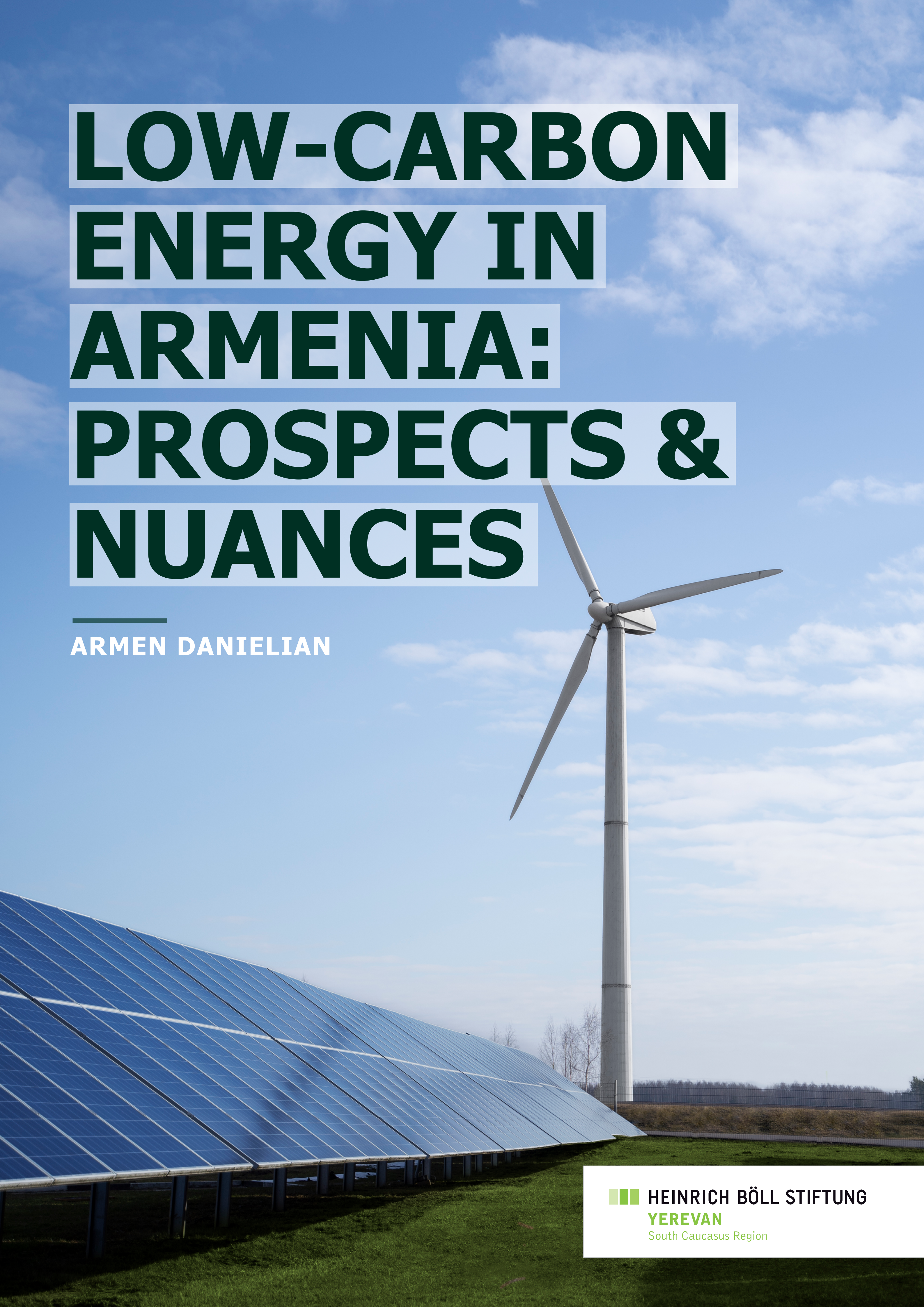

LOW-CARBON ENERGY IN ARMENIA: PROSPECTS & NUANCES

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Overview:

This article discusses the challenges of transitioning to low-carbon energy from an economic point of view, using the Armenian context for illustrations and examples. It draws attention to the varying nature of the costs and benefits that low-carbon energy sources can provide, depending on the particular contexts, systems, and extent to which a given source is utilized. Social, environmental, and system costs are discussed, among others. The article rejects the categorical designation of different energy sources (e.g. solar, wind, hydropower) as good or bad, encouraging rather to look at them incrementally. Separate attention is given to nuclear power as a special case. While the article does mention certain quantitative estimates of renewable energy potential from the existing literature, its main focus is on formulating the economic approach to the issue.

Photo on the cover by freepik

About the author:

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1 Introduction

Like many topics that involve national security and international relations (as well as large spending), energy is a highly politicized topic, and like in many other politicized topics, its issues are often discussed in categorical rather than incremental terms. For instance, energy sources may be categorized as “clean” and “not clean”, or “safe” and “unsafe”, when in reality these qualities are relative, not only in terms of how one energy technology compares to another but also depending on the extent to which a given energy source is utilized or exploited. Of course, we have to categorize to keep the discussion clear and concise; however, it is important to remember that there are rarely categorically “good” or “bad” solutions, and most of our choices involve trade-offs.

The first lesson of economics is scarcity - there are never enough resources to satisfy everyone’s desires, and trade-offs have to be made. The first lesson of politics, as the economist Thomas Sowell puts it, is to disregard the first lesson of economics. Political strategies and goals often aim to accomplish seemingly everything, and trade-offs are not a popular thing to mention. For example, Armenia’s Energy Sector Development Strategic Program[1] has a vision of the energy sector’s development that is simultaneously “inclusive and diversified”, with the “highest level of energy independence”, “clean”, “energy efficient”, “sustainable”, “reliable”, “safe”, “accessible and fair to everyone, sufficiently available to the vulnerable group, as well as attractive to investors”. While each of these is good on its own, what is implicitly missing is the idea of costs - and therefore of priorities - in a vision that hopes to accomplish everything. The point is not to complain about a specific program - this is a common approach in policy-making - but to recognize the difference between how things are presented and how they may actually be. In actual decision-making, some of those goals are incrementally sacrificed for others.

This article aims to inform readers who do not necessarily have much prior knowledge of the energy field, but who are interested in its current situation (including specifically in Armenia) and in being educated citizens on this topic. In particular, the focus will be on low-carbon sources, which do not have direct carbon emissions that would affect the climate and are seen as critical in discussions on climate change and energy security, especially for import-dependent Armenia. The term “low-carbon” is used rather than

1| Republic of Armenia Energy Sector Development Strategic Program to 2040 “clean”, since all low-carbon technologies have other environmental costs, which can be higher than the costs of carbon emissions, depending on the specific manner and conditions in which they are used. Of course, many specifics and facts presented in this article may no longer be relevant in 10 or even 5 years, given how quickly the energy field is developing. However, if the reader gets a general understanding of the various energy sources and common trade-offs that Armenia faces, then the article will have achieved its purpose.

