# Comparative Study of Clean Energy Technologies for a Decarbonized Future

Objective: To evaluate the feasibility of transitioning from carbon-emitting sources to non-carbon-emitting source- solar, nuclear and hydrogen- for global energy demands through secondary research: assessing multiple parameters, obstacles and advancements for their respective expansions up to 2050.

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# 1. Preface

This paper aims to analyse the feasibility of transitioning to non-carbon-emitting sources by 2050, focusing on solar, nuclear and hydrogen energy. While the main sections provide an in-depth research and analysis, this preface serves to address specific criteria that may not be explicitly required in the analysis.

## Addressing Criteria 1.1 through 1.5

### *1.1. Refer to page*

I will have achieved my aim if:

- I have established basic knowledge regarding the functioning of each of these energy sources
- I have analysed performance metrics of each of these energy sources and understood what each of them means for the functioning of that energy source
- I have used necessary data values to analyse how feasible it is for each of the energy sources to meet necessary future requirements, and comment on how likely it is based on current trends
- I have made a final pie chart of the future energy mix based on the analysis

Objectives:

a. Research about greenhouse gas emissions and what sector each of them come from. Use this to pinpoint what sector to analyse and why → Analyse the electric sector
b. Research different upcoming sources of energy, such as solar, wind, geothermal, nuclear, hydrogen and select 3 of them to analyse

c. Research about the functioning of each of these energy sources, including certain benefits, drawbacks, their efficiencies, future advancements and more
d. Find publicly available performance metrics for each of these energy sources and analyse them in depth, using that same data at a global scale to see the possibility of their future expansion
e. Form a conclusion using IEA guidelines in the form of a energy mix pie chart for 2050 and critique its likeliness based on current trends

### *1.2.*

The wider purpose of the project is to pave a pathway to achieving a decarbonised economy in the future. Even though the analysis focuses on only solar, nuclear and hydrogen, its beyond just these sources as well. This project serves as a model of constructing a realistic pie chart for 2050, that can spread awareness about energy planning at even international levels. It demonstrates the scale and urgency of the transition required away from fossil fuels, and how we have the capability to meet rising energy needs while also producing that energy in a more sustainable manner. Thus, this research aligns with IEA and other global agency's' vision for net-zero emissions and aims to support development and awareness around decarbonisation.

### *1.3.*

Through this project, I demonstrated multiple approaches to gathering my information. By diving my study into sections, I was able to use what I learnt from one section in the others. For instance, the only reason why finding particular performance metrics for me wasn't too much of a hassle was due to me understanding what it meant from my background research, or from the functioning of the systems. This brought my directly to the comparative analysis, where I used collected data to produce a rough estimate of a potential energy mix for 2050.

*1.5.*

This method is described at the beginning of the analysis section, while also including other limiting factors for each of the energy sources.

However, despite my approach, there are quite a few limitations and there certainly is room for error, especially in the analysis. One of the primary challenges was extrapolating the data of one particular system in a country to a global scale. Even so, this cannot be done with complete accuracy due to regional changes in climate, infrastructure, resource availability and other factors and conditions. For example, solar panels in Germany will definitely not produce the same output as those in India, just as nuclear infrastructure in some places may not be as good as in others. While the project certainly provides a good enough estimate, aforementioned discrepancies introduce error and highlight the error of linearly scaling up energy systems. In reality, it would require a lot more localised data and modelling

*1.4.*

My approach for this project involved three key stages: structuring the entire plan, doing background research and coming up with the analysis and conclusion of the energy systems taking into consideration performance metrics, costs and other limiting factors while projecting the data to 2050. I chose this approach because it allows me to focus on the scientific and procedural aspects of each energy source, while also investigating the more practical aspects of each energy source. Doing all of this together also allows a comparative framework, allowing me to look at them side by side. By integrating secondary data and projections, this ensured that the final model which will be used by policymakers and researchers will be based on actual operation data from these sources. Due to obvious practical limitations, collecting primary data for such a large scale topic was very unlikely.

*1.5.*

I began structuring my project during my Christmas break, early December, spending nearly the entire month planning my flow and overall project. Prior to starting, I spoke to my mentor and interviewed a couple of professionals in the industry. Then, I spent about more or less 1 week finalising each of the energy sources' background research, after which I spent the same amount of time per analysis. Additional time was spent on putting everything together, inserting citations, formatting tables and writing reflections, while simultaneously taking feedback from my mentor and revisiting my structure. Finishing this by the end of March, and spending about a week of time polishing everything up allowed for ample room for revisions and ensured that everything was developed and structured.

## Addressing Criteria 2.1 and 2.2

For this project, I believe I made effective use of what I had available to me, especially in terms of resources for my research. My mentor played a key role in guiding me, helping me structure the entire paper, analysis, finding goals, and refining the project draft after draft, while also helping me stay on track. I also used available reports for performance metrics, such as what I used to analyse solar farms in the USA, or nuclear plants in China. In terms of tools, I used citation hubs, workflow managers, AI tools to help extract data and explain basic concepts to me, and even giving me summaries to see if the resources I had were worth doing deeper research on. This project has relied heavily on secondary resource, all which have been referenced using MLA8 citations in the references section of the paper. The use of human support and digital tools significantly strengthened this project's foundation.

## Addressing Criteria 3.1 through 3.3

### *3.1.*

After analysing the data for each of the energy source, I concluded that while each of them has the potential to reduce carbon emissions, no single source can be the only one that should be implemented independently to meet growing energy demand. My project emphasises how what truly is required is an energy mix with a balance which will likely vary from region to region, something unfortunately not taken into account in this project. I believe that this analysis can guide global decarbonisation policies and spread awareness about long term energy planning, making it clear that a shift away from fossil fuels is essential, but is something that will require investment of time, money and an increase in innovation to spark the transition.

### *3.2.*

After analysing the data through extrapolations and calculations based on IEA guidelines, I drew conclusions regarding what percentage of the energy mix each of the energy sources should contribute to. For instance, that solar will be the main factor driving the renewables alongside wind energy, while taking support from nuclear power, hydrogen and other renewables while simultaneously trying to minimize fossil fuels. These conclusions were based on the previous analysis of their feasibility and I have effectively connected it back to my original aim. However, had I not used the IEA guidelines alongside the metrics, the project wouldn't have had a specific conclusion, and it would be a lot vaguer regarding the potential expansion of each of these energy sources. Moreover, without the usage of performance metrics, an accurate estimate of how expanding by a particular amount would affect the future energy mix wouldn't have been possible to create.

