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ANALYSIS

# The impacts of shale gas supply and climate policies on energy security: The U.S. energy system analysis based on MARKAL model

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A B S T R A C T

**Shale gas development has grown in recent years in the U.S. This paper addresses the environmental and energy security issues associated with the shale gas boom in both a "business as usual" case and a variety of alternate scenarios. The paper examines the impacts of the shale gas supply on the U.S. energy security in the short and long-term future and will help guide policy making by identifying the extent to which climate policy can reinforce energy security objectives.**

**The U.S. and other high-income countries face several long-term challenges relating to energy. One is climate change and another, also highly complex and controversial, is energy security. Energy security refers to the robustness, sovereignty, and resilience of energy systems. Energy security and climate policy are frequently presented as two aspects of the same issue. This paper evaluates energy security under long-term energy scenarios and provides analysis to help maintain energy security while meeting other energy challenges. The framework considers vulnerability as a combination of risks associated with energy trade and resilience reflected in diversity of energy sources and technologies. We apply this framework to five scenarios modeled with MARKAL: reference, high shale gas reserves, restricted access to shale gas, $CO_2$ taxes that are equal to Social Costs of Carbon (SCC) and environmental regulation in power sector. Scenarios with high shale reserves and scenario with power sector regulations are associated with lower diversity of energy options. A few risks do emerge under $CO_2$ taxes scenario after 2030 that include potentially high inter-regional trade in natural gas and electricity and low diversity of electricity sources. Net import is lower in the high shale reserves scenario while diversity is higher in a scenario that limits the shale reserves development.**

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## 1. Introduction

Energy security means different things for different people. Stagliano [1] argues that various policy actors apply very different definitions: market advocates defined energy security in terms of reducing economic vulnerability to supply disruptions and price shocks [2]; environmentalists see the road to energy security through efficiency and reduced energy consumption, and energy producers look to increased domestic production to attain energy security.

In addition, the energy security literature is focused mainly on securing supplies of oil and gas [3,4]. Many existing studies present energy security concerns through the prism of the oil and gas trade and future resource scarcity [5–8]. Since the 1970s, energy analysts have generally agreed that the state's oil dependence puts national security at an increased risk. Many of the U.S. energy analysts considers achieving oil independence to be either impossible or undesirable [9–11] and a task force of the Council on Foreign Relations declared the feasibility of achieving energy independence is a myth [12].

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Yet, electricity, which now ranks second only to oil products in terms of final energy consumption, is the world's most dominant form of energy supply to the economy, making it critical to energy security [13,14]. Thus, Sullivan and Blyth [15] point out that the reliability of electricity systems is extremely important given the growing penetration of intermittent renewables, which require back-up generation capacity.

The reasons why the concept of energy security is widely used, despite the lack of consensus on its precise interpretation, is that there are multiple dimensions of energy security relating to the availability, accessibility, affordability and acceptability of energy. Currently the threats to energy security are broader and more complex than just concerns about oil import dependence. Therefore, there is no one ideal indicator, as the notion of energy security is highly context dependent.

The goal of this paper is to utilize a method for assessing energy security implications under different policy and technology choices. The objectives of present study are application of a coherent energy security concept that reflects historic, current and future energy security concerns; converting this concept into energy security indicators, and applying this assessment framework to the various scenarios. The next section addresses the energy security concept and framework that we applied for our study.

## 2. Energy security indicators

Translating this broad definition into energy security measurement is a challenging effort. One of the ways to assess the level of energy security is to use indicators. An energy security indicator is a special index that gives numerical values to important issues for the security of energy sector. Various indices measure energy security at the national and regional levels, estimating independence of the energy system and diversity of the energy mix and sources [16–18]. Two dimensions are common to these contributions: the availability and the affordability of energy. Two other, different dimensions are acceptability or sustainability and dependency or diversity.

Although many different types of energy security indicators are summarized in the literature [e.g., 16,17,19–21], we chose the quantified method for energy supply security that is contingent on the establishment of "efficient" diversified portfolios of primary and secondary energy sources. However, most of the quantified indices in the literature cannot be used to analyse energy security in long-term projections [see 20 and 22]. The exceptions are the Herfindahl-Hirschman index and the Shannon–Wiener diversity index[3] that are used in connection with long-term future energy security studies [see 22–24].