The article touches on a variety of topics relevant to low-carbon development. For a deeper analysis of some of the issues raised (especially on the role of nuclear power and renewable energy in Armenia’s energy security and independence), the reader can look into IEA’s Armenia 2022 Energy Policy Review and FAST Foundation’s Armenia’s Energy Independence Roadmap.

2 Low-carbon energy and security

2.1 Where Armenia Gets its Energy

Armenia is a highly import-dependent country when it comes to energy. Most of its primary energy supply (about 90%) is imported in the form of natural gas, oil, and nuclear fuel (see Figure 1 below). At the same time, however, nuclear power is often considered a domestic source of energy, for reasons explained in the last section of this article. What makes Armenia›s energy security particularly vulnerable is not only its high dependence on imports but also the lack of diversity among suppliers. Nuclear fuel, about 70% of oil,[2] and the vast majority (about 83%)[3] of natural gas are imported from Russia, while the rest of the natural gas is imported from Iran. Armenia's limited integration in the regional energy systems, due to historically hostile relationships with Turkey and Azerbaijan ever since its independence, has limited its options for energy supply.

2| https://evnreport.com/economy/armenias-economic-dependence-on-russia-how-deep-does-it-go/

3| https://psrc.am

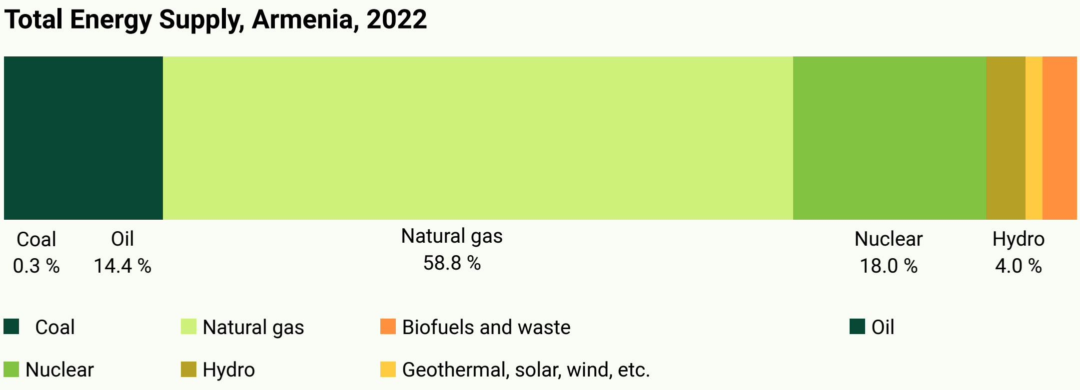


Figure 1: Armenia's primary energy supply. Sourc: Armenia - Countries & Regions - IEA

When speaking about "primary energy supply", it is important to remember that much of that energy is lost in the process of conversion, and only part of it is used at the end. For example, only about one-third of the uranium fuel's energy is converted into electricity at the nuclear power plant, and some of that energy is further lost in the transformers, substations, and power lines before it reaches the buildings. While the image above is not identical at the point of consumption, the general picture of high energy dependence is still true.

Energy used for transportation and heating comes predominantly from natural gas and oil, although solar water heaters have become increasingly popular over the last years. In electricity, about 40% is generated by thermal power plants that use natural gas as a fuel. The other major sources of electricity are the nuclear power plant, hydropower plants, and recently developing solar photovoltaic (PV) power plants. Figure 2 below shows how electricity was generated in 2024. The green area represents nuclear power, the orange one is gas-powered generation, the blue represents hydropower plants, and the yellow is solar PV. Imports and exports are likewise included.

Armenia's Annual Electricity Load Profile 2024

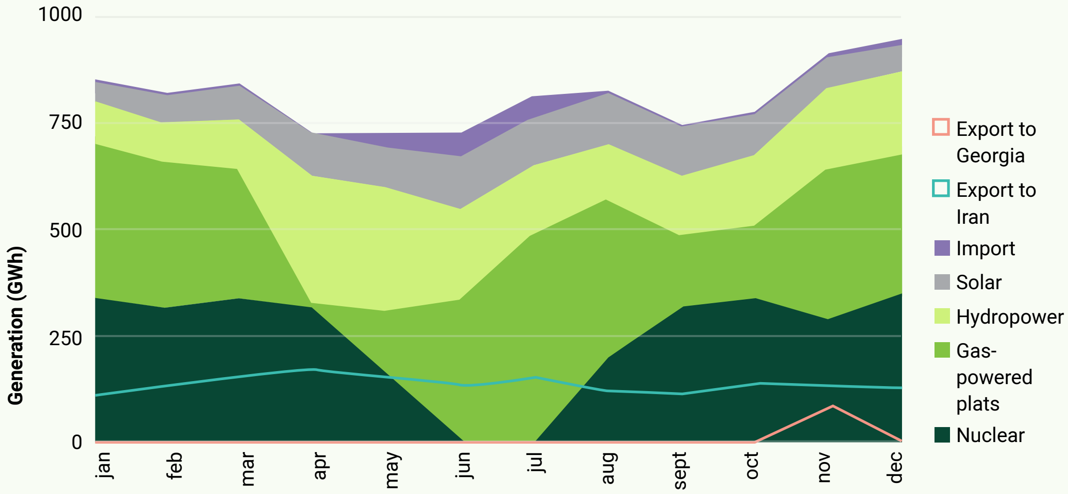


Figure 2: Annual electricity load profile constructed by the author. Data source: psrc.am

Several points are worth highlighting in the context of low-carbon generation and energy security. First, low-carbon sources provide about 60% of Armenia's electricity generation; of them, nuclear is the most reliable in terms of its output, though yearly shutdowns happen for refueling or life extension activities (as in the summer period in this case). The backup power for such periods usually comes from natural gas; planning it in late spring - early summer provides additional compensation from hydropower generation due to higher precipitation. Hydropower itself is seasonally variable, low in fall-winter and higher in spring-summer; there can also be significant annual variability. Lastly, solar power is similarly variable, higher in summer and lower in winter, in addition to having high variability throughout the day-night cycle. No other significant sources of low-carbon generation are present in Armenia, though plans for wind and geothermal power development are discussed.

What do these observations show? The current contribution of low-carbon electricity sources to Armenia's energy independence varies depending on time. In terms of monthly variation, April sees the highest level of independence (again, taking nuclear as a domestic source of power, for reasons explained later). On the other hand, the power system is most vulnerable in the winter months, because of the higher electricity demand and the low availability of solar PV and hydropower generation. Winter evenings in particular are the least "energy-independent" periods for Armenia. Winter season likewise raises the natural gas demand for heating, adding to the need for imports.

