Leverage demand-side policies for energy security

Conventional supply-side approaches overlook potential benefits

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Energy security is a top priority for governments, companies, and households because energy systems and the critical functions that they support are threatened by disruptions from wars, pandemics, climate change, and other shocks (1). More often than not, governments rely on policies focused on energy supply to enhance energy security while generally ignoring demand-side possibilities. Further, the indicators traditionally used to measure energy security are also tilted toward the supply side; this fails to capture the full spectrum of vulnerability to energy crises. Energy security assessments need to reflect the wider benefits of security-related interventions more accurately. To that end, we develop a systematic approach to measuring the energy security impacts of policy interventions that explicitly considers energy demand (buildings, transport, and industry). We determine that demand-side actions outperform conventional supply-side approaches at making countries more resilient.

Energy demand links more directly than supply to the satisfaction of critical social functions and human well-being that are at the core of energy security. Yet, demand-side perspectives tend to be neglected or underrepresented in analysis and policy debates on energy security. Factors that contribute to this supply-side bias include the traditional sectoral organization of industries and policy institutions along fuels (coal, oil, and gas) and energy forms (electric utilities) as well as the decentralized and multivaried activities characteristic of energy demand (from vehicles to household appliances to manufacturing and more), which leads to a multitude of actors and institutional fragmentation. The basic fundamentals of energy systems and markets, where demand and supply are intricately linked, have also not yet risen from vague awareness to a central organizing principle among policy-makers for structuring the energy security discourse.

SUPPLY AND DEMAND IMBALANCE

The energy security literature describes a plethora of indicators and multi-indicator indexes. However, two-thirds of the indicators and more than 80% of the indexes focus on the energy supply side [see fig. S1 in the supplementary materials (SM)], aligned with the International Energy Agency (IEA) approach to define energy security solely as the security of energy supply (*2*). In addition, energy security analyses often rely on a small number of indicators, such as import dependency, diversity of energy sources (both produced and imported), or cost of energy imports as a proportion of gross domestic product (GDP) (*3*–*7*). In the few studies that also consider demand indicators of energy security [a noteworthy exception being (*8*)], these metrics are rarely quantified (see box S1 in the SM).

Not only is the structure of measures of energy security imbalanced, but the predominant indicators do not reflect the full picture. For example, a reduction in energy demand may leave a country's import dependence ratio unchanged—by simultaneously reducing both the volume of imports in the numerator and total energy consumption in the denominator. In this case, the unchanged ratio masks a marked reduction in the country's energy vulnerability—a smaller system being more flexibly satisfied from different sources—as well as benefits for the environment and trade balance.

Moreover, important gaps remain in the usage of indicators for energy security assessments. Some studies use scenarios for assessing future energy security (*9*). Others analyze the evolution of energy security in retrospect (*3*, *7*). To our knowledge, no assessment has yet combined scenario-based and historical analyses to determine the impact on energy security for different policy options. To be sure, demand-side indicators of energy security are neither perfect nor all-encompassing; still, they merit greater consideration for comprehensive energy security assessment.

FACTORS ENHANCING ENERGY SECURITY

Indicators used to measure energy security tend to emphasize supply diversification and substitution, costly storage, and redundancies in energy infrastructure. This overlooks the scale of vulnerability to energy crises; the benefits of energy demand reduction; and the energy cost burden to countries, firms, and households. Meanwhile, demand-side indicators more directly measure the satisfaction of individual needs and well-being because the focus is on access to and use of energy services. Examples of demand-based indicators of energy security include energy intensity of the economy (energy needed per unit of GDP), energy efficiency (the inverse of intensity), energy expenditures, and access to critical energy services (*10*). However, data availability can present a challenge to operationalizing the use of these indicators (*11*).

Illustrating the importance of including energy demand in energy security analyses, our analysis of Organisation for Economic Co-operation and Development (OECD) countries found a positive relationship [coefficient of determination ($R2$) = 11%, P = 0.08] between the ratio of energy expenditures to GDP and energy intensity (see fig. S2 in the SM). In other words, countries with higher energy intensity (less energy efficient) tend to face higher energy cost burdens. We also found a robust negative correlation between energy intensity and the Shannon diversity index—a supply-side measure based on the diversity of a country's energy sources—for a set of 20 countries and macro regions ($R2 = 48\%$, $P < 0.0001$, in 2014; $R2 = 56\%$, $P < 0.001$, in 2019; see fig. S3, A and B, respectively, in the SM) (*12*). Put differently, a discernible trend between higher efficiency and diversification is evident across several countries over the past century (see fig. S3C in the SM).