### *3.3.*

This project offers a clear understanding of how each of the analysed sources can expand and thus contribute to decarbonising economies worldwide, and can be used as a simpler model for evaluating policies to see where resources should be allocated for expansion. One improvement that would make it more accurate would-be incorporating region specific data and subsequent analysis. Furthermore, using primary data, especially for hydrogen and solar which could have been possible, could have increased precision and real-world plausibility of my findings.

## Addressing Criteria 4.1 through 4.5

### *4.1.*

Throughout the project, I have demonstrated a substantial understanding of the scientific principles that support each energy source. For nuclear, I explored in depth fission reactions, reactor types, radioactive decay and more. Similarly, for hydrogen fuel cells, I understood the basis of electrolysis in the form of redox reactions, and even Gibbs free energy to determine the maximum efficiency. By connecting all of these scientific reactions to real world applications in the form of these energy sources, I made sure that my analysis reflected both theoretical concepts while also delving into practical constraints, aligning with my IBDP Chemistry and Physics HL

### *4.2.*

While I did have a mentor for guidance, majority of this was an independent project, which involved a lot of planning, analysis and research while also managing schoolwork and deadlines. I overcame several challenges, like not finding appropriate data in certain reports, understanding extremely technical terms, dealing with inconsistent data, or the analysis completely deviating from IEA guidelines. I solved this by refining my methodology, talking to my mentor, while also doing brainstorming on my own where I could have gone wrong. An ideal mix of my own work, with my mentor's gentle nudges helped synthesising and interpreting the complex information at hands.

### *4.3.*

While this was a science-oriented project, I believe I applied creativity in how I navigated the analysis section. Instead of a typical case study, I created a hypothetical model for energy using evaluation metrics, extrapolating them, and combining them with IEA guidelines for the future to create my final "goal pie chart." Integrating this was a unique way to present a decarbonised future, and acted as a plan of action for countries and firms to take on in the future. The method of combining the actual data, with other factors such as cost and other limiting factors brings out multiple perspectives, while the final critique on the pie chart also keeps it realistic.

### *4.4.*

This project spanned a little over 3 months, and being consistent was quite challenging, especially during my exam period. There were periods where I was overwhelmed with deadlines, or I didn't understand the report series, or where I felt stuck, especially while comparing unclear metrics. Despite these challenges, I stuck with it, took guidance from my mentor and continued working. My largest struggle came while researching for solar panels, as I wasn't able to find a good number of metrics. However, my mentor informed me of a way to directly search for PDFs online, which then lead to me finding an ample number of sources. I took this as an opportunity to learn about typing keywords while searching, and was also how I found the reports for the nuclear analysis.

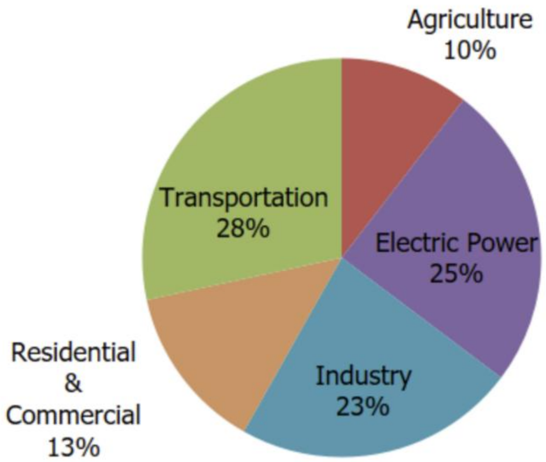
# 2. Introduction

Chemical reactions are at the heart of our modern world. From our morning cup of tea to switching off the lights at the end of the day, chemistry is everywhere. As Human civilisation grows, and rising prosperity delivers a higher quality of life to everyone on the planet (higher than it has ever been in modern times), chemistry is more important than ever before. Chemistry today faces its leadership moment as the world looks to switch from human development driven by carbon emissions to human development less dependent on, and, in the distant future, being independent of carbon emissions, in the hopes of creating a more sustainable world.

The goal of this project is to create a goal pie chart of a future energy mix. By first establishing knowledge required about each of these energy sources, and then analysis performance metrics to identify key factors driving the growth of these energy sources in the future. By looking through IEA guidelines about requirements in the future to ensure a decarbonised future, a final energy mix will also be created. The final pie chart will also be critiqued based on how realistically achievable it is as well.

In 2022, the total global greenhouse gas emissions by the USA alone were 6,343 million metric tons of $CO_2$. These emissions come from sectors including transport, 28%, electric power generation, 25%, industry, 23%, residential and commercial, 13%, and agriculture, 10%. To address this issue and mitigate climate change, the Paris Agreement's goal is to have 2025 as the threshold for maximum emissions, reduce them by 43% by 2023, and to achieve net-zero emissions by 2050.

**Figure 1. Represents the total greenhouse gas emissions in the USA by economic sector in 2022, EPA**




One of the largest contributors is the electrical power sector at 25% of all $CO_2$ emissions. This is primarily due to the heavy reliance on fossil fuels such as coal, natural gas, and oil-based power plants, which release large amounts of $CO_2$ into the atmosphere. The IEA(International Energy Agency) has set another goal for its plan to reach net zero: by 2050, 90% of all electricity must come from low-carbon sources such as nuclear, solar, wind, and hydrogen-powered energy systems. Thus, the goal of this research is to determine the best upcoming and current technologies, and find optimal combinations of them to both reduce emissions while also producing more energy for the ever-growing population.

This will be done using a “goal” pie chart, which is an energy mix predicting the future state of generating electricity and will be based on projections set by bodies like the IEA and the Paris Agreement targets while also individually analysing different methods of energy generation in terms of scalability, efficiency and cost. This research will create a map showing the transition to a lower-carbon economy to achieve neutrality in some of the best ways possible.

Thus, this paper will analyse solar power, hydrogen, and nuclear power to find the best path to decarbonisation of electricity generation. Each of these will have thorough research, including an overview of their mechanisms, their general advantages and disadvantages, and even efficiency. Furthermore, upcoming developments to better this technology are also explored. After the background research, each of these sources will be analysed through secondary data on the operation of these energy sources, which will be used to evaluate their viability; this will be used as a base to create the future projected energy mix.