2.2 Contribution of renewables to the energy security of Armenia

This brief overview of the current situation can help us to examine how low-carbon technologies can contribute to Armenia's energy security. We will start with electricity generation. One of the fastest-growing sources of electricity in Armenia is solar power, going from less than 0.3% of electricity generation in 2020 to 8.3% in 2024.[4] Armenia being a relatively sunny country, its potential for solar energy is always brought up in discussions on energy security and climate change. However, not only do higher shares of solar power generate balancing issues in the grid (more on this in the next section), but the contribution of solar power to energy independence has a limit due to what is called **"autocorrelation"**. Autocorrelation is a technical term for, in this case, a very simple phenomenon - all solar panels produce electricity at the same time of the day. Place one solar panel in Syunik, and another in Shirak, and the two will, in the best-case scenario, start producing electricity in the morning, peak in the afternoon, and decrease their output in the evening. Of course, in worse cases, cloudy weather may prevent one or both from producing much electricity. Installing more and more solar panels eventually results in excess electricity produced during the afternoon hours, for which there is simply no demand. The excess electrical energy therefore ends up being wasted - **curtailed**. An example is shown in Figure 3 below, showing California's electricity generation on April 16, 2024.

4 | Based on data from psrc.am . Approximately half of that electricity comes from autonomous solar power consumers.

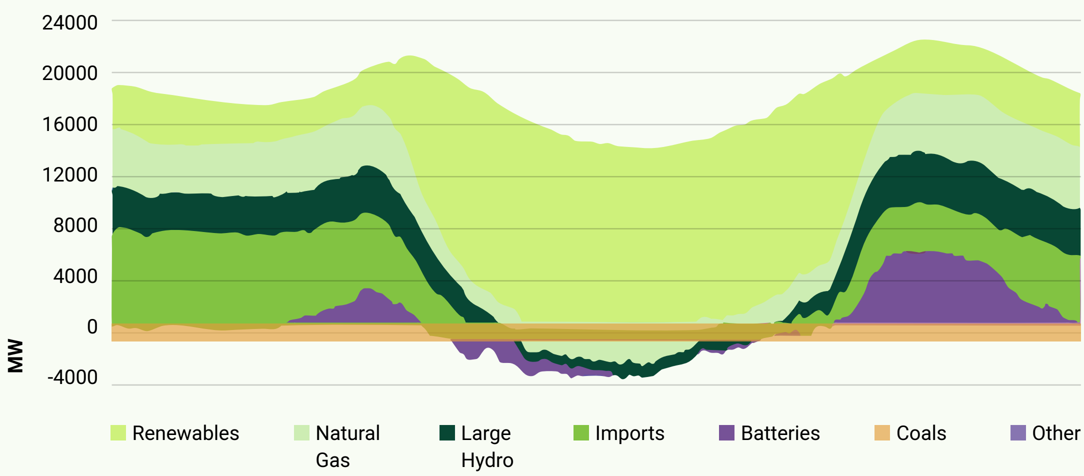


Figure 3: California's electricity generation on April 16, 2024.
Source: https://www.caiso.com

The growth of renewables in the afternoon hours, as seen in the picture above, comes from solar power. While some power plants, such as natural-gas-powered ones, can adjust to this by reducing their output, others, such as nuclear, are less flexible. Even for thermal power plants such as gas and coal, shutting down completely and then restarting is expensive; nor will other renewables (such as wind or hydropower) simply slide aside to allow incoming solar power to take over the revenues.[5] The result is excess and often wasted electricity generation in the afternoon. At this point, adding more solar panels may provide some energy independence for the cloudier days, but that would come at an increasingly high cost given all the electricity that would be wasted on sunny days. April is an illustrative example, as that's the month when California curtailed most of its wind and solar electricity generation - 12.7%, partly because of lower demand during that month (not much need for heating or air conditioning).[6]

Three approaches are used to deal with this problem of autocorrelation. The most obvious answer is to trade - sell the extra electricity to the neighbors. This allows to push the share of solar in the mix a bit further, but problems arise when the neighboring countries start investing in solar panels as well. Unless such trading happens across time zones, so that different areas experience different levels of solar activity, trading will not substantially solve the problem. It is important to remember that Armenia does not, as of today, possess electricity trading opportunities across time zones, being limited to Iran and Georgia. The other approach would be storing the extra electricity during the afternoon and reselling it later in the evening. The issue is that electrical storage has been extremely expensive, though the costs of chemical batteries have been falling rapidly over recent years.[7] Finally, lowering the electricity prices during afternoon hours - when there is excess electricity - can incentivize individuals to shift some of their consumption to those hours. Innovative tariffication schemes and digitization technologies (having "smart" appliances that automatically adjust to price variation) can allow such an approach, though most consumers remain unaware of electricity generation costs in real time. In short, while each of these approaches is utilized to some extent, the challenges remain. Even though annually Armenia receives far more solar energy than its electricity consumption, the fact that this energy is highly concentrated in limited hours during the day limits solar's contribution to energy security.

Wind power, though not yet developed in Armenia, has some advantages compared to solar when it comes to energy security. Firstly, windy areas usually have wind flows both day and night; secondly, the wind is often more available in the winter when the demand is higher,[8] as well as at night, complementing solar energy; thirdly, the degree of autocorrelation is much lower. Place one wind turbine in Shirak, and another in Syunik, and their high generation hours may be quite independent. For these reasons, countries have been able to push the grid far more in wind generation than in solar generation. Global leaders in terms of solar power share in the grid have not been able to push it beyond 15-20%; some countries have achieved a higher proportion of solar in their energy generation, but they are also net importers of electricity. On the other hand, further strides have been made in wind generation, the most notable example being Denmark, with almost 60% of its electricity generation coming from wind.[9] Open waters in particular are attractive for wind turbine installation. However, similarly to solar power (though not identically), wind power struggles with periods of overgeneration and undergeneration. While wind power is

5 | The reasons natural gas power plants would willingly adjust their output is that solar electricity is able to undersell them, since it requires no fuel to produce electricity. However, even for gas or coal-powered generation, let alone for nuclear, reducing power output completely to just restart it a few hours later in the evening every day can be prohibitively expensive and technically challenging.

6 | Based on data from CAISO Monthly Renewables Performance Report - April 2024. Electricity can also be curtailed because power lines do not have enough capacity to transmit all of the electricity generated by solar, which illustrates the upcoming point on high costs of storage.

7 | Batteries and Secure Energy Transitions (IEA 2024), figure 1.2

8 | Although Armenia's summer power consumption has been approaching winter's due to air conditioning.