Such analyses, possible only by including demand-side indicators, help in gaining a deeper understanding of the factors that reinforce or jeopardize a country's supply security. Yet, to our knowledge, such analyses have not been central to the scientific or policy discourses for many years.

COMPARING ENERGY SECURITY POLICIES

Four stylized policy interventions aimed at enhancing energy security are devised and their effectiveness is compared across a range of security indicators. Each of these aim at the same target, an ~10% change (reduction or reallocation) in total primary energy (i.e., unconverted natural resource inputs, such as coal, oil or gas, uranium, wind, or solar). These interventions are targeted at one of several points along the energy conversion chain: primary (PE), final (FE) (energy converted and delivered to end users—e.g., electricity or refined petroleum in the form of gasoline for vehicles), and useful (UE) (energy actually put to the intended use—e.g., the light resulting from the electricity used by a light-emitting diode light bulb).

We use an accounting model based on physical energy flows that first calculates conversion efficiencies throughout the energy system from primary to useful energy for specific end uses (mobility, thermal comfort, etc.). The model then calculates changes backward from useful to final to primary—e.g., reflecting how reduced gas use to provide low-temperature heat (useful energy) would affect the primary energy balance for gas and the corresponding potential to reduce gas imports (see box S2 in the SM for more details about the method and data). The four policies analyzed are import diversification (PE 1), fuel substitution (FE 1), reduction of low-temperature heat demand in buildings (UE 1), and transport electrification (UE 2) (see box S3 in the SM for more details about the policies).

An additional, somewhat extreme scenario estimates the impact on energy security of ensuring only the most basic energy services that guarantee critical social functions (CSFs) (minimum thermal comfort in buildings, transport, illumination, etc.). The CSF scenario assesses the ultimate social vulnerability of countries to energy crises and illustrates the upper potential of demand-side policies that is far larger than in the four other scenarios examined.

Historical analogies help to put the stylized policy measures into context and to demonstrate the order of magnitude of interventions (see boxes S3 and S4 in the SM). On the energy supply side, Germany's reduction of imports from Russia since the start of the war in Ukraine is an example of rapid import diversification that involved around a third of primary energy (PE 1). The Brazilian ethanol program illustrates fuel substitution (FE 1) that reached an impact equivalent to 10% of primary energy. On the demand side, Germany's reductions of gas demand—mainly from buildings (UE 1)—saved 5% of primary energy in 2022. Sustained promotion of electric vehicles in Norway enabled a 10% reduction of primary energy in 2021, an example of the benefits of enhancing transport efficiency through electrification (UE 2). Similarly, the Corporate Average Fuel Economy (CAFE) standards in the US have saved more than 10% of primary energy over time (*13*). Finally, as an example of energy demand reduction from reduced activities, the COVID-19 response measures in the US led to a 7.5% decrease in primary energy in 2020 (*14*) (followed eventually by a rebound back to prepandemic amounts).

