator, that parameter is assigned the worst value (0%).

The list of missing indicators is provided in the Supplementary Material.
Appendix A in Azzuni and Breyer (2020) provides the full methodology for defining each dimension, its parameters and indicators.

2.1.4 Energy security data collection

After the set of indicators is established, researchers begin collecting the corresponding data. After assembling all indicator values, they typically encounter three major challenges, each requiring different methodological responses. The first challenge concerns the unequal scales across indicators, which makes normalization essential. Prior studies have applied several normalization techniques, including min–max scaling (Gnansounou, 2008; Kamsamrong & Sorapipatana, 2014; Lefèvre, 2010), distance-to-reference methods (USChC, 2012), and standardization (Martchamadol & Kumar, 2012; Sovacool & Brown, 2010). Among these, the max–min approach remains the most widely used, as summarized by Ang et al. (2015).

3. Conclusion

Energy security has become a multidimensional challenge that extends far beyond traditional supply concerns. As the report highlights, *"energy security… lacks a universal definition because of its multidimensional character,"* reflecting the interconnected nature of modern energy systems. Contemporary assessment frameworks now integrate environmental, social, technological, economic, and political factors, acknowledging that *"the above dimensions are interrelated and are not completely independent."*

The literature shows that no single indicator can capture this complexity; instead, comprehensive composite indices and holistic models are required to identify vulnerabilities and guide policy. Strengthening energy security therefore demands long-term planning, diversified energy mixes, technological innovation, environmental protection, and informed public engagement. A multidimensional, data-driven approach is essential for building resilient, sustainable, and equitable energy systems in an increasingly uncertain global landscape.

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Appendix A: Dimensions, Parameters and Indexes of energy security ((Azzuni and Breyer, 2017).

Dimension	Parameter	Index
Availability	• Existence of resources • Access to energy sources (secure infrastructure, transport and technology needed to convert energy sources into energy services) • Existence of means of transport (access)	Reserve-to-production ratio (Kruyt et al., 2009, Jansen, 2009) Reserves per capita (Narula and Reddy, 2016) **Total resource estimates** (Martchamadol and Kumar, 2012) Total energy resources per capita (Sovacool, 2011a) **Final energy consumption per capita** (Kanchana and Unesaki, 2015)
Diversity	• Diversity of sources • Diversity of fuel (energy carriers) • Diversity of means (technologies, transportation) • Diversity of consumers	Mix of energy sources in total primary energy supply Total primary energy supply, electricity generation and transport (Jewell et al., 2014) Herfindahl–Hirschman (HH) Index adjusted for political risk (Narula and Reddy, 2016) Energy trade relative to GDP Import dependency (Haghighi, 2007) Shannon–Wiener Index (Phdungsip, 2015) **Share of renewables in the energy system** (Jansen, 2009)
Cost	• Energy price (consumers, producers, pricing system/subsidies, energy poverty, peak oil, and stability/volatility) • Cost of disruption • Cost of securing the system	Capital stock renewal costs, GDP impact per percent change in energy prices (Koronov, 2014), Price volatility (Narula and Rerry, 2016) Market costs of energy in €/MWh (Franki and Viškovi, 2015) Carbon-price–related costs (Jansen, 2009) Value of lost load (VoLL) (Rutherford et al., 2007)
Technology and efficiency	• New technology advancement • Energy system efficiency • Energy intensity • Energy conservation	R&D spending (Sovacool, 2013) The share of equipment past its service life (Koronov, 2014) Electricity distribution losses (Sovacool, 2013), **Energy intensity** (Erdal et al., 2025; Gnansounou, (2011).
Location Energy	• Energy systems boundaries • Location of energy source • Density factor (centralized/decentralized) • Land use • Globalization • Population settlement and distribution • Geography • Industrial intensity	Nuclear waste per m2 Environmental footprint of energy facilities or the distance for energy delivery from suppliers to consumers (Le Coq and Paltseva, 2009)
Timeframe	• Timeline • Length of the event • Length of the effect (struggle or impact)	Life expectancy index (Ürge-Vorsatz et al., 2012) Technology cycle (WEC, 2008) Timely bilateral agreements
Resilience	• Adaptive capacity	Emergency stockpiles Capacity margins Backup production and storage National emergency plans Resilience Capacity Index (RCI) Ratio of total primary energy supply to GDP