9 | 64 Countries Whose Electricity Generation in 2022 was 50-100% Wind-Water-Solar (WWS) (Mark Z Jacobson, Nov 27 2024). Namibia has the highest share of solar in its electricity generation - 38%, but it imports about 70% of its electricity consumption *(IEA 2024)*, making the share of solar in its overall electricity supply closer to 12%.

often present day and night, there can be long periods (whole days or more) without much wind, whereas the Sun will predictably rise in the morning even if diminished by the clouds. In addition, many of the windy areas in Armenia are hard-to-reach areas, making it costly to install wind turbines and the corresponding infrastructure. It is likely that, despite wind power being more utilized globally, wind power's role in Armenia will be less than solar's, though its contribution in the evenings and in winter is more valuable.[10]

All of this is to say that, even though technically there is sufficient potential for wind and solar electricity to fully meet Armenia's demand during certain hours of the year, their variability and autocorrelation create practical issues that limit their development. As noted in the introduction, the question is not whether solar and wind power are categorically good, but how much benefit we get from incremental additions of solar and wind power. As seen in Figure 4 above, abstract modeling done by OECD-NEA shows how quickly the value of solar and wind electricity drops as their share in the electricity generation increases - a factor that also depends on the presence of interconnectors and storage (in this case, pumped hydropower facilities or dams). Once storage technologies become sufficiently cheap, the contribution of wind and solar power to Armenia's energy security can rise drastically. In particular, the rapidly falling costs of chemical batteries in the medium term and hydrogen storage in the long term can enable much higher shares of solar and wind power. However, in the near term, more reliable sources of low-carbon electricity have to be used to provide more stable electricity, including for periods of low wind and solar power generation. Out of these, nuclear power will be discussed in the last section. Other major sources worth mentioning include hydropower, geothermal, and biogas.[11]:

10 | Various sources place wind potential in Armenia lower than solar. Armenia's national energy strategy aims to have 1000 MW of solar capacity by 2030, while only up to 500 MW of wind capacity by 2040 (pages 25-26, though direct capacity comparisons can be misleading). Armenia's energy independence roadmap presents in its accelerated scenario 2605 GWh solar electricity generation and 1340 GWh wind electricity (p 41). A 2023 World Bank study in its high variable renewables scenario estimates roughly 4000 GWh of solar and 1300 GWh of wind electricity by 2040 (p 50).

11 | While biogas does emit carbon, that carbon originally came from the atmosphere itself and does not contribute to a net increase in the concentration, unlike fossil fuels.

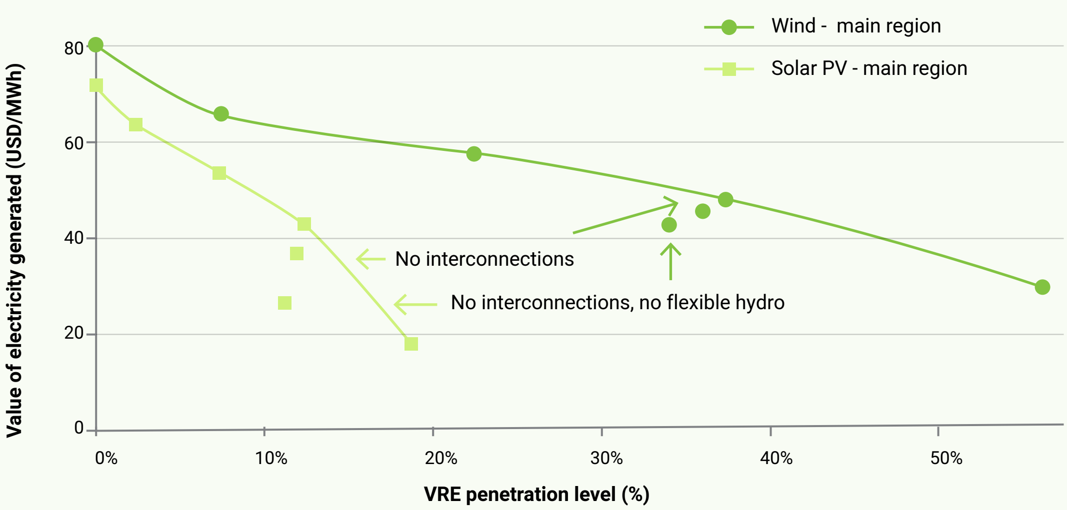


Figure 3: The market remuneration received by wind and solar PV as a function of their share in the electricity mix. Source: OECD-NEA, 2019

Once again, while each of these has a role in contributing to energy security, none of them can act as complete solutions. Armenia's hydropower potential has been developed to a significant extent, but it depends significantly on precipitation in a given month, and the country does not have vast natural reservoirs of water like Switzerland, Norway, or Georgia do. Monthly hydropower generation can vary by a factor of 3-4. Over the past few years, hydropower has been providing about 20% of Armenia's electricity generation; while some spots for development remain, it is unlikely that the share of hydropower will change significantly; more water can be drawn from Lake Sevan, but that would be at the expense of the Lake's water level. Geothermal power, though not developed in Armenia, has a potential of around 150 MW;[12] this would provide about 17% of Armenia's current annual electricity consumption at a stable year-round generation - a major advantage compared to solar, wind, and even hydropower. In biogas generation, while Armenia produces a lot of agricultural waste, the realistic contribution is currently uncertain as significant logistical costs can arise in collecting all the waste and converting it into useful energy. While theoretical potential has been estimated at 412 million cubic meters[13] (covering approximately 15% of current natural gas consumption), a more certain estimate will be provided by a current study led by the Acopian Center for the Environment.

12 | The World Bank, 2015

13 | Acopian Center for the Environment, 2020

3 Costs of low-carbon sources

3.1 Levelized cost

The economics of low-carbon sources are typically associated with high investment costs and low to negligible variable costs.[14] Construction takes up the biggest chunk of the cost for a wind turbine, solar PV farm, hydropower, or geothermal power plant. Once the plant and necessary infrastructure (such as power lines) are set up, electricity is generated at a very low additional cost. This is in contrast to natural gas or coal power plants, where fuel has to be burned continuously, and the lifetime variable costs of generating electricity are more comparable to the costs of constructing the power plant.[15] Due to these differences, energy economists utilize a metric called **Levelized Cost of Electricity** (LCOE) - calculated by combining all of the producer's costs (construction, operation, fuel, etc) and dividing them by the total amount of electricity generated by the power plant throughout its lifetime.

14 | An exception would be biogas, where significant variable costs exist in supplying the fuel.