# 3. Background

This section aims to provide a functional understanding of the respective energy sources that will be analysed further in this paper. While exploring their fundamental mechanics, it also discovers their benefits and drawbacks in certain situations, efficiencies and even the technological advancements that are being made as of today in these technologies. By creating a solid foundation of the basis of these sources, it can also help us understand the feasibilities of their expansion in the near future, and it acts as a point of reference for the subsequent analysis.

## 3.1. Solar Power

Solar Power is quite a modern technology, only truly making significant progress in the last decade. Thus, it must be further improved upon to ensure that solar power can be the best it is capable of to better the process of transitioning to a lower-carbon economy. Firstly, let's look at solar power in depth. Solar power comes in multiple kinds, either being concentrated solar power, solar thermal, and solar power through photovoltaic cells. While they all have different mechanisms, they are all based on using energy derived from the sun.

**Mechanisms**

Solar panels are made up of tiny, individual cells, known as photovoltaic cells. As derived from the name, they use photons to generate a volt. In simplicity, this is a photovoltaic effect. Each of these cells is made of silicon, which has two layers. There is an n-layer, which is coated in phosphorus, and a p-layer, coated in boron. When sunlight lands on the cell, its photons knock electrons out of their atoms, causing the electrons in silicon to gain some energy and move from the p-layer to the n-layer. This movement of electrons generates a current, as there are now opposing charges present in the cell. Individual efficiency of the photovoltaic cells depends on the quality and purity of the silicon used in that cell. While there is no inherent chemical reaction, the basis of the movement of electrons due to their change in energy originates in chemistry and physics.

**Advantages and Disadvantages**

Regarding the generic photovoltaic cell, the main advantage is that they are capable of producing clean, renewable energy with no pollution. Furthermore, once installed, PV(photovoltaic) cells have very low operational costs as they require no recurring input and minimal maintenance. Additionally, PV cells have extremely high scalability as they can go from being installed on the roofs of houses to large-scale farms. When it comes to efficiency, commercial silicon PV cells are between 18 and 26% energy efficient, and other designs, such as perovskite cells, can achieve higher efficiencies in testing. However, they are not commercially used yet.

However, PV cells are known to degrade due to continuous ultraviolet exposure and fluctuating temperatures, their efficiency decreases up to about 1% a year. On average, a PV system has a longevity of about 25 to 30 years. While this is relatively long, constantly replacing these cells may not be profitable or sustainable in the long run. Additionally, PV cells are heavily reliant on batteries. If the electricity generated by PV cells isn't being instantly used, it must be stored in batteries for later use, which is a large limiting factor. Similarly, due to the lack of sunlight year-round in other areas, it might be difficult for certain countries to rely largely on them.

**Future Advancements**

PV cells are being heavily researched and have many promising advancements. One of the major developments in solar cells, as previously mentioned, is Perovskite-Silicon Tandem Cells. Materials made of Perovskite are a promising lead in solar technology due to their high light-absorption ability and how cost-effective they are. Perovskites are crystalline compounds with a generalised formula of $ABX_3$, where A and B are cations, while X is an anion (mainly a halide). In the solar industry, methylammonium ($CH_3NH_3^+$) halides are the most mainstream Perovskites. They exhibit large amounts of absorption throughout the visible spectrum. While being used simultaneously with a traditional cell, Perovskite cells are coated on top of the silicon cell, allowing the entire solar panel to absorb a wider range of the incoming spectrum. Perovskite is more adept at absorbing high-energy photons, whereas silicon absorbs the lower-energy photons. One of the major benefits of the perovskite layer is the increased efficiency when used with traditional silicon cells. For example, cells achieved over 28% efficiency with their tandem cell. Furthermore, as perovskites are produced using low-temperature techniques, their manufacturing costs are much lower than those of traditional silicon cells.

Another upcoming innovation which has already been adopted is Bifacial solar panels, which are made to capture sunlight from both sides, effectively increasing the total energy generated from individual panels. It is based on absorbing the reflected light from the ground and surrounding surfaces, making it extremely effective in areas with higher albedos. While the chemical mechanism that generates power is the same, it is now adopted on the rear side of the panel. Using transparent or frameless back sheets, the rear side of the panel can also capture reflected sunlight, increasing energy yield. Studies have shown up to a 30% increase in energy output compared to generic, single-sided PV cells. A particular advantage is their durability. As bifacial panels are built to expose both sides, they have a robust construction process, leading to longer lifespans. However, they require much larger capital costs, and their efficiency may vary depending on the albedo of the area, further complicating installation.

**Conclusion**

Solar energy has been a promising source of renewable energy recently, and will only increase in importance in the near future. Its main benefits lie in its almost infinite supply, easy deployment, swiftly reducing costs and a large number of technological advancements through perovskite silicon tandem cells, bifacial modules, and even advancements not explored thoroughly during this evaluation. Furthermore, developments in energy storage, which is necessary to overcome the intermittency drawbacks of solar, particularly in newer battery technology and integration, further increase the reliability and the ability to provide energy throughout a time period. As we approach a higher need to decarbonise rapidly, solar power is no longer just an alternative source of energy. In fact, it is very likely to become one of the primary drivers of energy derivation in both developing and already developed regions. With all this, and so much room for improvement, solar energy is placed to be an essential aspect for the decarbonisation of the economy.

## 3.2 Hydrogen

Hydrogen is a pivotal transition point on the path to clean energy in the future. It is capable of producing considerable amounts of energy in a largely environmentally friendly manner. Hydrogen can be harnessed through a variety of methods, primarily fuel cells, hydrogen gas turbines, and even through co-firing in existing power plants. Hydrogen, especially through fuel cells, can power anything, all the way from vehicles to regular power systems. Hydrogen is also considered a spectacular energy carrier rather than a source, making it the perfect fit to complement other renewable sources. This section will deep dive into hydrogen as a clean energy source, delving into its mechanisms of fuel cells, efficiency, and other long-term elements, and further innovations to truly transform the energy situation of the whole world.

