Why nuclear power is necessary

A discussion document of The Workers' Party of Ireland

Introduction

Nuclear power has a checkered past. In the 1950s, when countries began attempting to transition nuclear technologies to civilian use, the optimism was tremendous. Many talked of limitless power, "too cheap to meter". As a result there was a massive expansion of nuclear in the United States, and then subsequently into Europe. An alternative and parallel development occurred in the Soviet Union which also developed civilian nuclear power but without the advantages of western cooperation.

France and Sweden embraced nuclear as no other countries had before or since. In France's case, around 70% of all electricity is now provided by nuclear power, making it one of the most efficient countries in terms of carbon emissions in the world.

Yet all was not roses. The United States' aggressive foreign policy created an ever heightening threat of nuclear conflict with the Soviet Union. By 1983, nuclear bombers were flying weekly just up to the edge of Soviet airspace to let them know that doomsday was imminent. This policy alarmed the Soviets greatly, however, it also alarmed European populations which could see clearly that they would not escape the cross-fire of a nuclear war between the two cold war powers. Between 1979 and 1983, mass protests against nuclear weapons and nuclear power were held all over Europe.

And then a massive accident at the Chernobyl nuclear power plant in 1986 lead to significant radioactive release and contamination of surrounding areas. This accident, the greatest nuclear accident so far, decisively turned the majority of the public in the developed West against nuclear power.

Yet this is not the end of the story. The worst nuclear disaster of all time was severe, but according to the World Health Organisation, all told, around 4,000 people are expected to die in total[1] as a result of the reactor explosion and subsequent contamination. Of the "liquidators”,' those people directly involved in the cleanup, over 99.8% survived or died of unrelated causes, such as accidents. Contrast this with the estimated 2 million who die every year from coal-related pollution and it becomes obvious that the scale of the disaster is not being treated proportionally.

Since Chernobyl, reactors of its type (RBMK with no containment structure) are no longer built. And despite high-profile accidents at Three Mile Island and Fukushima, the resulting total deaths from direct causes were zero and one, respectively. Safer pressurised water reactors are the norm and even safer reactors based on more advanced technologies are possible.

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[1] *Health effects of the Chernobyl accident and special health care programmes.* World Health Organisation, 2006

Aside from the dangers that coal and other fossil fuels present, there is now the ever more dangerous looming threat of climate change. Climate change will have profound impacts on the human population, leading to changes in the amount of arable land, to rising sea levels, increased extreme weather events, as well as extreme temperatures. This is likely to lead to large scale human displacements, which will in turn create the conditions for resource conflict.

While it is too late to stop rising temperatures over the next few decades, it is not too late to start slowing it down until we can turn the other direction. We will have to cope with the costs of temperature increase, but the sooner we start improving the situation, the less damaging these costs will be.

Preserving *any* future is an absolute prerequisite for a positive future. Yet nuclear power also holds out the possibility of a rich and abundant future. While it is impossible to achieve abundance for everyone on the planet with fossil fuels due to the combination of their destructive impacts and limited quantities, with nuclear it is feasible to power the entire world for millennia.

Power sources cannot be looked at in isolation. It is necessary to compare two power sources in terms of their impacts, and again to compare the cost of *not* having power. Without this careful approach to comparison arguments lose connection with reality. The cost of not having power can mean not having clean water, not having sufficient heating or cooling, not having sufficient food, not having adequate hospitals, and not having decent transport. Power impacts the entire hierarchy of needs and the costs of power-poverty are tremendous.

When the comparative approach is taken, nuclear takes the lead. There is simply no way to address human energy needs and climate change using known technology or near-term technology without having nuclear technology as a key component.

Structure of this document

This document contains both technical information about the scientific basis of nuclear power, as well as comparative analysis and economic and strategic reasons to support the use of nuclear power. Each section is written to be as self-contained as possible, but if they are taken in progression the reader may find each of them easier to understand.

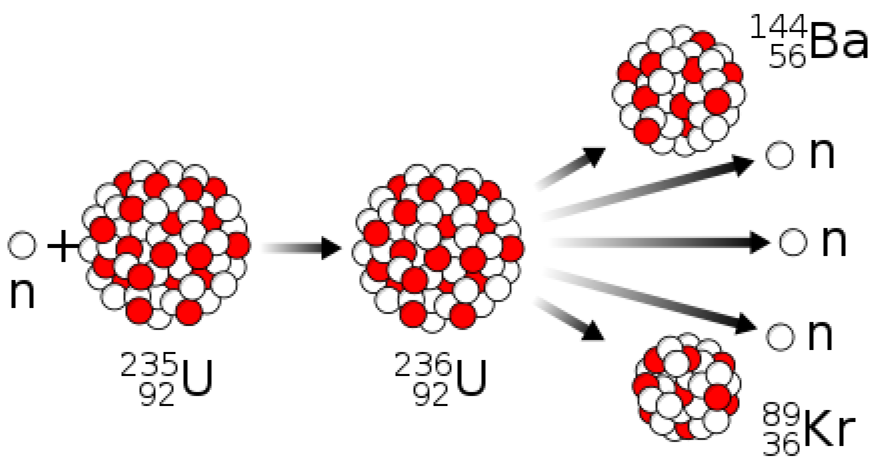
The first section **What is nuclear power?** speaks to the physical and technical basis of nuclear power. Those who are more interested in the arguments in favour of nuclear can skip ahead to **Nuclear for Ireland's energy security?** (p. 9). From there, the reader can refer to specific sections (outlined in the Table of Contents) which address their specific interests and concerns.

What is nuclear power?

We are all familiar with the process of burning wood to obtain heat. At base, this heat comes from a chemical reaction which releases energy present in the chemical bonds between atoms. Most of human power now originates from such chemical reactions. However, there is another way to obtain heat, by releasing the energy present *within the atoms themselves*. The energy density present in these internal bonds is fantastically huge compared to the binding energy in chemical bonds. As an example, about 20 million times more energy is released from the splitting of one atom of Uranium than one oxidation of methane.

Fission

Not all atoms will readily free their internal binding energies. There are certain atoms which are near enough to instability that we can easily push them over into splitting, but not so unstable that we can't find them in nature. These atoms are called *fissile*. By striking the fissile atom with a neutron, we can help it to release some of its internal binding energy and split into other smaller atoms.



A typical uranium 235 fission event releasing Barium 144 and Krypton 89

The nucleus of an atom is made up of smaller particles called neutrons and protons. Each element has a specific number of protons corresponding with its *atomic number*. This number of protons dictates its chemical properties. However, it may have a varying number of neutrons in a range that is determined by the nuclear interactions. This leads to each element having a number of possible *isotopes* corresponding with different numbers of neutrons. This isotope is described by giving its atomic weight, which is the number of neutrons plus the number of protons.

The most readily available fissile atom is Uranium 235. Most other fissile atoms are rare or must be manufactured. There are additionally classes of atoms which can readily absorb a neutron, turn into a heavier particle, and become one of these fissile atoms. This expands the amount of nuclear fuel which is available by an enormous amount. For example, the much more abundant Uranium 238 can be converted by neutron absorption into Plutonium 239 which is itself fissile.