15 | Lazard LCOE+ (June 2024), p 31-32

Comparing power plants in terms of their LCOE gives an idea of the overall costs of producing electricity and how they have changed. As can be seen in Figure 5 below, the costs of wind power and especially solar photovoltaic panels have fallen dramatically over the past two decades, the two becoming the cheapest sources of electricity even with construction costs taken into account. Naturally, this is the case for the relatively sunnier

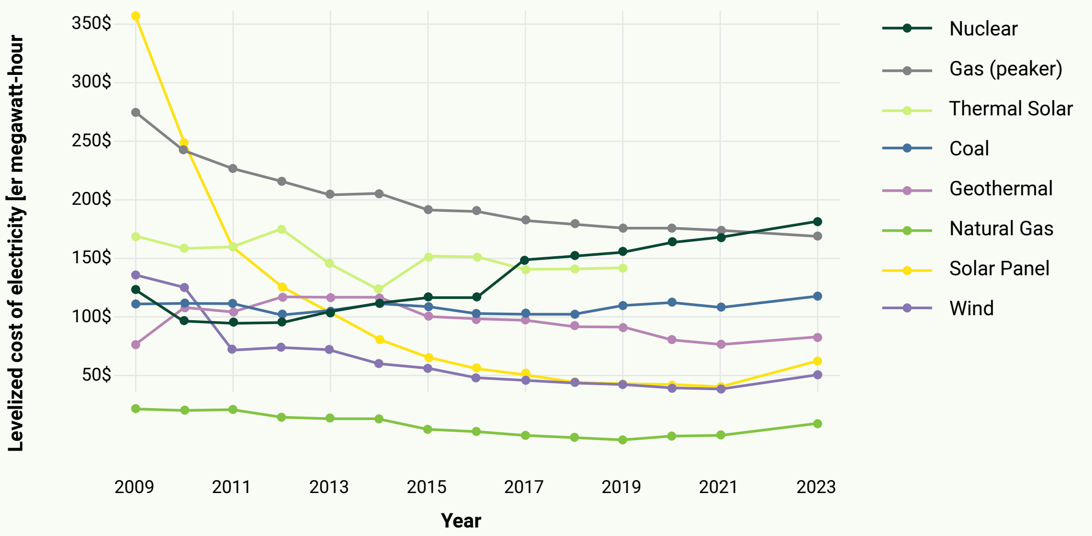


Figure 5. Developments in levelized cost of electricity by source. Source: Lazard, Wikipedia

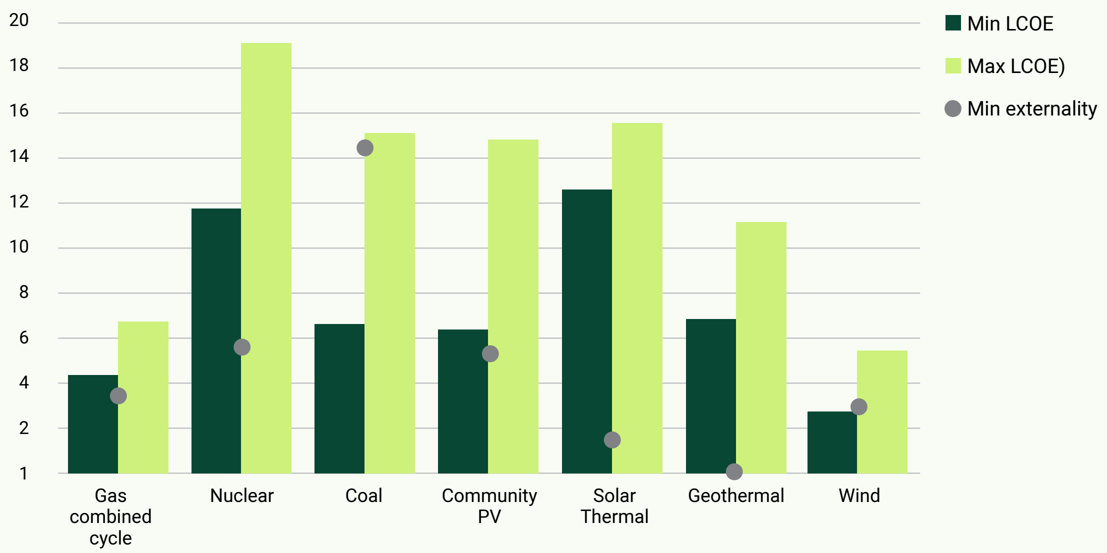
and windier areas. Less optimal areas would have a higher LCOE, as the total costs would be divided by a lower lifetime electricity generation. This is an important point, as it goes back to the idea of looking at sources incrementally as opposed to categorically.

Imagine installing wind turbines in the windiest areas in Armenia. Even though the cost of installation would not be cheap (moving those rotor blades through Armenian roads is a challenge of its own), these turbines will generate a lot of electricity, reducing the total cost per unit of electricity (or LCOE) to a reasonable level. However, once all such reachable locations are taken up, now the wind turbines have to be installed in less optimal locations. The amount of electricity generated from these additional wind turbines will not be as high, and the cost per unit of electricity will increase. Once those locations are taken, even less optimal ones will have to be used, with higher electricity costs, and so on. In short, wind electricity is not categorically cheaper than, for example, natural gas powered electricity. It is only cheaper up to a certain point, given more or less optimal conditions for wind power generation. This is true of energy sources in general - as more and more of a given indigenous source is used, costs of electricity will tend to rise as less suitable locations are picked for construction of the new power plants.

3.2 Environmental costs

As more and more of a given energy source is used, levelized cost is only one of the factors that get affected by the changing conditions. Other types of costs don't stay fixed, either, and it is important to keep a dynamic picture in mind of incrementally changing energy production and associated costs, rather than a static and categorical image of how these sources compare to each other. Environmental and health costs are an important aspect of almost any type of energy generation; air pollution from coal power plants, bird deaths from wind turbines, hydropower plants' impact on local habitat, and land loss, and so on. On average, some of these sources tend to have lower environmental costs (also called **externalities**, as they are external to the producers' costs unless the government forces them to compensate) than others, and Figure 6 below gives an idea. As can be seen, many low-carbon sources can still have significant externalities, especially if their production and end-of-life management are taken into account. These externalities can be comparable to, if not higher than, the actual sum of construction, operation, and other costs per electricity generation, that is, LCOE. This is one of the reasons why labeling low-carbon sources as "clean" can be misleading. Net-zero carbon energy transition plans (which aim to reduce carbon emissions to zero) implicitly assume that other sources that replace fossil fuels will have lower environmental damage. This may be true on average, but not necessarily in every single case. As with levelized costs, environmental costs change depending on the situation.

Figure 6: Comparing LCOE with externalities costs for various sources of electricity, in US cents per kWh. Source: Sovacool et al, 2021



For example, imagine utilizing more and more of the hydropower resources in Armenia. At first, additional hydropower constructions will not generate much environmental costs - in fact, ideally, projects with low environmental damage should be prioritized if other things are equal. However, as the hydropower plants fill up the country, the environmental damage from additional constructions will increase: river flows will become increasingly disrupted, dams will accumulate more precious and scarce water, and raising the outflow from Lake Sevan will reduce its water level. *In short, the environmental costs per unit electricity of hydropower, just as for any other resource, are not fixed - they depend on the extent to which a given resource is exploited and used*. For this reason, for example, the Armenian government adopted a law forbidding permits for new hydropower plants at rivers which are spawning grounds for endemic fish species, or where too much water is diverted through diversion pipes for hydropower use.[16] Though a hydropower plant may be generally “cleaner” than a fossil fuel power plant, that comparison is not constant. Constructing a modern coal-powered plant in an area with clean air, particularly if it is far from a populated center, may generate less environmental and social costs than constructing a hydropower plant that diverts the little remaining water, or a solar PV plant that occupies valuable agricultural land.