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Environment	• Exploration rate and resources' location • Extraction and transportation methods • Outcomes from energy use • Impact resulting from environmental change • Relationship to water	Generation of energy related radioactive waste, lifecycle carbon emissions, or water withdrawals per kWh (Sovacool, 2011a) Water stress (WEC, 2013), CO^2 emissions per capita (Phdungsilp, 2015) Carbon intensity, i.e., CO2 production per kWh consumed (Badea et al., 2011; Grigoroudis et al., 2015)
Health	• Impact of people's health on the energy system • Impact of the energy system on health of (energy sector workers, consumers, and society)	United Nation Human Development Index (WEC, 2008) Infant mortality rate (IMR) (Reddy, 2015) Emission per capita (Epstein et al., 2011; Buonocore, 2016).
Culture	• Cultural effect on the energy system [production, connection, consumption, cultural acceptance (NIMBY] • Energy conditions shaping cultural aspects	Human Development Index (HDI) (Erdal. 2015). Hofstede's indexes (Hofstede, 19
Literacy	• Information availability (quality, market information, public awareness, and structured educational program) • Information presentation and provision • Usage of energy information	Public resistance to new energy projects (Sovacool, 2011a) Innovation research investment (Yao and Chang, 2014) Number of courses related to energy in schools
Employment	• Effect of energy security on unemployment rate • Effect of employment rate on energy security	Employment in the energy sector (Sovacool and Mukherjee, 2011 and Chang, 2014).
Policy	• Political system, democracy/dictatorship (nature, stability, citizen's will, and internal and external relationship) • Regulations (liberalized and controlled market, rules, and subsidies) • Governance (flowing the rules (transparency), following the rules selectively, not following the rules, • corruption)	Regulatory standards (Jansen, 2009) Transparency indexes Political stability measures World Bank's Worldwide Governance Indicators (IEA, 2007) Energy efficiency standards (Reddy, 2004)
Military	• Energy use for military purposes • Militarization • Energy as a mean in a military conflict (energy weapon) • Destabilization factor (resources curse, environmental deterioration, and economies of violence)	Energy consumption for military purposes (Smil, 2004) Military expenditures (Stern, 2010).
Cybersecurity	• Connectivity (Cyberattacks) • Software use (Supervisory control and data acquisition, SCADA, program failures) • IT skills	Frequency of cyberattacks on the system Economic losses caused by those attacks

Appendix B: Dimensions, Parameters and Indexes of energy security (for calculations) (Azzuni and Breyer, 2020).

Dimension		**Index**	**Unit**	**Normalization**
Availability	A_1 A_2 A_3	Total available resource of fossil fuel and potential renewables (IEA, 2016; Breyer et al., 2017). Population (UN, 2015). Number of airports (CIA, 2018).	TWh Persons Numbers	Max-min Dividing by the world's population Dividing by the maximum in the world
Diversity	D_1 D_2 D_3 D_4	Simpsons Diversity Index of sources (IEA, 2016). Simpsons Diversity Index of carriers (IEA, 2016). 1: Simpsons Diversity Index of Technologies (Farfan et al., 2017) 2: Simpsons Diversity Index of Transportation (Photius Coutsoukis, 2015). Simpsons Diversity Index of consumers (IEA, 2016).	Percentage Percentage Percentage Percentage	Already normalised Already normalised Already normalised Already normalised
Cost	Co_1 Co_2 Co_3	1: Diesel prices [Wagner, 2015] 2: Weighted average price of power demand [Breyer et al., 2017] Income at risk due to power outage (income loss) [WB, 2011; Nationmaster, 2018]. LCOE total [Breyer et al., 2017]	1:$/litre 2: €/kWh €/capita €/MWh	Dividing by the maximum in the world Dividing by the maximum in the world Max-min
Technology and efficiency	TE_1 TE_2 TE_3 TE_4	1: Number of patents in force by the filling office [WIPO, 2016] 2: Scientific and technical journal articles [WB, 2018a] Supply efficiency [Breyer et al., 2017] Energy intensity level of primary energy [WB, 2018b] (gasoline equivalent) Fuel economy [IEA, 2017]	Number Percentage MJ/USD_{2011} PPP GDP (Litres/100 km, WLTC	Dividing by the highest Already normalised Dividing by the maximum Max-min
Location Energy	Lo_1 Lo_2 Lo_3 Lo_4 Lo_5 Lo_6 Lo_7 Lo_8	Area [WB, 2018c] Distance between production and consumption [BP, 2017; DFT, 2018] Energy use per area [WB, 2017a] Terrestrial and marine protected areas [WB, 2018d] 1: Trade (% of GDP) [WB, 2017b] 2: KOF Globalisation index [60] Population density [UN, 2015, BT, 2017] 1: Number of countries with shared borders [CIA, 2018] 2: Seaports infrastructure [CIA, 2018] 3: Total renewable surface water [FAO, 2018] Industrial added values [WB, 2018e]	km2 km kWh/km2 Percentage Percentage Persons/km2 1: Number 2: Scored nr 3: m3/(year_km2 USD/km2	Dividing by the worlds area Max-min Dividing by the highest Dividing by the highest Already normalised Dividing by the largest country Dividing by the maximum Dividing by the second highest
Timeframe	T_1 T_2	Life expectancy at birth [WB, 2018f] 1: Electrical outages [Nationmaster, 2018] 2: Average weighted age of powerplants [WB, 2011]	Years 1: Days 2: Years	Max-min 1: Dividing by the maximum in the world 2: Max-min