In order to create a practical power device, we need to create a self-sustaining *chain reaction*. When Uranium 235 is bombarded by a neutron and splits, it generally breaks into two or three smaller atoms called *fission products*, and some number of neutrons. If one of those neutrons hits another Uranium 235 atom and splits it, then we have a self-sustaining chain reaction. In practice, many things happen to the neutrons which means some care must be taken to ensure enough neutrons are there to continue the reaction. Neutrons can fly out of the core, they can be absorbed by Uranium 238 or they can be absorbed by any of the fission products leading to a smaller number of neutrons.

Moderators

The velocity (or energy) of the neutron is also very important to how likely it is to split or be absorbed by other atoms. Different atoms are more or less fissile depending on the velocity of the incoming neutron. In order to tune the behaviour, many reactors use a *moderator*. When neutrons first exit a fission event, they are extremely *fast*. In fact, we call them *fast neutrons*. We can slow them down by knocking them into other atoms that will absorb some of their energy. We have to be careful which material we use for this purpose. We want the number of collisions to be few (so they don't fly out of the core first) and we want a material which will not be converted into something else by absorption of the neutron.

In practice, this means that the most common moderators are:

- hydrogen (bound with oxygen to make water)
- deuterium (hydrogen with an extra neutron in what we call *heavy water*)
- graphite
- beryllium

It is also possible to make a *fast reactor* and not slow down the neutrons at all. However this requires very different design decisions.

The core

The release of energy from nuclear fission manifests itself as *heat*. That is, it increases the general energetic motion of the fuel particles. This must then be transmitted to the outside, and ultimately to some other process which either uses the heat (process heat) or a mechanism which converts the heat difference into electricity.

The core is where we put the fuel. In most reactors, fuel is *enriched* uranium, meaning uranium in which the fraction of uranium 235 (the fissile portion) is increased. However, we could use plutonium 239, or even uranium 233.

It is possible also to burn natural Uranium (unenriched), given a suitably good moderator. The only commercial reactor of this type is the CANDU (Canada Deuterium Uranium) reactor which uses heavy-water as a moderator.

Some reactors, *breeder reactors,* not only burn fuel, but also convert fissile elements into fertile elements; they *breed* more fuel. This allows us to turn Uranium 238 or Thorium 232, both of which are quite abundant, into fuel. Finding safe and cheap ways of doing this would give humanity access to tremendous amounts of power that would last many thousands of years.[2]

In standard pressurised water reactors (PWRs), the fuel is either enriched Uranium or a mixture of Uranium and Plutonium.

The form of the fuel is also important. In practice, nearly all reactors use Uranium oxide, or mixed oxides which include both Uranium and Plutonium. Russia is carefully evaluating a safer fuel with higher density and better heat transfer properties: Uranium-nitride, but a suitable industrial fuel synthesis process has not yet been developed.

The fissile elements are generally kept in a suitable *cladding*, a protective jacket that helps to keep the fission products from being released. In light water reactors this is typically a zirconium-steel alloy (zircaloy).

There have been other experimental reactors with liquid cores. Some in aqueous solution, some as molten salt. These liquid core reactors have many potential advantages over conventional solid core reactors, but they are not ready for commercial development except perhaps for production of rare radioisotopes. Unfortunately, they still require prototype development.

Control

The core also often contains some control features used to slow the nuclear reaction. These control features are sometimes passive. For instance, increasing heat can cause bubbling in a water coolant, reducing the moderation of neutrons and thereby slowing the reaction rate and cooling the reactor.

Some of these features are active. This often means using a *neutron poison*: an element which is highly likely to absorb neutrons slowing the reaction. One common method is the use of control rods.

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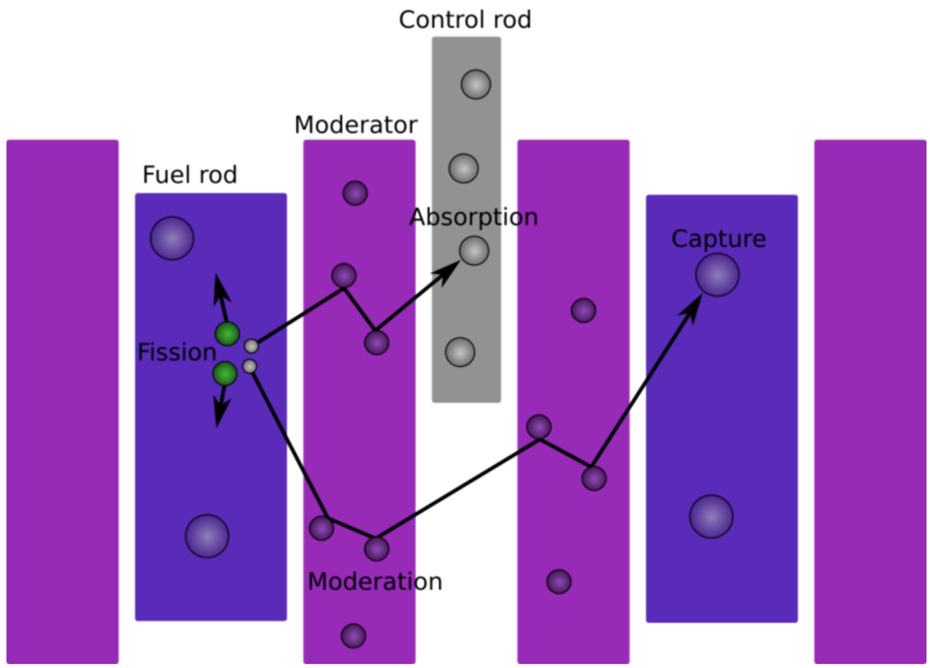
[2] "Breeder reactors: A renewable energy source", American Journal of Physics 51, 75 (1983); Bernard L. Cohen http://large.stanford.edu/publications/coal/references/docs/pad11983cohen.pdf

These can be made with a range of materials: boron, cadmium, silver, etc. It is also possible to introduce a neutron poison to the coolant, such as boric acid.

In a typical light water reactor, shut down of the reactor is achieved by using several control rods at once, effectively killing the chain reaction. Controlling the reaction rate of the reactor is one of the most critical areas of safety.