16 | https://www.arlis.am/documentview.aspx?docID=151502

3.3 System costs

Finally, just as with levelized cost (which includes construction, operation, and maintenance) and environmental costs, the costs that various energy sources impose on the system must be considered, and these do not remain constant either. This is particularly true for electricity generation in the grid, where generation and consumption must always be matched. Variable sources such as wind and solar (and other power plants to a lesser extent) can make it more costly to run the electrical grid, even if their own individual construction and operation costs (expressed through LCOE) are relatively low. Some researchers have come up with the term **System LCOE**, to incorporate system costs in the comparison of different sources.[17] A brief overview of system costs will also help to understand why they increase (per unit of electricity) as the share of certain renewables in the grid goes up.

17 | E.g. System LCOE: What are the costs of variable renewables? (Ueckerdt et al, 2017), Levelized Full System Costs of Electricity (Idel, 2022)

Firstly, the cost of transmitting electricity from power plants to the consumer can change, depending on location. This entails not only building power lines with sufficient capacity but also ensuring the proper flow of electricity across various points in the grid. Of course, this is true for any power plant - a nuclear plant located far from major cities needs access to enough transmission capacity to transport its energy. However, renewables like wind and hydropower tend to be constrained geographically - compare natural gas power plants in Armenia, located in Yerevan and Hrazdan, to potential wind turbine sites which are in areas much further from cities - e.g. in the hills of Sisian. Once again, starting with more optimal conditions, we would choose locations which aren't too far from the cities and factories where electricity is consumed; but as those locations get taken, new power plants will have to be constructed further and further away, increasing the **connection costs** (connecting the power plant to the grid) and **grid costs** (managing the transmission and distribution of electricity).

Secondly, renewables like solar and wind are intermittent and hard to predict. Their electricity generation can change within minutes, but the system operator needs to keep the grid constantly in balance, which means that **balancing costs** have to be taken into account, often covered through storage technologies or imports, which help to compensate for the changes in wind and solar power. For Armenia, the interconnection with Iran serves as a balancing source - Iran's much larger power system acts as a reserve that helps manage fluctuations in the Armenian grid. For this reason, enhancing the interconnection with Iran is one of the prerequisites for installing more wind and solar power in Armenia.

Thirdly, the largest category of system costs is called **"profile costs"**. Profile costs arise because of the variability of energy sources and the resulting need for backup capacity. A specific example will be illustrative. Imagine Armenia constructing more and more wind turbines. Those turbines will generate a lot of electricity, taking away profits from, say, natural gas power plants. Yet we cannot let the natural gas power plants close down, as they are needed for periods when there is no wind. The result is that now twice the capacity has to be sustained despite electricity consumption staying the same, and the cost per unit of electricity rising as a result. These costs are often covered through a tax on electricity, which is used for capacity payments - a common way of addressing profile costs by paying certain power plants for their installed capacity in addition to generated electricity.[18] After all, the grid operator needs to ensure that gas power plants will remain available (and that new ones will be constructed in the future) despite wind turbines and solar panels taking away much of their profits.

18 | Some electricity markets, like in Texas, do not give capacity payments, instead relying on high electricity prices to incentivise investments.

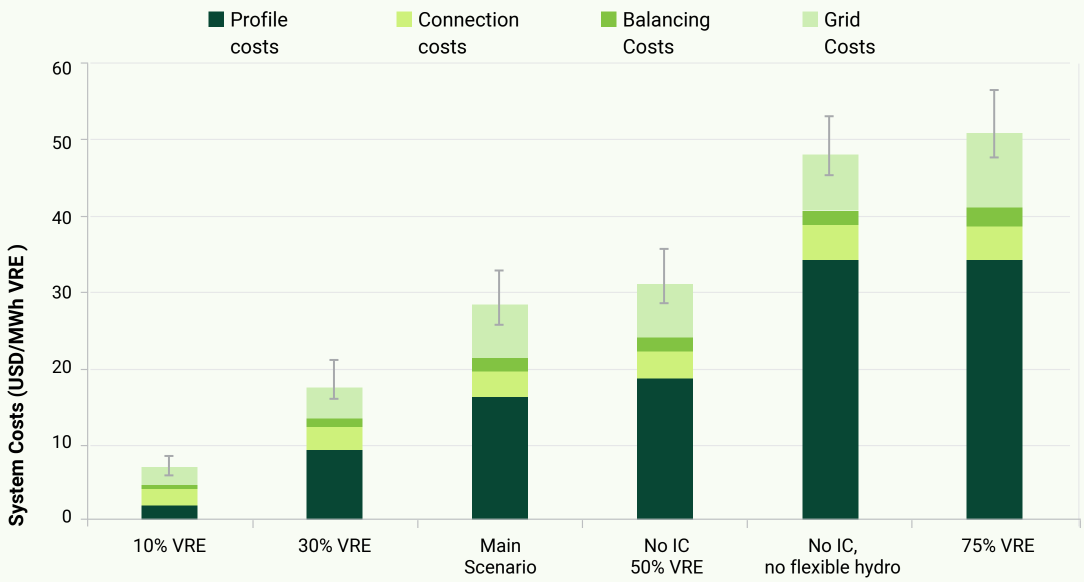


Figure 7: System costs per unit of electricity of variable renewable sources (VRE), depending on their share in the electricity mix. *Source:* OECD-NEA, 2019

These various system costs can be reduced to a certain extent - e.g. having flexible tariffs to adjust consumption - but they generally tend to rise as the share of variable renewable generation (wind and solar) increases, though other power plants can also impose some of these costs. As seen in Figure 7 above, the increase can be substantial, especially if there is no interconnection and flexible hydropower source, leaving the costlier solutions of batteries and capacity payments. In short, system costs, just like other costs, can and do change, not only depending on how much variable, intermittent, and geographically constrained energy sources are exploited, but also depending on the conditions of the energy system - its trading opportunities, storage possibilities, and flexibility of the demand. Just like with other costs, the main implication is that things should be looked at incrementally, rather than categorically. When we start building solar panels in Armenia, the costs of electricity will decrease as solar power is very cheap. However, as there are more and more solar panels, the costs of balancing, backup, and grid enhancement increase, and at some point adding more solar panels makes electricity costlier, not cheaper.