	T_3	Number of years that are needed to achieve 100% renew. electricity output [WB, 2010; WB, 2015]	Years	Dividing by the maximum in the world
Resilience	R_1	Resilience Index [FMGlobal, 2018]	Percentage	Already normalised
Environment	E_1 E_2 E_3 E_4 E_5	Ecological footprint (number of earths required) [GFN, 2016] CO_2 intensity [WB, 2017b] Total GHG emissions excluding land-use change and forestry per GDP [WB, 2011; WRI, 2017] Temperature anomalies [NASA, 2017] Water stress [UN, 2017]	Number kg per kWh energy use $MtCO_{2eq}$/USD Celsius Percentage	Max-min Dividing by the maximum in the world Dividing by the highest in the world Dividing by the highest in the world Normalised, values>100% set to 100%
Health	H_1 H_2	1: Health expenditure [WB, 2017d] 2: Mortality rate, infant [WB, 2017e] Number of deaths attributed to cancer in population [WB (2017f]	1: Percent of GDP 2: Number Percentage	1: Optimal value 2: Dividing by the highest in the world Dividing by the maximum I the world
Culture	Cu_1 Cu_1	1: Poverty headcount ratio at national poverty line [WB, 2017g] 2: GINI index [WB, 2017h] 3: Population ages 15–64 [WB, 2017i] 4: Coverage of social protection and labour programs [WB, 2017j] Energy use per capita [WB, 2017a] Air transport, passengers carried per capita [WB, 2017k] Food supply (crops, livestock and fish) [FAO, 2017] Human Development Index [UNDP, 2018]	1: % of population 2: % of population 3: % of population 4: % of population kWh/capita Number per capita g/capita/day Percentage	Already normalised Already normalised Max-min Already normalised Dividing by the maximum in the world Dividing by the maximum in the world Dividing by the highest in the world Already normalised
Literacy	Li_1 Li_2 Li_3	Citable documents [SJR, 2017] 1: Expenditure on education as percentage of total government expenditure [WB, 2018g] 2: Research and development expenditure (percentage of GDP) [WB, 2017l] Percentage of tertiary graduates from science, engineering, manufacturing and construction programmes [UN, 2018a; UN (2018b]	Number Percentage Percentage	Dividing by the highest in the world Dividing by the highest in the world Dividing by the highest in the world
Employment	Em_1 Em_2	Employment in the power sector [Ram et al., 2017] Unemployment (percentage of total labour force) [WB, 2018h; Ram et al., 2020]	$Jobs/TW_{hel}$ Percentage	Max-min Dividing by the maximum
Policy	P_1 P_2 P_3	1: Democracy index [EIU, 2016] 2: Fragile States Index [FFB, 2016] 3: Political stability/absence of violence and terrorism (percentile ranking) [WB, 2018i] 4: Polity data series [CSF, 2017] 5: Human freedom index [CATO, 2016] 6: Freedom in the world [FdH, 2017] 1: Subsidies and other transfers (percentage of expense) [WB, 2018j] 2: Regularity indicator for sustainability (RIES) [Banerjee, 2016] 1: Rule of law [WB, 2018i]	1: Percentage 2: Score 3: Percentage 4: Score 5: Percentage 6: Percentage Percentage Percentage	1: Already normalised 2: Dividing by the maximum possible 3: Already normalised 4: Theoretical max-min 5: Already normalised 6: Already normalised Already normalised Already normalised