**Mechanisms**

Fuel cells function based on electrolysis, which involves an electrochemical reaction that produces electricity from chemical energy from hydrogen($H_2$) and oxygen($O_2$). As previously mentioned, it only produces water. The fundamental reaction powering this whole process is a net reaction of the two reactions at the electrodes

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l),\ \Delta H= -285.83\ kJmol^{-1}$$

While this reaction releases 285 $kJmol^{-1}$ of energy, only 237.1 $kJmol^{-1}$ are actually usable, while the rest is waste heat. However, this is still highly efficient in generating electricity. Furthermore, comparing the ratio of the Gibbs free energy change to the enthalpy change of the reaction, a hydrogen fuel cell can theoretically be as high as 83% efficient. However, practically, efficiencies are generally lower, ranging from 40-60%, as more energy is lost as heat in the process. However, this is still relatively higher than the efficiency of combustion/fuel engines, making hydrogen fuel cells an extremely viable future energy source. Furthermore, they only produce water as a waste product, and are also a source of clean energy.

However, it isn’t necessary that hydrogen can only be utilised through fuel cells. For instance, energy can also be generated through hydrogen gas turbines, similar to the ones in traditional power plants. These turbines can generate electricity at quite high efficiencies of up to 60%. While the usage of these turbines does periodically release oxides of nitrogen, which are harmful greenhouse gases, these can be mitigated using advanced combustion techniques. For instance, Japan and Germany are in the process of creating a large-scale hydrogen turbine to provide electricity for grids. Similarly, another avenue where hydrogen can be directly used is blending it with natural gas in functioning power plants. By adding hydrogen, carbon emissions are reduced without changing any technology, making it considerably cheaper. As of today, the standard is a 20-30% blend of hydrogen, and a newfound potential to even reach 100% operation. Co-firing, as it is called, enables the transition to hydrogen while addressing the scalability issues of fuel cells. These methods only make it easier for hydrogen to take over in the future, and with technological advancements, hydrogen’s role in producing clean energy will complement renewable energy sources. However, aside from actually implementing them, these technologies might not have as much room for improvement as fuel cells.

## Advantages and Disadvantages

While HFCs are promising, many challenges are still being faced in implementing them on a larger scale. One of these is Hydrogen storage, which is a problem due to the liquid's low density of 0.089886 $kgm^{-3}$. To combat this, it needs to be stored at extremely high pressures of up to 700 bar. Alternatively, it can also be stored as a liquid at temperatures below -253 °C. Both of these options are energy-intensive and may be counter-intuitive for temporary sustainability, requiring very specialised and costly infrastructure. Additionally, the small molecular size of hydrogen makes it very prone to leakage, and as hydrogen is extremely flammable, this poses inevitable safety risks.

## Future Advancements

Furthermore, hydrogen holds a lot more potential for newer innovations and developments. Many innovations hold the promise to make fuel cells, in particular, much more effective, widespread, and cost-efficient in the coming years. One of the key innovations is Proton Exchange Membrane (PEM) fuel cells. This is a key element in particular HFCs (hydrogen fuel cells), as they work as an electrolyte allowing $H^+$ ions generated to pass through the circuit, in turn generating electricity. These particular fuel cells, as opposed to a generic one, work at a relatively low temperature of 80 degrees Celsius, making them ideal for applications in the vehicular industry, and maybe even for portable power. Under normal working conditions, PEMs are susceptible to degradation due to repeated chemical and heat stress, especially if used for longer periods. This is due to their material, perfluorosulfonic acid. While it provides good proton($H^+$) ion conductibility, it suffers under higher temperatures. PEM cells can be a good addition to using energy that isn't concerned with the direct uses of electricity, such as in industry or, as previously mentioned, vehicles.

## Conclusion

Hydrogen fuel cells are a large step on the path to cleaner energy in the future, primarily due to their ability to generate energy while only having water as a byproduct, making them a true non-emitting energy source, aligning with future energy requirements. Innovations for HFCs are also plentiful in the form of PEMs, non-platinum catalysts for HFCs, and overall increasing the HFCs' capacity to work at lower temperatures. Such innovations allow a mass adoption of hydrogen shortly, which is only augmented by improving energy storage and clean methods of producing it. As development continues, hydrogen is a true contender towards a net-zero carbon future, at least when it comes to producing energy, bolstered by its capability of producing clean and efficient energy.

## 3.3. Nuclear Power

Nuclear power is an extremely energy-dense and reliable form of electricity generation, offering a sustainable pathway to meet energy needs, while at the same time, mitigating the problem of greenhouse gas emissions. This makes it an important source of energy in the future due to its minimal carbon emissions. While it may not be renewable, as nuclear fuels are also a limited resource, they can provide electricity regardless of the weather, time of day, or region. This already makes it more reliable than sources such as wind, solar, or geothermal. To analyse the extent to which they will be part of the future energy mix, this section will delve into the basics of nuclear power.

**Mechanisms**

Nuclear power relies on fission, a process where the nucleus of an atom is split into smaller nuclei upon being bombarded with a neutron. This allows a very large amount of energy to be released in the form of primarily heat. This heat is used to heat steam, which spins a turbine, thus generating a large amount of electricity. The primary fuel used in traditional nuclear reactors today is Uranium-235, represented by $^{235}U$. The primary chemical reaction is shown by:

$$^{235}U + n \rightarrow {}^{236}U^*$$

Here, a $^{235}U$ atom is bombarded with neutrons. In the process, ti captures one, forming an excited $^{236}U^*$ atom. Due to the latter's instability, it quickly splits into Barium-141 and Krypton-92, along with 3 more neutrons per fission event.

$$^{236}U^* \rightarrow {}^{141}Ba + {}^{92}Kr + 3n\ (+\ 200MeV)$$

These 3 neutrons released can trigger further reactions if there is $^{235}U$ in the vicinity, as they will absorb these neutrons. This leads to a self-sustained reaction, which is controlled to prevent an endless reaction. This mass amount of energy released is then used to heat water, turning it into steam, which spins turbines, generating electricity.

Note: Both 141Ba and 92Kr are highly radioactive, decaying and releasing beta rays and ..

Controlled fission, as mentioned, avoids an endless chain reaction. In most modern reactors, control rods are used to keep the reaction in check. The ability to absorb these excess neutrons depends on the material itself, and is known as the neutron absorption cross-section, expressed in barns, where 1 barn = $10^{-28}$ $m^2$. Commonly used materials include boron and cadmium.