Coolant

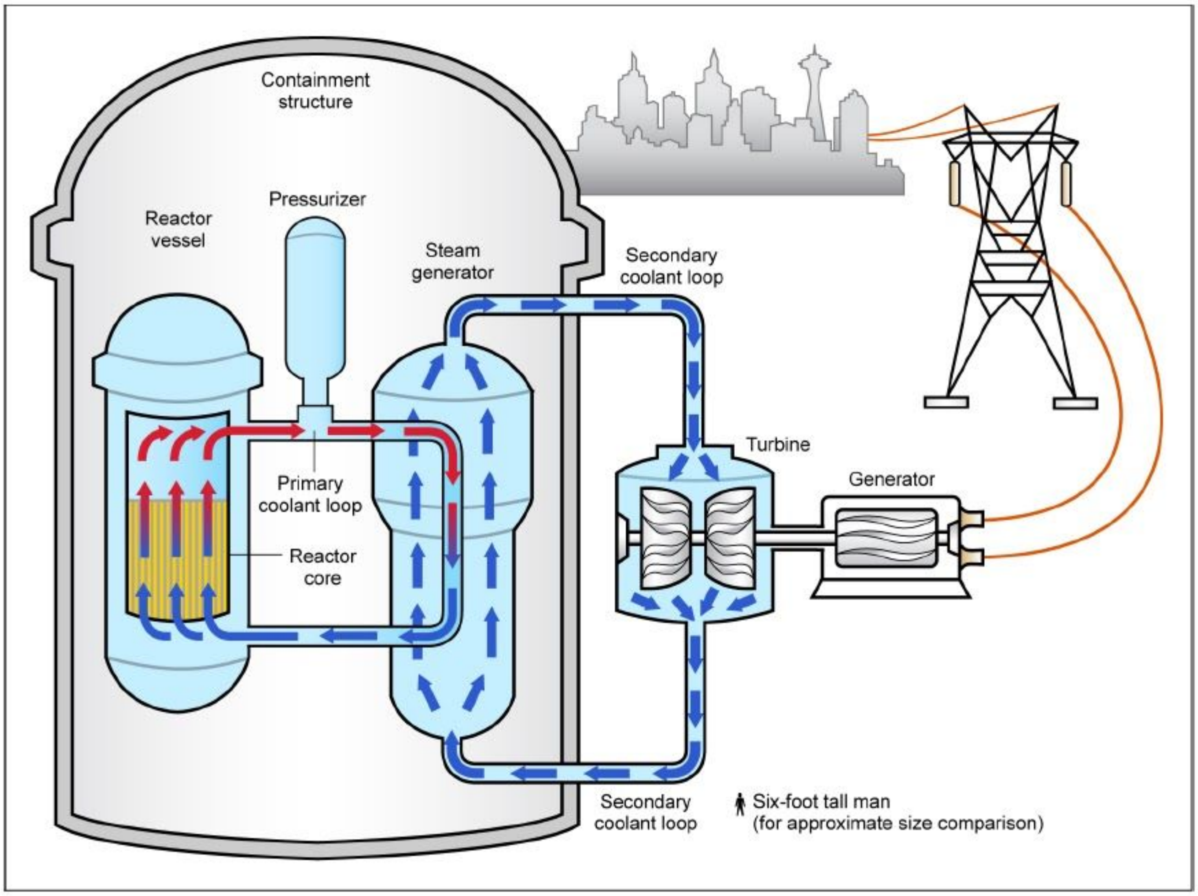
The core gets hot, but we need to move the heat away from the core either to use it as process heat, or towards a *heat engine*, in order to turn it into mechanical energy. This process requires a coolant. There are many potential coolants and many factors that influence coolant choice, yet almost all commercial nuclear reactors use either water, or heavy water, as the coolant.

There are also fast reactors which require that the coolant also functions as a moderator. That is the coolant must be largely transparent to the neutrons so as not to slow them down. These generally choose one of liquid lead (typically Lead-Bismuth eutectic) or liquid sodium.

Exotic coolants include molten salts such as sodium chloride, lithium fluoride and beryllium fluoride, gas cooling with CO2 or helium, or even organic fluids.

Heat use

Process heat is the use of heat to perform some useful function. This could include district heating reactors such as those built in China, or it could be something such as desalination, extracting clean drinking water from sea water which is used in several countries, or for chemical synthesis or other industrial processes.



Source: GAO, based on Nuclear Regulatory Commission documentation. | GAO-15-652

The most typical use of the heat however is to generate electricity. A light water reactor uses the heat from the core to heat up water. This heated water is then used to generate steam. The steam then spins a turbine which generates work. At the end of the day, the light water reactor is not that dissimilar to a uranium powered steam train.

The future

As we have seen, there are many available types of reactors, and many reactors which could be developed in the future. These developments should be primarily driven by two factors: safety and sustainability.

Great strides have been made in the safety of conventional light water reactors. New reactors are much safer than the ones built in previous decades and old reactors have been retrofitted with new active and passive safety measures. Yet to take another big step forward in safety requires substantial redesign.

Proposals for some reactors in development which claim greater safety include:

- Molten salt reactors (MSR)
- Liquid metal cooled fast reactors (LMFR)
- Small modular reactors (SMR)
- Pebble bed reactors (PBR)

In terms of sustainability, light water reactors in their present form only burn some 1% of the fuel they are given. If the entire world were to switch to nuclear, this level of inefficiency would put pressure on Uranium reserves and it would generate an unnecessarily large amount of waste. However breeder reactors can provide a solution to this problem by increasing the conversion to energy (known as burn-up). Some designs can get arbitrarily high burn-up. Fast reactors can even transmute long-lived radioactive waste into short-lived waste. This makes fast reactors a very desirable medium to long-term research goal.

Nuclear for Ireland's energy security

Any country which hopes to control its policy and make its own decisions must have the tools to make those decisions for itself. Energy security is core to the goal *functional* sovereignty. While everything of value requires human labour, *most* things of value also require some energy input. This means energy can be (and has been) a critical choke point that can facilitate autonomy if energy is available in abundance, or crush it utterly in the case of embargo.

For those who would like to take a very different political economic path, one based on equality and the public ownership of production, the threat of foreign manipulation can never be far from their mind. The global world order is a capitalist one, and those who don't play ball do not have smooth sailing ahead of them.

Ireland is a very small country, which means it is even more sensitive to economic pressure than a country such as France. A US embargo on oil today would grind the entire island to a complete halt. With an independent power source, we could weather the storms of fortune with far greater confidence.

Ireland has been endowed with just such a power source. As luck would have it, we have natural uranium at such concentrations that mining companies have been interested in obtaining mining licences. It is not clear exactly how much uranium Ireland has as yet but power densities in uranium are so high that even small amounts could power the small population of the island for a very long time.

A state driven investigation into the total quantities and locations should be undertaken. Without that information it is impossible to know for sure how long uranium supplies would last for a standard light water nuclear reactor. However, we do know that there are significant concentrations in Donegal due to mine prospecting going back to the 1980s. We also know that uranium concentrations in water are quite high in Westmeath, Wicklow and Carlow due to leaching into the water supply. And indeed this matches with areas known to be high in radon release: another indicator of the presence of uranium.

The development of this resource would require significant investment, but given Ireland's very small energy requirements, it's highly likely that it could not only satisfy Ireland, but become a lucrative export. It would create a large number of jobs in prospecting, mining, processing and fuel fabrication. And it would save Ireland on the cost of importing oil and free it from the vagaries of the international oil market.

With nuclear as a baseload power, and wind power to top it up, Ireland could be completely self sufficient and even be a consistent exporter of power abroad. Even more importantly, it could do so without releasing almost any CO2 in the process of power generation!

Nuclear is safe

Nuclear power evokes fear in the hearts and minds of many. But is this fear well-founded or is this danger little more than a myth?

When we compare nuclear power to other energy sources, the safety of nuclear power becomes apparent. The European Union did a survey of *externalities* of power production by source and location called ExternE[3]. This survey concluded that of the power systems used in Europe, the cost in human life per terawatt-hour (a very large unit of energy) was lower for nuclear than for any other power system save hydroelectric, a power source unavailable in significant quantities in Ireland due to geology. This is not an isolated study, another giving by Markandya, A., & Wilkinson[4] in the Lancet journal found effectively the same result.