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		2: Corruption Perceptions Index (CPI) [TI, 2016]		
Military	M_1	Energy consumption in military sector [WB, 2017a; WB, 2018k]	kWh	Dividing by the maximum
	M_2	1: Military expenditure (percentage per GDP) [WB, 2018k]	Percentage	1: Max-min
		2: Active armed force (percentage of the population) [IISS, 2017]		2: Dividing by the maximum in the world
	M_3	1: Share of coal production to the world total [IEA, 2016]	Percentage	Dividing by the maximum in the world
		2: Share of oil production to the world total [IEA, 2016]		
		3: Share of gas production to the world total [IEA, 2016]		
	M_3	1: Energy imports, net (percentage of energy use) [WB, 2018l]		1: Dividing by the highest absolute
		2: Income from net exporting minerals classification [Hausmann et al., 2018]	USD	2: Dividing by the maximum in the world
Cybersecurity	Cy_1	Individuals using the Internet (percentage of population) [WB, 2018m]	Percentage	Already normalised
	Cy_2	Global cybersecurity index - technical [Brahima, 2017]	Score	Already normalised
	Cy_3	Global cybersecurity index - capacity building [Brahima, 2017]	Score	Already normalised

Appendix C: Security Parameters, Indexes and Description (Li et al., 2019)

Parameter	**Index**	**Index Description**	
Supply Stability	Self-sufficiency rate	The percentage of a country's energy consumption that is provided by its own production	+
	Reserve-production ratio	The ratio of remaining recoverable reserves to annual production	+
	The index of diversification of production	The higher the diversity index of energy production in a country, the richer the variety of energy production, the weaker the influence of various energy resources on the total energy supply, and the diversity of energy production contributes to the improvement of the stability of energy supply/demand.	+
	The proportion of fossil fuels in energy consumption	This index refers to the proportion of fossil energy in primary energy consumption. The larger the proportion, the less safe it is.	-
	The proportion of renewable energy generation	The index reflects the share of renewable energy in an area.	+
	Per capita installed capacity	Installed capacity generally refers to the rated capacity of the generator installed in a power station.	+
	External dependence	$ED = \sum_i (P_i) \ln P_i$ where P_i is the share of energy *i* import from country P in total energy imports. The bigger the index, the greater the concentration of energy imports, and the greater the impact on the overall energy security once the supply of energy suppliers is interrupted due to political, economic and other reasons.	-
Use Safety	Energy intensity	Ratio of energy use to economic or material output. At the national level, energy intensity is the ratio of total domestic primary energy use or final energy use to GDP.	m
	The index of diversification of consumption	The higher the diversity index of energy consumption in a country, the richer the types of energy consumption, the weaker the influence of various energy resources on the total energy demand, and the diversity of energy consumption contributes to the improvement of the stability of energy demand.	+
	Availability of energy on the international market	The index examines whether the domestic energy supply and demand gap can be met at a reasonable price through the international market	+
Technical reliability	Electrified rate	This index can reflect the electrification level of an area to a certain extent.	+
	The rate of line loss	The percentage of power consumed in the power network and supplied to the power network and is used to evaluate the economy of power system operation.	-
Social and environmental sustainability	Carbon intensity	Amount of carbon dioxide emitted per unit of GDP, and the level of carbon intensity does not indicate the level of efficiency. Generally, the index declines with technological progress and economic growth.	-
	The index of PM 2.5	PM2.5 refers to particulate matter smaller than or equal to 2.5 microns in diameter in the atmosphere, which is also known as luggable particulate matter. The higher the index value is, the more serious the pollution is. The negative impact of energy utilization is relatively large, which is unfavourable to the sustainable development of energy.	-

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