Boron has a relatively high neutron absorption cross section of 3840 barns, and can be found in reactions in control made of Boron Carbide $B_4C$, present in coolants, or even in boric acid $H_3BO_3$. This allows the Boron to absorb neutrons in the following reactions.

$$^{10}B + n \rightarrow {}^{11}B^*$$

$$^{11}B^* \rightarrow {}^{7}Li + \alpha + \gamma$$

In this reaction, Boron-10($^{10}B$) absorbs a neutron, entering an excited state of Boron-11($^{11}B^*$). This decays into Lithium-7, an alpha ray (helium nucleus) and a gamma ray. This removes neutrons from the reaction, preventing a continuous chain.

Similarly, Cadmium as well has a high neutron absorption cross section of $2 \times 10^4$ barns. Cadmium can mainly be found in control rods, along with silver and indium. This allows Cadmium to absorb the excess neutrons in the given reactions.

$$^{113}Cd + n \rightarrow {}^{114}Cd^*$$

$$^{114}Cd^* \rightarrow {}^{114}Cd + \gamma$$

Here, Cadmium-113($^{113}Cd$) absorbs a neutron, becoming an excited Cadmium-114($^{114}Cd^*$) atom, which then decays into Cadmium-114($^{114}Cd$), also removes neutrons to provide a controlled fission reaction. However, it also releases radiation in the process, mainly in the form of gamma rays.

**Advantages and Disadvantages**

Furthermore, fission is one of the most energy-efficient processes. Traditional reactors, known as pressurised water reactors and boiling water reactors, operate at efficiencies from 33-37% according to the IAEA. Approximately a third of the energy released is converted to energy. For such a large-scale reaction, due to their being considerably less heat loss, is much more efficient than traditional forms of generating electricity, newer reactors, namely Gen IV reactors and molten salt reactors aim to push these numbers past 45% by using advanced coolants, cycling fuels and more to reduce inefficiencies which will be covered in upcoming innovations. In addition to high efficiency, nuclear power runs at almost maximum capacity year-round. As they are not affected by the time of day, weather conditions, or any other external factors, they can operate at a capacity factor of 90% or higher. Other clean energy sources, such as solar or wind, which are limited by external factors, have a much lower capacity factor, anywhere between 15 and 35%. This ensures stable energy generation through the year, contrary to its alternatives.

**Future Advancements**

One of the most transformative upcoming advancements is small modular reactors (SMRs). These reactors are much smaller, and as their name suggests, they aim to mitigate the high costs and long setup times that are required for large-scale reactors. Unlike traditional reactors that require anywhere from $6 to $9 billion, and more than 10 years to construct, SMRs are factory assembled and can be up and running within 5 years. Not only does it reduce how much time it takes to start generating more electricity, but it is a much safer investment as there is lower risk, making it more appealing for governments looking to switch to lower-carbon energy sources. While they don't produce nearly as much energy as traditional reactors, as they are much smaller, typically generating between 50 and 300MW of power, they retain the high-capacity factor of traditional reactors, making them appropriate for smaller grids, industrial uses, or remote regions where building a full-scale reactor may not be practical. SMRs also offer increased safety features, including passive cooling systems that prevent meltdowns regardless of a power failure.

SMRs can also be used in tandem with hydrogen production to increase grid stability through high-temperature electrolysis, further tying back to hydrogen being used in already functioning power systems. While not increasing the energy output, this further supports decarbonization beyond electricity. To support the electricity grid, however, SMRs can also be integrated with other renewable sources and act as a backup source to solar/wind to compensate for their intermittency. As of mid-2024, China has developed the first SMR named 'Linglong One,' and other countries such as Russia and the USA already have commercial licenses for SMRs. However, SMRs require rather high upfront costs.  While they are still cheaper to operate than traditional reactors due to their smaller scale, nuclear fuel is still costly. Furthermore, mainstream fuels for SMRs include HALEU (high-assay low-enriched uranium), which isn't widely available yet. SMRs may also take a while to be implemented, as many countries still don't have licenses for SMRs yet.

**Conclusions**

Nuclear energy has recently been recognised as a fundamental to the acceleration of decarbonisation of the global economy, namely due to its ability to generate vast amounts of electricity without emissions, while still upkeeping a high efficiency. As of 2025, there are ample number of nuclear reactors to increase the amount of energy which can be generated by nuclear energy, and as further innovations fruition, this number is only expected to increase. SMRs, Generation IV reactors, and nuclear waste recycling reactors create a safe, efficient and clean path to mitigate the issue with the current energy sources. Simultaneously, these advancements also deal with earlier concerns about safety, waste management of nuclear fuel, costs, and many other factors which may sway governments away from using nuclear reactors. In the regions where deployment of renewable sources may be limited due to weather or location, nuclear power remains an exception, and although not renewable, with the right policies and developments similar to those being implemented, can be a cornerstone to decarbonisation of the economy while meeting energy needs and further improving technology.

# 4. Analysis

## 4.1. Introduction

This analysis will examine the real-world performance metrics of the discussed energy sources: solar (photovoltaic cells), nuclear power, and hydrogen as a source to determine the most scalable, efficient, and cost-effective combination of energy sources to not only meet growing energy demands but also meet decarbonization goals of achieving net zero emissions in the future. Due to limitations of not being able to visit energy sources in person, each output method's performance metrics will be analysed using secondary data available online.

By assessing multiple factors of each of these energy production methods, using data from existing power plants and installations, the final goal of this analysis will be to create a projected pie chart of the future: an optimal energy mix by 2050, and assess how realistic that is.

To effectively analyse the extent of each of the sources in the future, some calculations will be made. First, the global energy needs in 2025 will be predicted, along with calculating how much of that should be IDEALLY coming from the respective sources. Calculations will also be made on the assumption that all sources of the respective energy production methods have similar performance metrics to the ones analysed subsequently. Additionally, further predictions such as overall efficiency, land usage and performance ratio and capacity factor based on data reviewed.

According to the IEA, global energy needs are expected to rise 4% annually in the following years. Using a base of 24,398TWh in 2022, a 4% annual increase means 27,444TWh of energy will be consumed in 2025.