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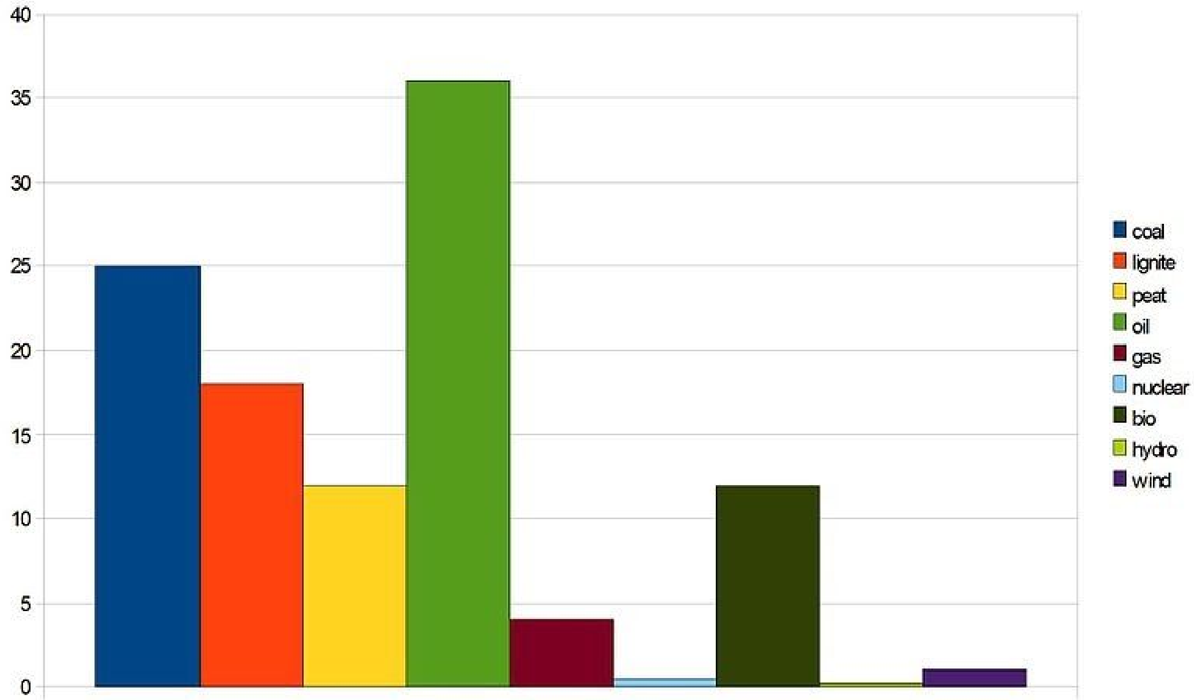
[3] *Electricity Generation - Taking into Account Health and Environmental Effects*. Nils Starfelt Carl-Erik Wikdahl, ExternE

[4] Markandya, A., & Wilkinson, P. (2007). *Electricity generation and health. The Lancet*, 370(9591), 979–990. doi:10.1016/s0140-6736(07)61253-7



Data From: Electricity Generation - Taking into Account Health and Environmental Effects Nils Starfelt Carl-Erik Wikdahl, ExternE

The resulting deaths from wind power are surprising to many. However, wind generates far less power than nuclear has ever done. And while there are no big catastrophes from wind and solar, there is a slow stream of deaths from smaller accidents. There are far more materials involved in solar and wind, requiring far more workers to install, remove and perform maintenance, and there is far less stringent oversight or regulation on the industry. For solar, a common cause of death is falling from heights during installation. For wind, the process of maintenance also requires ascending heights.

How could nuclear possibly be the safest option if the general public believe that it is so dangerous? Firstly, accidents are extremely rare, but very significant when they do occur. Nuclear accidents have been much more heavily covered in the media than other energy-related disaster and evoke unwarranted panic. At Fukushima, according to the WHO, there was one death attributed to radiation[5]. During the same earthquake, a natural gas plant exploded and five people were instantly incinerated. These petrol-related deaths provoked little concern from the public.

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[5] *Health risk assessment from the nuclear accident after the 2011 Great East Japan earthquake and tsunami, based on a preliminary dose estimation*; WHO

The wide-scale displacement of people in Fukushima *did* result in deaths from stress, panic and lower living conditions. Approximately 2,000 people are expected to have died from the evacuation, largely the elderly. In retrospect, this displacement should never have occurred.[6] Assessment of radiological impact shows that having *no* evacuation would have had a much lower cost of life excepting only for the zone immediately adjacent to the reactor facility. To make matters worse, the response of shutting down other functioning nuclear power plants during the alarm surrounding Fukushima led to increases in energy prices such that the mortality from energy poverty is higher than the accident itself.[7]

The only disaster in history with an unavoidable and large death toll due to radiation has been the RBMK reactor at Chernobyl. This reactor was built using incorrectly designed control rods and no containment structure allowing wide radiological release. All remaining RBMK reactors have been retrofitted to remove these defects, and no other nuclear power plants exist without suitable containment structures. Russia no longer builds RBMK reactors, preferring to replace its fleet with the newer VVER pressurised water reactor. This type of disaster will never happen again.

Safer again

Despite the comparative safety of nuclear power as compared to all other power sources, safer nuclear reactors which are simpler and less likely to have defects are highly desirable. One of the main causes of nuclear safety problems is the use of water as a coolant. Water has a very low boiling point. It must therefore be kept under pressure to keep it from flashing to steam. Once turned to steam, it will fail to evacuate heat from the core. To make matters worse, the cladding of fuel elements is typically made with zirconium which acts as a catalyst enabling steam to split into hydrogen and oxygen providing a readily explosive gas.

The hydrogen problem can be mitigated with the use of passive autocatalytic recombiners (PAR) which put the hydrogen and oxygen back together as water, and with proper venting systems. In fact, TEPCO, the operator for Fukushima had evaluated such systems but deemed them unnecessary.

The simplest solution to the problem is to shrink the size of the reactors. This loses some efficiencies, but the containment structures can be made virtually impregnable, significantly increasing the safety of the reactor. This is the approach taken by the SMRs (Small Modular Reactors). Since the SMRs are a scaled-down version of already existing reactors, the

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[6] *Was the Risk from Nursing-Home Evacuation after the Fukushima Accident Higher than the Radiation Risk?* PlosOne; Shuhei Nomura, Stuart Gilmour, Masaharu Tsubokura, Daisuke Yoneoka, Amina Sugimoto, Tomoyoshi Oikawa, Masahiro Kami, Kenji Shibuya

[7] *Be Cautious with the Precautionary Principle: Evidence from Fukushima Daiichi Nuclear Acciden*t; Matthew J. Neidell, Shinsuke Uchida, Marcella Veronesi, NBER Working Paper No. 26395

difficulties in implementation are likely much smaller than other experimental reactor designs. Yet no commercial installations exist, so there are some price and build-time risks which are associated with them.

The MSR (molten salt reactor) family of reactor designs takes a very different approach. It uses a coolant whose boiling temperature is extremely high and in which the main radioactive fission products and fuel are never volatile. Since the core is already melted, no meltdown is possible. During a disaster which includes a core containment breach, the release of radiation would be extremely localised, staying within the reactor building. This is in contrast to the case with light water reactors in which Cesium 137 and Iodine 117 can potentially be released as a gas. The MSR was actually trialled in the US in the 1960s and the Chinese are currently in the process of building *two* MSR experimental reactors. It is not, unfortunately, a solution which can be rolled out immediately.

Nuclear is cheap

When evaluating power solutions, price should not be the only factor considered. There are all sorts of other concerns which we must also way against including safety and sustainability. However, price should also be part of the story. If a solution is too expensive to feasibly deploy or so expensive that we have to radically reduce our power use, then it can not really be considered an effective solution.