3.4 More jobs from renewables - good news?

The question of costs in transitioning to high-share renewable systems is related to the question of jobs. Job creation or loss is often an important question in this topic, and is tied to both social and political considerations. Many studies have been done in this field;[19] a recent study specifically for Armenia has estimated the impact of net-zero carbon transition on job creation and losses across specific sectors (World Bank, 2024, page 72). More jobs would come from renewables and some sectors, although there would be losses in other energy-related sectors (such as transportation). On the net result, approximately 245,000 jobs would be lost based on the sectors analyzed in the study; a

19 | E.g. Job creation during the global energy transition towards 100% renewable power system by 2050 (Ram et al, 2020) more detailed picture shows some sectors gaining and others losing jobs, with the overall result being the aforementioned net loss. If true, is this good or bad news?

The question of jobs in itself is in some way a red herring; the real question is not the amount of jobs created in any particular sector, but the value that these jobs generate for others. It may be true that within the power sector, more jobs will be added by renewables as a net result. That is certainly good news for those who will be employed in the sector, but what it means is higher costs for the rest of the consumers. If one person is getting a job with a high salary, someone else must pay to provide that salary. What matters is whether the new situation brings additional benefits that justify the additional costs. If cleaner air from renewables substantially reduces healthcare costs, and higher energy security generates substantially more economic investments, then these benefits can justify the additional costs of energy.

The same logic applies to job creation across different sectors. It can be misleading to look at how many jobs are created or lost within one sector; technological progress often comes at the expense of jobs within a given sector but at the benefit of more jobs in other sectors (including the creation of whole new sectors of employment). For example, agricultural technology has drastically reduced the share of the population that has to grow food to sustain itself; but what that has meant is lower cost of food for everyone and extra wealth, time, and resources that can be used for other things (including writing articles on energy!). While a net loss of 245,000 jobs may occur across the sectors covered by the World Bank report, the additional benefits (such as saved costs of healthcare) will spill over into new opportunities for the whole economy that are harder to account for directly.

4 Nuclear Power

4.1 The role of nuclear power in Armenia's energy security

I wrote earlier that it is important to look at energy sources, their costs, and benefits incrementally, rather than categorically. Historically, nuclear power is one of the areas where the possibility for incremental addition has been the hardest. This is because large nuclear power plant designs have tended to dominate the market, as heavy investment costs made it important to achieve economies of scale so that a large power plant would produce as much electricity as possible and would spread out those investment costs. The techno-economic constraints on size and the resulting heavy investments, combined with only a few countries possessing the technology and skills for constructing a nuclear power plant, have in many cases made nuclear power as much a political consideration as an economic one.

In the case of Armenia, the construction of a new nuclear power plant to replace Metsamor by 2036 (as is the current government plan) has both economic and political implications. Economically, it is an investment on the scale of billions of dollars, with a payback period of two or three decades.[20] A nuclear power plant the size of Metsamor would cost around $3-5 billion[21] - about half of Armenia's current annual government budget (though, of cours,e construction would take place over a period of years). Politically, such an investment and corresponding supply of nuclear fuel means a partnership with whichever country constructs the power plant.

It is important to highlight the role of nuclear power in Armenia's energy security in order to understand some of the motivations behind constructing a new nuclear power plant. A reliable baseload power source, which produces stable output throughout the year, is important in order to cover the minimum electricity demand that is always present. Some countries rely on abundant hydropower and geothermal sources for baseload; however, Armenia does not possess either to such an extent. In the absence of a nuclear power plant, baseload supply in Armenia would have to be mostly provided by natural gas power plants. Even though the fuel itself (uranium and natural gas) is imported in both cases,

20 | Financing nuclear projects – The Path to a New Era for Nuclear Energy – Analysis - IEA.

21 | At a rate taken from of $7,500 - 12,500 per kW from Lazard's Levelized Cost of Energy Analysis

there are several reasons why nuclear power is often considered a domestic source of electricity and beneficial for energy security.

One of the reasons is that uranium fuel has extremely high energy density and lasts much longer in a nuclear power plant, with one-third of the fuel being replaced every 12-18 months.[22] This results in much lower dependence on imports at any given point in time, unlike natural gas power plants, where fuel input has to be provided continuously.[23] As an additional benefit, nuclear fuel has a lower susceptibility to price fluctuations in fuel costs. As can be seen in Figure 8 below, a 50% change in fuel costs can have a significant impact on natural gas LCOE, as fuel costs comprise a significant share of total natural gas power generation costs. However, for nuclear power, the overwhelming component of the costs is construction, and fluctuations in fuel costs barely impact the total nuclear power costs as a result. The supply of nuclear fuel is likewise more flexible logistically, as it does not rely on extensive infrastructure such as pipelines and compressor stations, especially for a landlocked country such as Armenia. On the other hand, nuclear fuel has certain variations depending on which nuclear reactor design is implemented and therefore is tied to a particular supplier, though some flexibility is present depending on the specific technological requirements - see Bulgaria and Ukraine switching to US nuclear fuel supplier from a Russian one.[24] An additional disadvantage is presented in the flexibility of nuclear power itself; due to technical and economic constraints, nuclear power does not provide flexible output that adjusts throughout the day and is mostly used as a reliable baseline with unchanging power output. The additional benefits of nuclear power to energy security therefore are not constant, but drop significantly once baseline power is covered.[25]

Aside from high investment costs, an often raised question on nuclear energy is its health risk, especially in the context of nuclear accidents and Armenia's high seismicity. As the issue itself is highly specific and complex and lies outside the scope of this article and the author's expertise, only brief notes will be made. Firstly, nuclear power is certainly not "safe" in the absolute sense; if it were, it would be the only safe energy source on the

22 | Nuclear Fuel Cycle Overview (World Nuclear Association)

23 | While there is a natural gas storage facility in Armenia that can provide backup in case imports are interrupted, its volume is equivalent to about 7% of Armenia's annual gas consumption, planned to almost double by 2025 (Armenia 2022 Energy Policy Review)

24 | Westinghouse, 2024; Reuters, 2022

25 | Of course, the excess nuclear power generation that is not used domestically can be exported; however, that is a benefit different from energy security, as well as with substantial economic risk of relying on sufficient foreign demand to cover billions of dollars of investment.