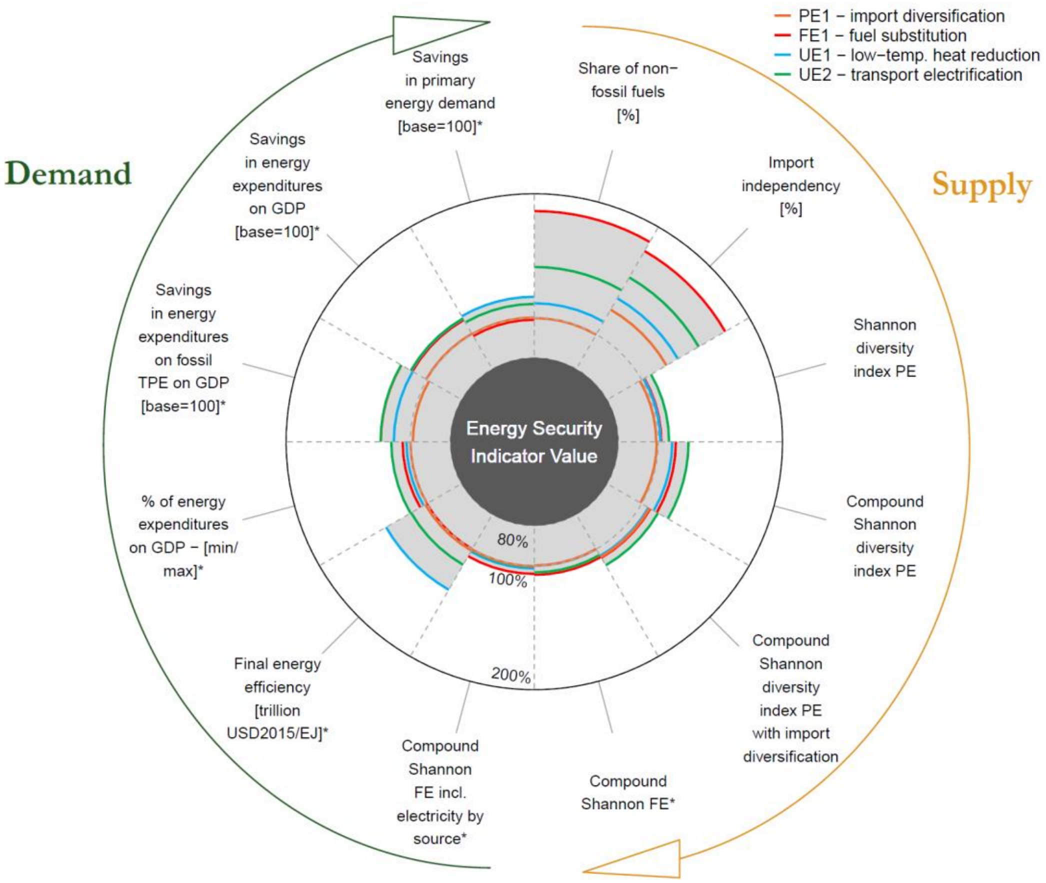
We use statistical data for a representative sample of 14 countries in 2019 to simulate the impact of the various policy interventions on national energy security. These countries account for two-thirds of global energy use in 2019 and include a diverse mix of high income and low income nations as well as energy importers and exporters (see SM). We quantify a set of 12 indicators of energy security from both demand and supply perspectives (see box S5 in the SM) to assess the impacts of each policy for each country. The choice of indicators followed three criteria: They must be representative, feasible to calculate, and complementary to each other. For example, four diversity indexes are included to assess different configurations of the energy system (e.g., different importing regions, different primary energy carriers, and different structures of energy demand).

To reach the same goal of changing 10% of primary energy, the four policies entail very different changes in energy flows at different points along the energy conversion chain (see the figure). A 10% change in primary energy (PE 1) required only a 9% change in final energy (FE 1) and only between a 5% and 3% change in useful energy level (UE 1 and UE 2, respectively), reflecting the corresponding conversion losses in energy systems. The difference is higher for exporting countries (see box S6 and fig. S4 in the SM). Overall, interventions at more-downstream levels benefit from a leverage effect by avoiding cascading losses in the successive stages of energy conversions.

The effects of the four stylized policy interventions for all indicators are presented separately (see the figure) for the average of the 14 countries in the assessment. Fuel substitution leads to the highest impact on only two indicators—the share of nonfossil fuels and import independency—confirming the bias against energy efficiency of these two popular energy security indicators. Demand measures score best in 8 of the 12 indicators, with transport electrification the most impactful (seven indicators). Import diversification is consistently the least effective intervention, despite being the most applied in Europe as a consequence of the Russian invasion of Ukraine.

National contexts influence the effects of the policy interventions (see the Table, as well as table S1 and fig. S5 in the SM). Transport electrification enhances energy security indicators the most (150 times) and only leads to worsening in 12 cases, whereas fuel substitution more often (29 times) deteriorates energy security, although it also improves it in 117 cases. Low-temperature heat demand leads to improvements in 137 cases and worsening in 23. Import diversification, although a commonly applied approach by governments, has a relatively muted effect—improvement in only 19 cases and worsening in nine.

Fig. 1. Impact of the policy interventions on enhancing energy security as shown by the 12 indicators. Indexed (base=100%). All policies aim at the same target (a 10% reduction in primary energy). Asterisk (*) identifies demand-side indicators.



Looking at four representative countries more closely (see fig. S6 in the SM), Japan and Australia (both high income economies) show a similar pattern, with transport electrification being the most effective policy. Meanwhile, Japan and China (both large energy importers) share more similar results than energy exporters such as Australia and Nigeria.