The standard Herfindahl-Hirschman index originally was used in industrial organization literature to evaluate market concentration and it equals the sum of the squares of each participant's market share. The Shannon–Wiener index has been a popular diversity index in the ecological literature and was originally proposed by Claude Shannon to quantify the uncertainty or information content in strings of text. The Shannon–Wiener index means that the energy system is more diverse and more secure with more different fuels in energy mix and with equal proportional fuels abundances [see Box 1]. The difference between the Shannon–Wiener and Herfindahl-Hirschman indices is that the Shannon–Wiener index puts relatively more weight on the impact of smaller market participants, while the Herfindahl-Hirschman index places more emphasis on larger suppliers [25]. We selected the Shannon–Wiener index because it reflecting both variety and balance in an even way.

[3] Shannon–Wiener diversity index is also known as Shannon's diversity index, the Shannon- Weaver index, and the Shannon entropy.

The Shannon–Wiener diversity index [26,27] is applied as a measure of primary energy supply security [e.g., 19,22,28] and electricity supply security [29]. A more diverse system is perceived as having a number of benefits that make it preferable to one that is less diverse. In particular, diversity contributes to achieving energy security since disruption of any one source will have a smaller impact on overall energy supply. In addition, increasing diversity is beneficial for an energy system through extending choice and increasing competition. Diversity could be achieved by a mix of fuel sources and by a preference for domestic over imported energy supplies. Since a direct presentation of multiple energy security indicators may be insufficient for energy security assessment, energy security studies often use compound indices to reduce the amount of data and increase the accessibility of the results of an energy security assessment, for example, through including a net import variable into the index's equation.

Thus, we use a relatively simple taxonomy to define security: resilience based on the degree of diversity of types of energy sources and independence of the energy system based on the degree of net energy import. The independence dimension is incorporated by limiting energy trade to a fraction of energy through Compound Shannon–Wiener Diversity Index. In addition, for electricity security we included into the Compound Shannon–Wiener Diversity Index a dimension of affordability based on the degree of marginal electricity costs' growth deviation (see Box 1 for details).

Box 1. Energy (Electricity) security indices.

The Shannon–Weaver diversity index reflects diversification of energy (electricity) supply and is calculated as follows:

(1) *SWDI* (*SWDIE*) $= -\sum(p_{ji*}\ln(p_{ij}))$, where $p_{ij}$ is the share of energy (electricity) fuel $i$ in total energy (electricity) supply in year $j$.

Measures of energy (electricity) trade (reflecting supply disruption concerns and resilience) and diversity (reflecting resilience concerns) can be aggregated into a single index called a compound *SWDI (SWDIE)*. This compound indicator differs from the simple *SWDI* by excluding the net imported energy in a diversity index:

(2) Compound *SWDI* (*SWDIE*) $= -(1-m_j)\Sigma(p_{ij*}\ln(p_{ij}))$, where $p_{ij}$ is the share of energy (electricity) resource $i$ in total energy (electricity) supply in year $j$, and $m_j$ is the share of energy (electricity) that is supplied by net imports.

Electricity price fluctuations (reflecting affordability and price volatility concerns), and diversity can be aggregated into an index called a compound *SWDIE*. This compound indicator differs from *SWDIE* by including deviation of electricity price growth from historical average into diversity index:

(3) Electricity Sector Compound *SWDIEP* $= -(1-m_j)\ \Sigma(p_{ij*}\ln(p_{ij}))_* exp(k-c_j)$, where $p_{ij}$ is the share of electricity resource $i$ in total electricity supply in year $j$, $m$ is the share of electricity that is supplied by net imports, $c_j$ is electricity marginal costs growth rates and $k$ is historical average electricity prices growth rate.

Compound indices have a limitation: if diversity and import dependency are within a moderate range of values and correlate with each other, the compound diversity index reduces the number of variables that need to be considered in the assessment. This index also can hide the trade-offs where diversity and import dependency tell different stories. The limitation of compound index with price