## 4.2. Analysis of 75 Solar Farms in the USA, 2021

Secondary Research Source: A report provided by the USA's department of energy regarding the performance of 75 solar farms across the USA in 2021. Figure 2.1 is extracted directly from the report and figure 2.2 is made using data from the report.

**Figure 2.1 represents statistics taken from the report of analysis of 75 federal PV**

**systems in 2021**

**Table ES-1. Key Performance Indicators Resulting From the Analysis of 75 Federal PV Systems**

| | Minimum | Average | Median | Maximum | Standard Deviation |
|---|---|---|---|---|---|
| Availability | 31.0% | 95.1% | 98.0% | 100.0% | 8.8% |
| Performance Ratio | 46.0% | 78.6% | 79.0% | 101.0% | 11.7% |
| Energy Ratio | 29.0% | 74.6% | 76.0% | 101.0% | 14.1% |

**Figure 2.2 shows a table with data extracted from the given report, paired with known information in general regarding photovoltaic cells**

| Parameter | Current Average | Current Range | Projected Future Values (5% increase) | Description |
|---|---|---|---|---|
| Installed Capacity (MW) | 30.7 | - | 32.3 | Total output installed |
| Performance Ratio | 78.6% | 46%-101% | 82.5% | Ratio between actual and expected generated power |
| Availability | 95.1% | 31%-100% | 95.1% | Percentage of the time that systems are operational |
| Capacity Factor | 23.5% | 15%-30% | 24.7% | Efficiency of solar farms based on maximum output |
| Degradation Rate | 0.6%-1%/year | 0.5%-1.5%/year | <1% per year | Annual efficiency loss |
| Land Use Efficiency | 5 acres/MW $2km^2$/100MW | - | $1.9km^2$/100MW | Land use for each 100MW of installed capacity |
| Expected Lifetime(years) | 25-30 | - | >30 | Operational time prior to replacement |

In 2024, solar power contributed to about 7% of global energy needs, an increase from 2023's 5%. Continuing on that trend, solar panels can contribute anywhere from 8-9% of global energy needs in 2025, producing upwards of 2,195 TWh(Terawatt Hours) annually. Assuming that solar panels globally have similar metrics to those 75 analysed above, further assumptions can be made regarding expansion through extrapolation. The US farms have a total installed capacity of 30.7 MW (Megawatts). Taking into consideration their availability of 95.1%, and the capacity factor of 23.5%, this solar farm produces 56.2 GWh (Gigawatt Hours) annually. In 2024, solar power reached 2000 TWh of energy produced. To match the increasing trend, 195 TWh more need to be produced. To fulfil such an expansion, based on our assumption that all solar panels have similar metrics, around 3000 additional similar solar farms would need to be installed worldwide. With each farm having about 30.7 MW of capacity, an additional 3000 farms increase installed solar capacity to 92 GW. However, to accomplish this, a lot of land would need to be used. With a land efficiency of 2 $km^2$ per 100 MW, over 1800 $km^2$ worth of solar panels would need to be installed. While this may seem like a very large number, India alone was able to expand its installed capacity by 100 GW (Gigawatts). Similarly, if all the countries in the world put their effort into expanding solar power, this goal can be achieved. Further, a $km^2$ worth of solar panels can help sequester up to 48,900 metric tons of $CO_2$ if used instead of polluting sources of energy. Thus, the additional 2000 $km^2$ installed can further reduce up to 97 million tons of $CO_2$.

Using the same 4% annual growth, energy demand is expected to reach 33,389 TWh in 2030. Similarly, if solar too continues to expand till 12% of energy in 2030, it should be generating around 4006 TWh, which is almost a double from 2025. However, with upcoming developments in solar, assuming a 5% increase in efficiency, land area efficiency and installed capacity in each of the solar farms, means an additional 30,600 such farms would need to be installed, requiring 17000 $km^2$ of land. Due to the increased efficiency, solar panels would also likely sequester more $CO_2$ emissions, up to 51,425 tons per $km^2$, and thus in total, reduce up to 870 million tons of carbon emissions, almost ten times of what it was 5 years prior, showing the high scalability and improvements in solar. However, expanding to such large scales in a short time might not be possible as of today, but with upcoming developments, it is certainly possible. Due to its limitations regarding batteries, which is a fundamental that cannot be changed to a large extent, it is unlikely that in the near future, solar power can completely take over. Thus, similar to the IEA's projected data, solar power should account for 70% of renewables together along with win, nearing anywhere from 12 to over 25% of total energy produced by 2050.

## 4.3. Analysis of Chinese Nuclear Reports, 2022

Secondary Research Source: A report provided by the IAEA regarding the performance of all nuclear power plants in China from 2019 to 2021, compiled and released in 2022. Figure 3.1 is made using data from the give report.

**Figure 3.1 is a table with data extracted from the IAEA's report**

| Parameter | Current Average | Current Range | Projected Future Values (5% increase) | Description |
|---|---|---|---|---|
| Installed Capacity (GW) | 53 +18.8(under construction) | - | 75.4 | Power output of all reactors in China |
| Capacity Factor | 85.8% | 84.3%-86% | 90.1% | Efficiency based on maximum possible output |
| Availability | 91.2% | - | 91.2% | Percentage of the time that systems are operational |
| Collective Radiation Exposure (man.Sv) | 0.252 | 0.000244-0.563 | <0.24 | Annual dose of radiation |

Similar to the calculations made for solar power for 2025, and for future projections, nuclear power will also be analysed thoroughly in the same manner, using key metrics from a report series of a nuclear power which has high load and regular use in The People's Republic of China. Assuming this(these) reactor(s) as a "base" or "average" reactor(s) which has(have) a high-capacity factor, and extrapolating the data to fit the global scale, the data will be matched up with IEA predictions to continue building the future pie chart.