ROBUSTNESS OF DEMAND ACTIONS

An extensive sensitivity analysis that calculates every combination of the 12 security indicators (from 1 to 12 indicators in each combination; see fig. S7 in the SM) strongly supports the robustness of our conclusions. For example, there are only 6 of the 792 combinations (0.76%) that are possible to create with five indicators where fuel substitution is the most effective of the policies in improving energy security. Demand-side options and particularly transport electrification rank first in the remaining combinations.

Table 1. Effect of the policy interventions on 12 energy security indicators, in number of countries (n=14). Green shading indicates the number of countries where energy security improved based on the given indicator due the intervention (i.e., indicator value increases), red shading shows the opposite. Policy interventions appear in decreasing order of performance (i.e., improved indicators).

		Demand-side Policies		*Supply-side Policies*	
		UE 2 - Transport electrification	UE 1 - Low-temperature heat demand reduction	FE 1 - Fuel Substitution	PE 1 - Import diversification
SUPPLY INDICATORS	Share of non-fossil fuels [%]	14	9	14	-1
	Import independency [%]	13	9	13	0
	Shannon diversity index PE	8	6	5	0
	Compound Shannon diversity index PE	8	6	5	1
	Compound Shannon diversity index PE with import diversification	10	8	6	10
DEMAND INDICATORS	Compound Shannon FE*	11	3	9	-1
	Compount Shannon FE incl. electricity by source*	7	7	9	1
	Final energy efficiency [trillion USD2015/EJ]*	13	14	0	1
	% of energy expenditures on GDP - [min/max]*	14	13	13	-1
	Savings in energy expenditures on fossil TPE on GDP [base=100]*	12	11	10	-2
	Savings in energy expenditures on GDP [base=100]*	14	14	12	1
	Savings in primary energy demand [base=100]*	14	14	-8	1
	total (improved net of worsened)	**138**	**114**	**88**	**10**
	of which: total (improved)	150	137	117	19
	total (worsened)	12	23	29	9

Our multidimensional indicator and policy modeling framework also allows for testing alternative policies beyond the four described above. For example, when considering a representative energy importer nation, such as Japan, fuel substitution (FE 1) with hydrogen (also domestically produced) instead of biofuels leads to a similar level of impacts on energy security for all indicators but lower final energy efficiency and lower savings in energy expenditures (i.e., hydrogen increases primary energy use and energy costs). Similarly, rolling out heat pumps instead of insulation (UE 1)—in this case, an active measure in place of a passive one—to reduce energy demand for low-temperature heat for buildings in Japan would not ameliorate the energy security indicators (see fig. S8 in the SM). The variations of the policies tested in the sensitivity analysis confirm the robustness of the order of merit of the interventions: Demand-side policies generally have more and higher positive impacts on improving energy security compared with supply-side measures.

Assumptions for fuel substitution with biofuels are quite optimistic. For example, not every country has enough available biomass, not to mention the potential land-use conflicts with agriculture and environmental concerns. Yet, even under these assumptions, demand-side policies remain the top choice in most cases. It is also worth noting that the higher scores of transport electrification compared with reducing low-temperature heat demand in buildings benefit from our assumptions that the needed electricity for transportation comes from domestic renewable sources. If, instead, this electricity is generated from, for example, imported natural gas, the policy would be less efficient compared with other policies.

The overall ranking of policy options also holds when looking at key indicators beyond energy security, namely carbon dioxide emissions reductions (see fig. S9 in the SM). For the four archetypal policy cases analyzed, demand-side policies again outperform supply-side policies (0% for PE 1 and -11% for FE 1 against -12% for UE 2 and -13% for UE 1), even if the ranking order of transport electrification over heating demand reduction reverses. The ultimate potential of demand-side policies is illustrated in the (extreme demand reduction) CSF scenario (-67%).

CONCLUSIONS

Demand-side policies offer clear advantages for energy security improvement across many dimensions, including continuity, affordability, and sustainability. They also have advantages in terms of flexibility. Demand-side policies give more opportunities for intervention at the national level, relative to fuel substitution, for example, which requires international coordination. Energy security is more than security of supply because there are other economic, social, and environmental aspects that are also relevant. Future studies should compare the benefits of different energy security policies more systematically by including a demand-side perspective instead of relying on partial assessments and problematic indicators, such as import dependency. They could also expand to encompass a more comprehensive assessment of the social and environmental effects. This approach would contribute to a more nuanced understanding of energy security and inform more effective policy decisions on both a national and a global scale.

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SUPPLEMENTARY MATERIALS

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