When evaluated in isolation, nuclear power's low-price is not always obvious. There are several reasons that this is the case. First, the up-front capital costs of nuclear power are quite large. Nuclear power plants are large high-tech construction operations. Obtaining the upfront capital for such a large undertaking often requires a state investment as the scales of capital required are so large.

However, the operating costs of nuclear power, including upgrades and retrofitting are low. The cost of fuel is generally below 5% of operating costs. This has the added benefit that the operating costs are resilient to changes in fuel supply costs. And importantly, the operational life of the plant is very long, allowing us to spread the capital costs over extremely long time frames. In fact, nuclear plants are so cheap to operate that they are competitive with coal and gas when they have been operating for over a decade.

However, many countries (rightly) require all waste management to be provided for by a nuclear power plant. This often means that the costs of waste management must be put into some sort of escrow account which guarantees proper disposal or caretaking. This is in sharp distinction to every other type of energy production - including solar and wind - in which the costs of disposal are not considered.

In addition to this, the costs of the overall grid management and storage are often not considered when people compare Watts produced from wind or solar power, and that produced from nuclear power. Nuclear reactors produce regular, constant and reliable power. This makes for simple, reliable and cheap grid technology. The fluctuations, load balancing and complexity of more diffuse power generation require much more extensive and expensive grid management. In addition, spreading of fluctuations requires energy storage which is expensive or replacement with power generation which can be ramped up quickly, such as natural gas which produces CO2.

In the final analysis, the numbers speak most clearly. The cost to the consumer for electricity in 2019 for Germany was 30.88 cents / kWh (0% domestic nuclear), while in France it was 17.65 cents / kWh (75% domestic nuclear). That is, relying primarily on nuclear power turned out to be half as expensive to consumers as attempting to rely on a mix of gas, coal, wind and solar. Similarly, we can compare the prices for Denmark at 29.84 cents / kWh (0% domestic) and Sweden at 20.15 cents / kWh (40% domestic nuclear). Clearly it is not only the CO2 profile which is better, but the price of nuclear is better as well.

Nuclear waste: A manageable issue

Perhaps the greatest worry that people have once they accept the relative safety of nuclear power generation is nuclear waste. The story is that nuclear waste lives for hundreds of thousands of years, and therefore we will simply accumulate an impossible problem for future generations.

Fortunately, the reality is not so dire. The current production of waste is extremely small. A typical household's lifetime power use would require around 2kg of uranium fuel using current light-water reactor technologies. And since this "waste" is the byproduct of burning uranium, your family is generating approximately 2kg of waste over their lifetime. Given that most of the byproduct is Uranium 238 which is highly dense, the total volume would fit into three of the small 100ml water bottles that are allowed on international flights.

This tiny amount of byproduct is therefore extremely manageable. Typically, a light water reactor facility will leave the spent fuel rods to cool for some period of time, after which they are moved to *dry cask storage*. These large dry casks are shielded and armoured making them extremely safe. One can see workers, evaluating temperature readings on the outside of these dry casks, wearing no radiation shielding since radiation levels are too low to matter. The image in people's minds of barrels of green goo bears absolutely no relation to reality.

Spent fuel material is not actually waste. In fact, 95% of the resulting material is Uranium 238 which is fertile, another 1% of it is Uranium 235 and a remaining 1% is plutonium, both of which are usable as reactor fuel. This means that only 3% of the material is unusable waste.

Spent fuel can be recycled to provide new *mixed oxide* fuel for light water reactors by *reprocessing*. This is the approach used by France, which says it has reduced mining requirements significantly.

Yet this is only a stop gap to the real solution to the waste question. The waste currently being generated is nowhere near to being used up. If we used a fast reactor, we could transmute the left over Uranium 238 into plutonium and burn it. There is so much available power using this approach that just from current US waste stocks, the US could be powered for over a thousand years.

This ”waste” really isn’t waste at all. It's fuel for which we have not yet built *commercial* reactors. This is no mere theoretical concept either. Numerous experimental fast breeder reactors have been built which can use up far more of the fuel.

But what about the long-lived waste products? Experimental evidence and modelling simulations have demonstrated that given a suitable fast reactor, we can convert 97% percent of what is currently waste into energy. The remaining products are largely those with short half-lives. These will remain quite radioactive for only a short time at which point we will have something which can be stored easily. The total time before these stored byproducts would reach the same radioactivity level as the ore which was mined in the first place is 300 years. And now, instead of 100 ml per person, we are storing only a tiny fraction. We could in fact store all of the waste for the entire world powered on nuclear power in a single super-tanker sized vault, in which we could wheel out the old stuff after 300 years and bury it back where we found the ore.

While widespread acceptance of a design for a commercial fast reactor is still unsettled, this is not a pressing concern as we have perfectly adequate storage in the interim. We can easily store the spent fuel until such time as we can burn it as fuel.

Nuclear is near-zero emission

All but the most backward have accepted that CO2 emissions must be reduced or we will suffer severe consequences. Yet deciding the means of achieving these reductions is more difficult than a mere acknowledgement of the problem.

The German *Energiewende* provides a useful case study. Germany embarked on a very ambitious plan to reduce carbon emissions which has incurred costs of around €200 billion. This involved a radical expansion in wind and solar energy capacity. At the same time, the German government decided to shut down their existing nuclear plants.

The result has been that German CO_2 emissions have remained almost completely stagnant despite this massive expansion in renewable energy. At the same time, a new coal plant is scheduled to go online in 2020 due to the shortfall in available energy.

By contrast, France has one of the lowest CO_2 emissions per capita of any country in the EU. This derives directly from the fact that around 70% of French electricity is generated from nuclear power. The other winner in the EU, Sweden, has even slightly lower CO_2 levels due to its use of nuclear power with around 35-40% of electricity provided. Sweden is able to make up much of the remainder with hydroelectric power and wind. Both France and Sweden rolled out these programmes in an extremely short time - around 15-20 years - about the same period of the German *Energiewende*.

Nuclear power puts more power into the grid faster than any low-CO_2 emission alternative available.[8] Beyond this, nuclear produces almost no direct CO_2 emissions, but there are emissions associated with building nuclear power plants, maintenance, mining and transport. Yet this also holds for solar, wind and hydro alternatives. As it turns out, when all is accounted for, CO_2 emissions associated with nuclear are significantly lower than the alternatives: half as much as wind, and a tenth as much as solar.