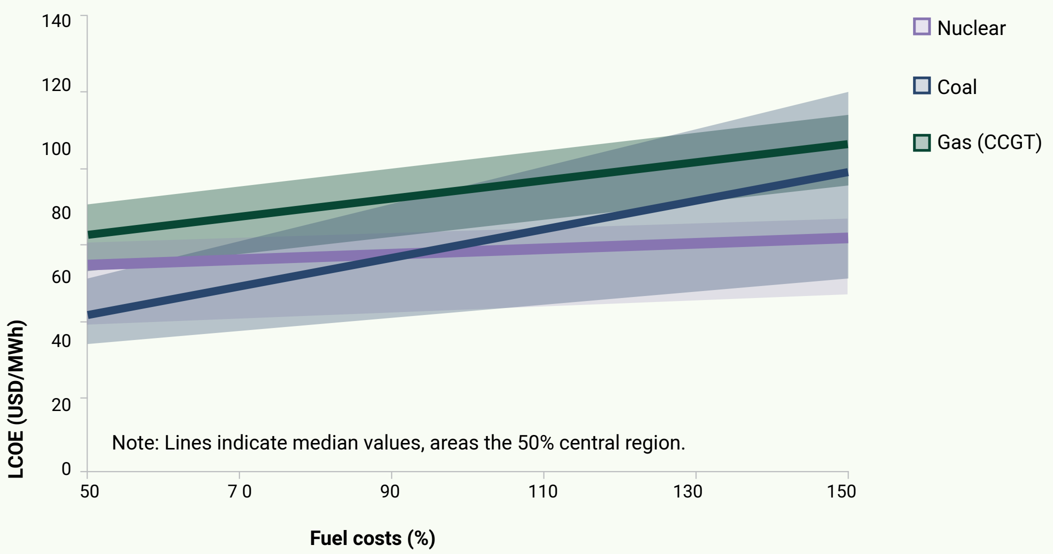


Figure 8: Effect of fuel cost fluctuation on the LCOE of nuclear, natural gas, and coal power. *Source:* OECD-NEA, 2020

planet. The question is how safe it is compared to other sources, and despite the public perception and scope of the few nuclear accidents that have occurred, nuclear power is one of the safest sources of electricity when measured in associated mortalities per unit of energy produced.[26] At the same time, both nuclear accidents[27] and, to a lesser degree, living and working in proximity of a nuclear power plant[28] have been argued to increase cancer risks, though the extent of this problem is uncertain.[29] Of critical importance is the growing safety of nuclear technologies, both in accident prevention and health impact minimization. After each historical accident, additional regulatory and engineering measures were taken to reduce risks, and new generation reactors are safer than older ones, such as Metsamor's power plant. In fact, more stringent safety requirements have been one of the reasons why the costs of nuclear power have grown significantly over the last 50 years.[30]

A similar concern is present with nuclear waste, which Armenia currently stores domestically, as opposed to the earlier practice of shipping it to Russia.[31] Unlike other environmental costs discussed earlier, where some level of pollution is tolerable, even small amounts of radioactive waste can be very dangerous if released into the environment. In other words, the incremental cost of radioactive pollution is high from the get-go. The creation of new storage facilities and improved treatment of radioactive waste is one way to mitigate this risk for Armenia.[32] The relevant experts, therefor,e need to communicate the relevant costs and benefits of constructing a new nuclear power plant in Armenia to the public.

26 | Death rates per unit of electricity production - Our World in Data

27 | Health effects of radiation and other health problems in the aftermath of nuclear accidents, with an emphasis on Fukushima (Hasegawa et al, 2015)

28 | Living near nuclear power plants and thyroid cancer risk: A systematic review and meta-analysis (Kim et al, 2016)

29 | Health Effects of Occupational and Environmental Exposures to Nuclear Power Plants: A Meta-Analysis and Meta-Regression (Lin et al, 2024)

30 | Michaelides, E. E. (2018). Energy, the Environment, and Sustainability. Taylor & Francis

31 | Armenia: Fears Over Nuclear Waste (Institute for War and Peace Reporting, 2020).

32 | Specifics of radioactive waste management at the power unit No.2 of the Armenian nuclear power plant (Hakobyan et al, 2024)

4.2 Small modular reactors

The last section of this article will briefly address the up-and-coming nuclear power technology of Small Modular Reactors (SMR). In light of the Prime Minister's statement that Armenia has made a strategic decision to use SMR to replace Metsamor,[33] it is useful to highlight the potential advantages and disadvantages.

33 | Armenpress, 2024

As mentioned earlier, large nuclear reactor technologies (around 1000 MW or higher) have tended to dominate the market due to economies of scale. However, as smaller countries and consumption regions expressed interest in nuclear power, research into smaller reactors (<300 MW) has been developing. The higher cost per unit of electricity as a result of smaller size would be brought down by a learning curve, the idea being that standardized parts would be manufactured in specialized factories and assembled on site. Nonetheless, commercial-level technology is still in the development phase, though market expectations received a boost in expectations after several tech giants announced investments in this technology.[34] The uncertainty of when the technology will be ready and how mature it will be is one of the disadvantages of SMRs compared to conventional large reactors.

34 | Hungry for Energy, Amazon, Google and Microsoft Turn to Nuclear Power (New York Times, 2024)

Should the technology develop in time, it will present some advantages to the energy security of Armenia. Perhaps the most important advantage is that placing multiple smaller reactors instead of one large reactor allows refueling them one at a time, reducing the need for backup in the system for the periods of refueling. Economically, the ability to construct smaller reactors also reduces the total investment cost and allows for more incremental additions over time as demand for electricity grows. However, as relatively few countries are expected to roll out SMRs, the choice of technology is still tied to political considerations and signaling.

5 Conclusion

Low-carbon energy presents significant opportunities for Armenia to enhance its energy security. At the same time, the costs and benefits should be measured incrementally, as both can change depending on the extent to which a given energy source is utilized or exploited. The benefits of some low-carbon energy sources, such as solar and wind, will eventually decrease due to a mismatch between generation and demand, while they impose growing costs as the rest of the system has to adjust to their variability and intermittency. Other low-carbon sources, such as nuclear power and geothermal, provide a reliable output but have limited flexibility, reducing their benefits after the minimum constant power demand is met. More flexible and controllable sources, such as biogas and stored hydropower, have rising variable costs if they use up more and more of their 'fuel' (biowaste and water, respectively). All low-carbon energy sources, depending on the extent to which they are used, can add environmental and social costs which, at some point, may exceed the costs of replaced carbon-based sources.

This does not necessarily imply that we *must* have a large diversity of sources, as environmental conditions, natural endowment, and other things have to be taken into account. Countries like Iceland, with a relatively small population, can have almost the entirety of their energy demand (except for transportation and heavy industry) supplied by geothermal and hydropower energy alone.[35] Given Armenia's conditions, if one wants to reduce fossil fuel consumption, it is harder to imagine such a simple combination of two or three sources, although dropping storage costs may eventually turn the tide in favor of renewables. Determining what this combination should be is a challenging task even for a sector with more centrally-run components, such as the electrical or gas grid. In overcoming this challenge, what matters in most cases for the fast-changing energy sector is not categorical political decisions prioritizing one source over another, but a set of incentives that can adjust more dynamically as both costs and benefits change due to technological, environmental, and economic development.

35 | The heat from geothermal plants is also used to provide heating via centralized distribution facilities.

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