In 2025, projected global needs are 27,444 TWh. The IEA also projects nuclear power to generate a record level of 9% of total electricity generated from 439-440 nuclear reactors, thus generating ~2469 TWh of electricity totally. China alone hosts 53 nuclear plants, with a total installed capacity of 71.8 GWe. Taking into consideration the capacity factor and availability of the reactors in China alone, they can generate up to 492.6 TWh at high efficiencies.  Assuming that all nuclear reactors have similar performance metrics and efficiencies, 440 nuclear plants can generate a whopping 4,090 TWh, which exceeds what nuclear power is expected to make. This demonstrates a higher installed capacity than required, which is very beneficial as it means that nuclear plants won't have to operate at maximum capacity through the year. However, it also takes into account that not all nuclear plants globally might work similar to those in China. However, with an increased usage of nuclear plants worldwide, the demand for $^{235}U$ also grows. 1g of $^{235}U$ can produce ~24 MWh, thus requiring a total of 102.9 metric tons of $^{235}U$. With a minimal carbon footprint of 15-50g of $CO_2$ per kWh compared to the carbon footprint of a gas power generator(450g/kWh) or a coal powered generator (1,050g/kWh), nuclear energy produced instead of using fossil fuels can save between 400 worth of $CO_2$, resulting in a total of 1.2 billion tons of $CO_2$ saved annually if nuclear power consumption increases in 2025. According to the IEA, 2025 will be the year showing the largest increase in nuclear power consumption. However, there are certain drawbacks too. An increase in the usage of nuclear fuels means a lot of increased nuclear radioactive waste, which can be extremely dangerous. Additionally, nuclear fuel is still not a renewable energy source, which means eventually, it may run out. If nuclear energy does expand, running out of it would be dangerous, as there would be no immediate substitutes, which may lead to an energy crisis in the future (that is if we over rely on nuclear power). However, this is a problem that will likely be faced after a long, long time, making nuclear energy a good substitute for the next few generations. To continue on this increasing trend, future projections of nuclear power will also be analysed.

IEEJ, The Institute of Energy Economics, Japan, predicts that nuclear energy's contribution to world energy needs will increase to 3511 TWh annually by 2050, and can even reach as high as 5565 TWh if all nuclear countries continue to increase their number of nuclear plants while simultaneously implementing aggressive decarbonisation policies. At the same time, the efficiency of nuclear plants will also be bolstered due to developments made over time. Taking into consideration the increases in the capacity factor and installed capacity in the near future, nuclear power worldwide can contribute up to 4507 TWh. However, this is only anticipating marginal increases in the near future. As mentioned, if countries do continue to increase their capacities at higher rates, reaching 5565 TWh in a span of grater than 20 years isn't impossible; in fact, it's more than likely what is going to occur if we are to reach a decarbonised economy and meet the Paris Agreement soon.

The IEA's World Energy Outlook in 2023 projects to increase global nuclear capacity from 390 GWe to 622 GWe by 2050, likely meeting the increased number of plants required. However, this will need almost doubling annual investments in nuclear power to about $120 billion by 2030, to make up for the costs of building nuclear plants, buying fuel, and further improving the technologies at hand. An increase in the capacity of nuclear plants will further help sequester $CO_2$ emissions, as 5565 TWh of energy generated through nuclear plants can save up to 2.78 billion tons of $CO_2$ annually, almost doubling how much is reduced from 2025. Due to nuclear power plants not needing to occupy more space to expand their capacity, the area taken up will not be analysed. On the other hand, their limiting factor is more so their fuel. To generate the aforementioned amount of electricity, 231 metric tons of $^{235}U$ would be required. While this is still manageable, the increased costs and an increase in nuclear waste may be a barrier. However, developments such as nuclear reactors, which can use the waste as inputs, can offset the drawbacks and help meet global energy needs. This shows how nuclear energy may need expansion to achieve its true potential, and thus even in the longer run, it may be beneficial to limit it to about 10-15% of energy production to ensure too much is not put into nuclear energy, and also to ensure that other alternatives, namely renewables are explored. These calculations show that the IEA's projection of 10% is an accurate estimate of what portion of the world's energy can and should come from nuclear power, at least till 2050.

## 4.4. Self-Analysis of Hydrogen

Between 2020 and 2021, global hydrogen demand increased by 5%, increasing to a total of 2.5%. As this was right after/during the recovery post lockdown, a slightly larger trend in the coming years can be assumed. If this rate of increase is anywhere between 5-15%, hydrogen should be set to generate over 4% of the world's energy demand in 2025, generating up to 1,097TWh. However, the majority of hydrogen today is used in industrial sectors rather than direct electricity/power generation. For instance, refining, steel manufacturing, iron extraction, and ammonia production are extremely reliant on hydrogen. Further, hydrogen is also utilised in support of electricity grids of telecommunication networks throughout the US, proving it to be a reliable source for further implementation in the future. Unfortunately, as of 2025, detailed data on hydrogen's large-scale contribution isn't easily available. Its use in power generation is still quite early on, with only minor portions of it being used at capacities they are capable of. For example, many of Germany's hydrogen-based turbines are capable of utilising 100% hydrogen fuel. However, for now, they still to lower % based blends. Despite the lack of data, hydrogen continues to play a crucial role as a supporter, and maybe as a standalone source in the future, as we shift to a low-carbon economy. While more judgements could have been made had there been easy access to data, its future impact is certainly explorable as well, and will only be more rewarding as hydrogen is adopted in the future.

However, hydrogen is said to make quite the jump by 2050, estimating to reach 12% of global energy demand. Estimates say that hydrogen altogether will be responsible for 7-10% of the total final energy by 2050. However, as previously mentioned, we don't have the capacity yet to scale so rapidly, due to a large number of limitations in infrastructure regarding hydrogen, which continues to remain a large bottleneck due to many regions lacking support to start using large-scale hydrogen systems. As the amount of hydrogen used will increase tremendously in the coming years, cost may likely be another issue. Hydrogen fuel comes in many types: blue, green, grey, and turquoise. The cost of producing green hydrogen, which is hydrogen that does not create any pollution while being produced, is significantly higher than the others. In areas with abundant forms of renewable energy, the cost can drop to €1/kg of hydrogen in 250, but other areas may require €2/kg, making production not profitable. This could lead to a variety of problems, which may require large-scale transport of hydrogen, which just so happens to be one of its drawbacks. While many advancements are being made, this remains quite an unstable area. Even with these advancements, cost reduction isn't significant, and thus, hydrogen will likely remain much costlier than traditional energy sources, limiting the number of governments and firms that truly use it.