[8] *Potential for Worldwide Displacement of Fossil-Fuel Electricity by Nuclear Energy in Three Decades Based on Extrapolation of Regional Deployment Data* Staffan A. Qvist, Barry W. Brook; PLOSOne

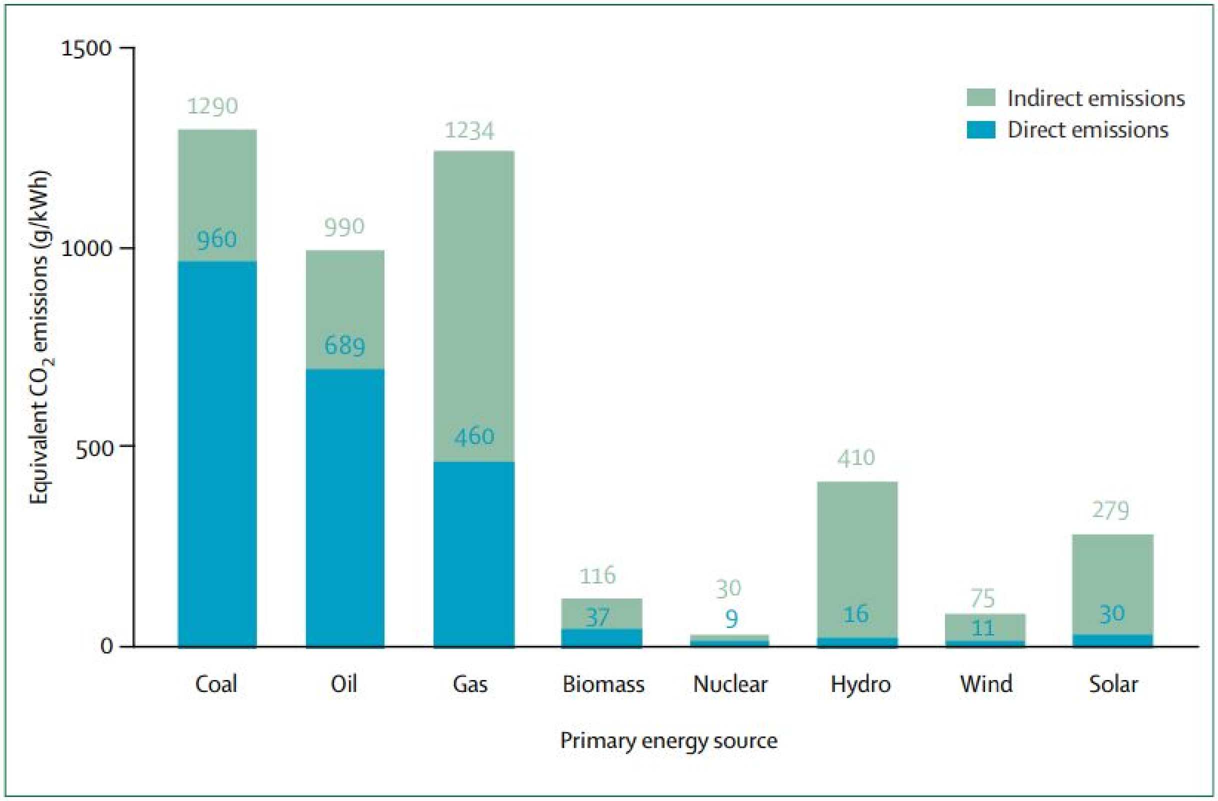


***Figure 2* : Full energy chain CO_2 equivalent emissions by primary energy source**
Data from IAEA, 2001.[40]

Real zero-emissions solutions

To become truly "zero emissions" we need to do more than generate electricity. We need to create transport solutions that do not use petrol and replace all fossil fuel use in process heat for industrial processes. This is a non-trivial task that requires research and development. Given sufficient motivation, it is very likely that this can be done, however it is best to focus on tackling the biggest issues first.

The first task at hand should be electricity generation. At that point, we should expand the use of electricity in transport. Once these *low-hanging* fruits are plucked, we should move on to the agricultural sector where process heat could be used for the manufacture of fertiliser. Tractors can be electrified or altered to use synthetic fuels generated from atmospheric carbon.

Eventually, we will need to find solutions to the manufacture of concrete which requires extremely high temperatures that are not likely to be feasible with nuclear reactors. We will also want a solution for jet flight, either with synthetic fuels or perhaps by replacing them with high speed trains.

Once concrete, transport and mining can be fully converted to electrical or closed-cycle synthetic fuel production, then the renewable sources can become truly zero-emissions. Until then, nuclear will lead the pack.

Alternatives?

But why not just use wind and solar? Most environmental campaigners have come to believe that wind and solar are perfectly suitable replacements for our current coal or natural gas generators.

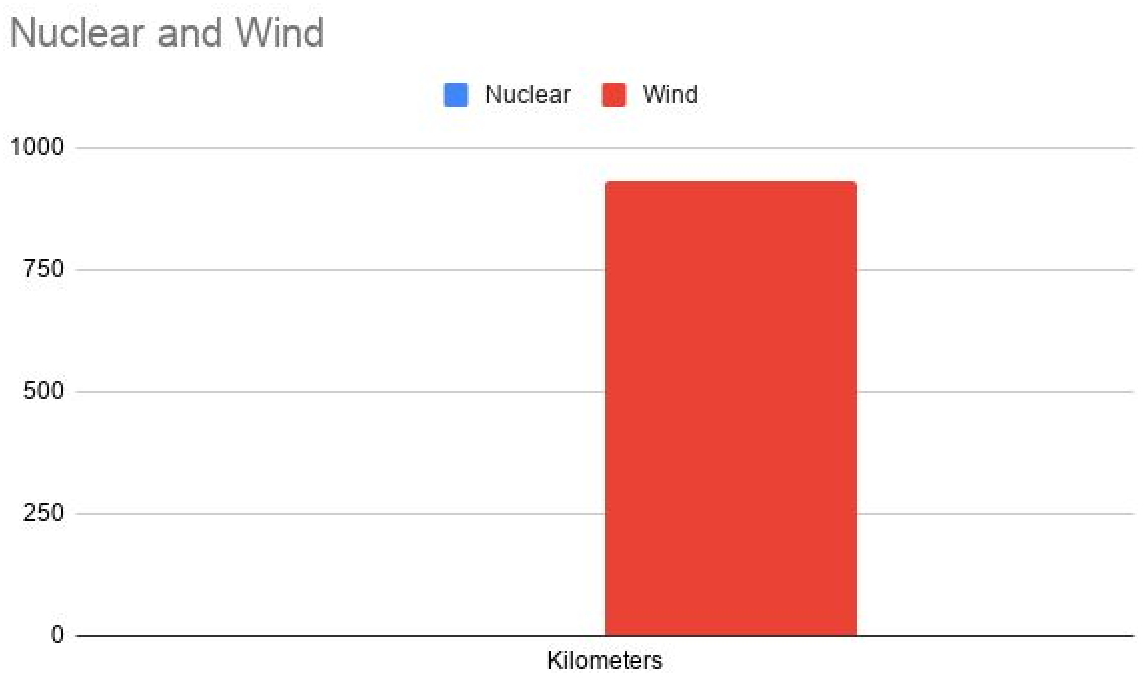
Unfortunately, they make very poor replacements and the steps necessary to make them suitable replacements, while not entirely impossible, are fantastically difficult. Aside from the fact that alternatives have higher CO2 release per unit energy than nuclear, and greater associated mortalities, they are also much more expensive and difficult to use.

In Ireland we can restrict our attention to the only immediately feasible renewable power source other than nuclear: wind.

Size and space

Nuclear power plants are relatively large. For safety and security reasons, they tend to have large footprints. Yet those footprints are absolutely dwarfed by the scale of wind installations.

A one gigawatt nuclear power plant, which would supply around ⅓ of Ireland's total electrical need, would take up around three square kilometers. To produce the same amount of wind would take almost 1,000 square kilometers of wind-farm. This means we are consigning nearly 3,000 square kilometers of Ireland to large spinning turbines if we want Ireland to be powered from wind. This is approximately the same size as County Antrim and bigger than County Limerick. The footprint of the nuclear facility is virtually non-existent in comparison. And this is before we begin to worry about storage!



Consistency

Modern society has come to depend on consistent power availability. When at work, we don't expect to see rolling blackouts. The productivity of our society requires that we not be interrupted periodically for short periods or even worse for weeks at a time. Yet the power generated from wind is inconsistent and interrupted. It comes and goes with varying regularity and can never be relied upon on any given day. This variability must somehow be smoothed out so that we can rely on the stream of energy.

Storage

There are a number of storage options which can help smooth out variability:

- Pumped water storage
- Heat storage
- Battery storage

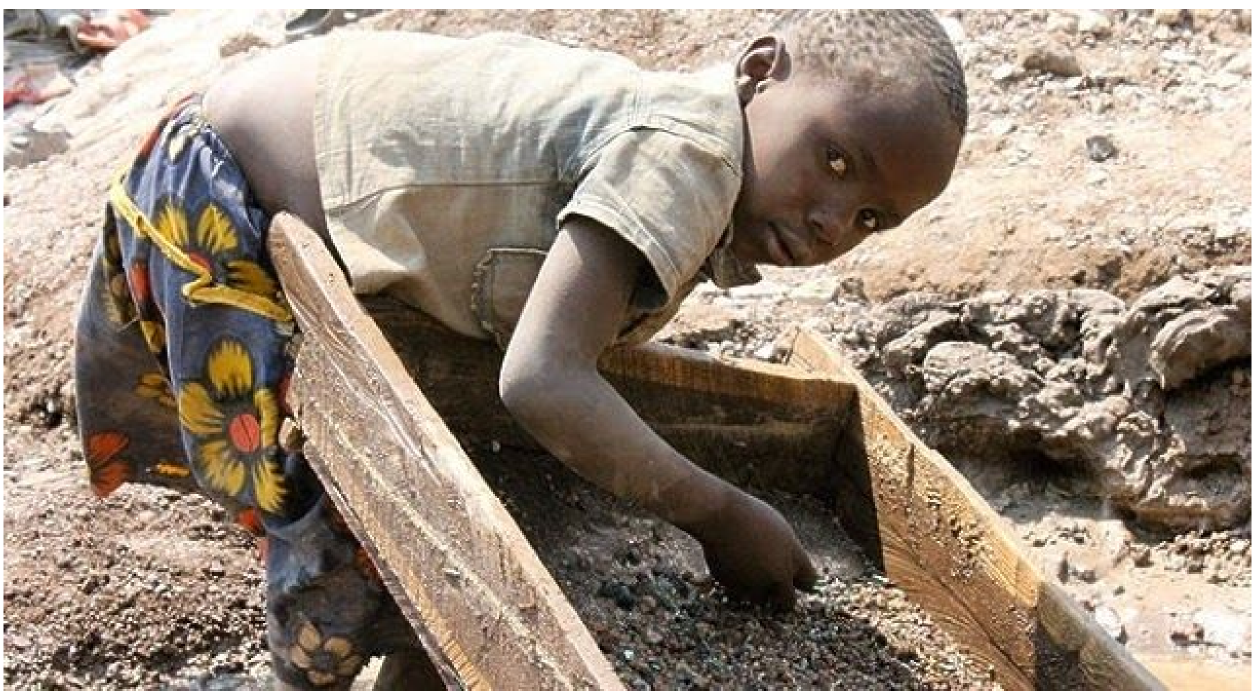
Given variability of wind power in the UK we can get an idea of what would be required in terms of storage in Ireland. The question is answered in some detail in "Sustainable Energy - Without the Hot Air" by David MacKay Regius Professor of Engineering at the University of Cambridge. Ireland has periodic lulls of 2-3 days without wind which happen every year, and not too infrequently lulls which last 5 full days. A 5 day lull in Ireland would require replacement with

1200 GWh. While sometimes lulls might last longer than this, this seems an adequate baseline which could be supplemented with emergency power facilities based on natural gas coupled with purchase of power from abroad via interconnects.

Pumped water storage is a proven technology which is already used in Ireland. It is among the most efficient of the storage options and works well for a range of power generation methods. However, it also requires enormous reservoirs of water which must be placed somewhere and a big infrastructure project with lots of concrete (which requires CO2). This method cannot provide power for very long unless it is used on a truly mammoth scale.

Turlough Hill, an impressive facility, has the capacity to provide nearly 300 megawatts of power, but only for about 8 hours. This comes out to about 2.4 GWh. To deal with the wind variability above we would need 500 Turlough Hills to cover total power requirements. The scale of the problem is obviously huge. The costs in infrastructure would be great, but so also would be the damage to the landscape.

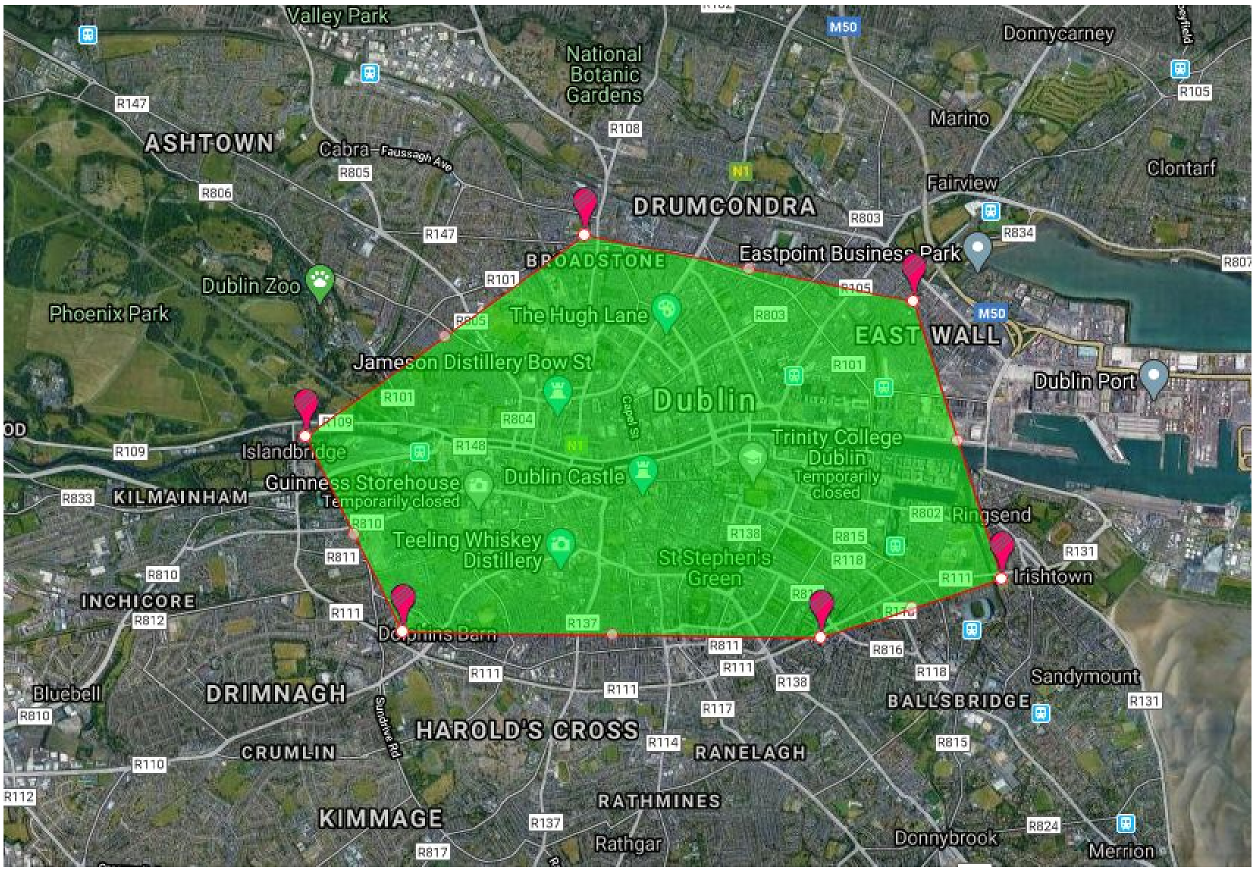
Heat storage would work best for concentrated solar where it shows promise, but it is not really a feasible option for Ireland, where solar is not naturally abundant.