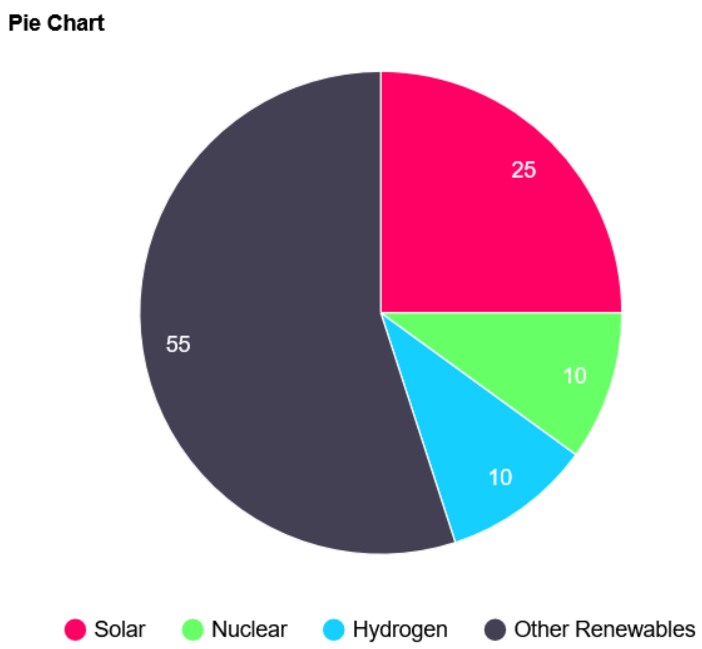
Despite the ambitious goals to adopt large amounts of hydrogen by 2050, the current trajectory doesn't meet what is required to meet global climate commitments and complete the Paris Agreement. By 2050, global energy demand is said to reach between 900-1000EJ, with hydrogen expected to supply up to 120 EJ. However, as of 2025, only about 1,079 TWh are produced. Additionally, only about 1% of hydrogen used today is classified as clean hydrogen. To meet said targets in 2050, the World Energy Forum and Hydrogen Council estimate nearly a 10x increase in the capacity of electrolysers to procure that clean fuel, and about 9000 TWh of renewable energy. Furthermore, there is also a large financial burden, requiring between 9-12 trillion dollars of total investment, with up to 400 billion annually just for increasing infrastructure. As previously mentioned, cost is also a problem, and regarding green hydrogen, even more so, with costs reaching up to $6/kg. To achieve goals in the financial plan, the price must drop to $1-2/kg, which is certainly possible through increasing the efficiencies of the extraction. This shows truly how ambitious this goal is, and also shows that without putting in an increased effort, 2050 projections and goals are unlikely to be met.

Contrary, achieving this goal is still entirely possible. However, it will require a large acceleration in production, infrastructure, and many more policies to support and incentivise the use of hydrogen fuel. Without hydrogen, the world may fall short, putting decarbonisation efforts at risk. Thus, the optimal role of hydrogen in the energy mix now requires it to produce a minimum 10% of global energy needs, further proving the IEA's projections correctly.

## 4.5. Final Insights

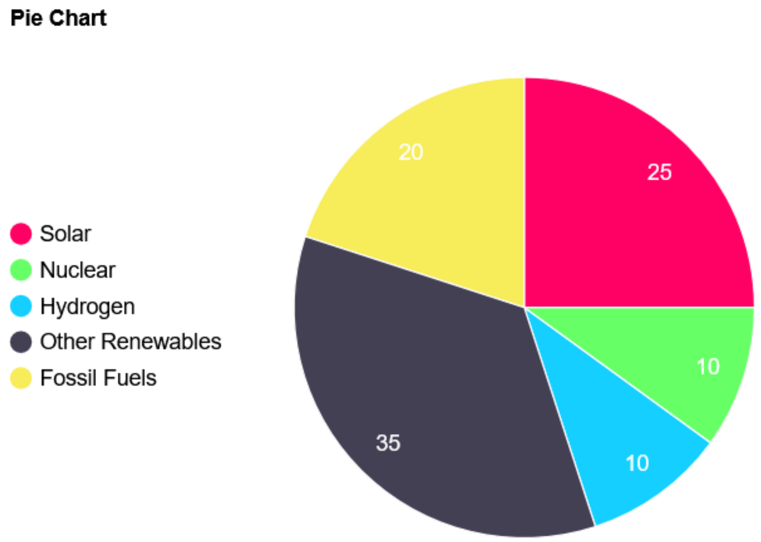
Based on the interpretations of previously mentioned sources of energy, a final projected energy mix can be established. As the IEA mentions, an expected 80% of global energy demands are to be met by renewable sources. Assuming that solar panels contribute to 25% of global energy demands by 2050, as calculated, other renewables should contribute to approximately 55%. Further, hydrogen and nuclear are each 10% as well. This is represented in the pie chart given below.

**Figure 4.1 represents an optimistic future energy mix based on calculations in the analysis section**




However, certain aspects of this mix make them overly optimistic and unrealistic, at least given current trends. Firstly, eliminating fossil fuels within just 25 years calls for a transformation far more extreme than anything we have seen. *The IEA's Net Zero by 2050* indicates that even under the most limiting policies, fossil fuels are still expected to contribute between 10 and 20% of global energy demands. Additionally, while expanding solar power to 25% is certainly feasible in the best of scenarios, other renewables, on the other hand, even though they are expanding, are extremely unlikely to contribute to 55% of global energy needs entirely alone. While this analysis didn't include other renewables, renewables contributing to 80% by 2050 as the IEA projects, might not be realistic based on the elements that were analysed in this section.

**Figure 4.2 represents a realistic future energy mix, adjusted from Figure 4.1**




A more realistic pie chart still consists of fossil fuels and other sources held between 10-20, thus reducing the other renewable sources to about 35%. Now, renewables as a whole contribute to 60% of global energy demand, which is still a lot. However, based on current trends, it is a lot more likely than 80%. This is represented in this second, more realistic pie chart.

# 5. Conclusions

The transition to a lower-carbon economy by 2050 is an ambitious yet achievable goal. While there are many obstacles in terms of scalability, cost, available infrastructure, and more, there are many advancements and expansions present to counteract this to achieve climate goals. Eliminating fossil fuels is unlikely, but reducing their usage in the energy mix will reduce emissions, paired with the fact that using these other sources doesn't pollute either. Achieving net-zero emissions depends on the aforementioned expansion and advancements, implementations of policies, and a lot of cooperation to ensure the same end goal. By harnessing the power of solar power, nuclear power, and hydrogen fuel, a decarbonised economy looks more and more likely over time.

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