A child sorts cobalt in the Congo

Batteries are falling in price, increasing in density and durability and have been suggested as a solution. However, they are still very inefficient and the sheer quantity of toxic materials required boggles the mind.

In order to cover similar requirements to the pumped storage example above using Tesla's new Megapack battery system, we would need 1200 Megapacks to cover our 5 day lull. This would require an installation space of about 1500 hectares. To get an idea of the size, this is roughly equivalent to all of the space in Dublin between the North and South circular road.



Area in Green is 1242 hectares

The batteries would also require huge amounts of the rare and toxic metal cobalt which is largely mined in the Congo, and often by children. The cost is difficult to predict as no one has ever created such a mammoth installation, but it would very likely exceed the cost of a nuclear power plant which could supply all of Ireland's power needs.

The grid

Greater grid integration is another possibility. The larger the space over which we can collect variable power, the more we can spread it out. With a suitably large grid, we could trade solar from Greece for wind from Ireland.

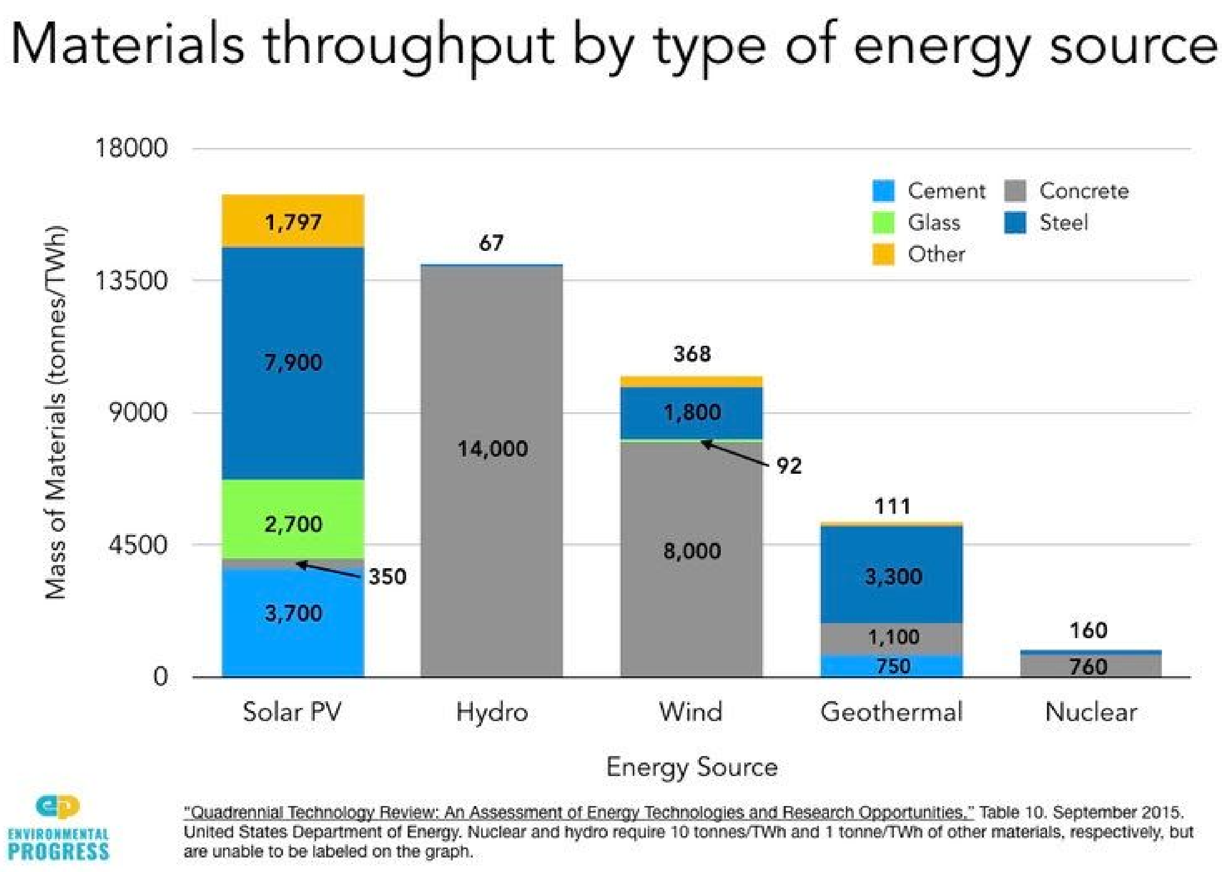
Yet, the use of large-scale grids is not all easy sailing. The larger and more complex the grid, the more complex the necessary control mechanisms, and the more they need to be integrated. Developments of smarter grids will certainly continue, but even *within* Germany, they have found the variability of solar to be a serious problem with stability. Scaling this up to a continental smart-grid is a massive public works undertaking and the EU is not structured in such a way as to undertake it.

The parts of the grid with the most consistent power find export to be easiest. It's no accident then that everyone is buying nuclear power from France to make up their short falls, as it is among the cheapest and most reliable in Europe.

And while it is convenient to rely on others for power, is it wise for Ireland to supply only irregular power abroad, while importing all of its baseload to make up for shortfalls?

Materials

Perhaps the biggest problem with wind is the scale of material usage. The sheer number of wind turbines that are required leads to huge material requirements in steel and especially concrete (which is why wind has such a large CO_2 release for production). In the figure below we see the material requirements, including depreciation and replacement required to generate one TWh. Here the steel requirements are ten times as great for wind as for nuclear and require ten times as much concrete. This will require ten times as much mining and all of the consequences that go along with that in terms of environmental degradation.



Yet wind and nuclear do not have to be at odds. Using wind only when it is plentiful could reduce the amount of space it takes up significantly. If this were coupled with nuclear power as a baseload, we could ensure consistency of power, while reducing the rate of nuclear fuel use. We could re-use all of the infrastructure already devoted to wind power and perhaps increase it as we find it convenient to do so.

Conclusion

One thing is certain about the future, and that is that the future is uncertain. We know that climate change must be dealt with, and this will require radical changes, politically, economically but also technically. In order to have a future we need to recast the world in a very different image. This task cannot be undertaken without a fight. But we cannot simply be antagonists. We need to be clear about what we need to fight for. What would we do if we were in power? How would we improve the lot of the working class? How will we provide for our children and future generations? These should not be treated as irrelevancies. We must grasp the nettle and seriously decide what could avert climate disaster, supply necessary power for everyone, scale up to provide for the whole world, and not leave a terrible mess for our progeny to clean up.

We have tried to show here by comparison with real alternatives that nuclear power is the most convincing answer to all of these questions.