THE IRISH ACADEMY OF ENGINEERING

ENGINEERING & TECHNOLOGY

THOUGHT LEADERSHIP IN A TIME OF GREAT CHANGE

SMALL MODULAR REACTORS

Ireland needs to consider SMRs to achieve a zero-carbon energy sector by 2050

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THE IRISH ACADEMY OF ENGINEERING

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EXECUTIVE SUMMARY

If Ireland is to become net-zero by 2050, the contribution of energy to national GHG emissions (53% in 2022) will have to be eliminated. In doing this, the total Primary Energy Requirement (PER) of the country will significantly reduce while the contribution of renewable electricity to energy services (transport, heating, lighting and industry) could increase sixfold from 12.9 TWh in 2022 to 80 TWh by 2050 *(Appendix 1)*.

There are many challenges to be overcome in this transition. This report focuses on the challenge to reliably generate electricity at the level that will be needed by 2050 with security of supply guaranteed.

Ireland has tolerated an increasing security of supply **RISK** that the growing dependence on imported natural gas (including to fuel our electricity system) exposed the country to as domestic reserves declined.

The objective of current energy policy is to power the country using renewables - primarily wind and solar - by 2050, now just 26 years away. If this is achieved, there is **CERTAINTY** that the country will, at times, be exposed to a lack of supply when renewables are not sufficiently available.

It is **UNCERTAIN** whether the means that might be considered to backup renewables – including green hydrogen, interconnection, and long duration energy storage (LDES) - will be available to provide the security of supply the country needs to compensate for the intermittency of renewables. If they can't, Ireland will need an alternative means of ensuring the security of our electricity supply.

Many other countries are planning to add small modular nuclear reactors (SMRs) to their generation mix - alongside renewables - to replace fossil fuels.

In the two grids with which Ireland is and will be interconnected, a sizeable proportion of domestic electricity generation is nuclear: 15% in Britain and 62% in France (*Appendix 2)*:

- The UK Government has set a target to increase nuclear generation capacity from 6,000 MW currently to 24,000 MW by 2050 based, primarily, on the roll-out of a large fleet of SMRs each with an indicative capacity of 300 MW.
- In February 2024, the European Commission established the *European Industrial Alliance on Small Modular Reactors* with the aim of developing, demonstrating and deploying SMRs by the early 2030s and, in April, gave *approval* for State aid for research and development of SMRs in France.

The Irish Academy of Engineering believes that Ireland needs to keep an open mind about the possibility of SMRs contributing to the achievement of net zero energy by 2050. A passive acceptance that the country might need SMRs is not sufficient, and an active response is required to ensure that, if SMRs prove to be economic, safe and reliable by the 2030s, Ireland is prepared to consider changes to national policies and legislation to permit their deployment.

An equivalent approach to that taken in response to the second oil shock of the 1970s is needed and the Academy recommends that institutional capacity be developed in organisations including EirGrid, ESB, CRU, and the EPA to,

- Engage with SMR manufacturers to evaluate the potential of SMRs with the realistic prospect that Government policy could change to allow them to be deployed in the future,
- Devise appropriate energy market structures - in consultation with SMR manufacturers and project developers and based on experience in other countries - to enable the introduction of SMRs, alongside renewables, into Ireland's energy mix, and
- Develop the necessary national resources to be able to assess the environmental impact of proposed SMR developments and to licence and regulate them.

The above approach is consistent with the milestone approach of the International Atomic Energy Agency (IAEA) for countries to develop a nuclear power programme.[1] The IAEA's first milestone is to reach the point where a country is ready to *make a knowledgeable commitment to a nuclear power programme*. The above recommendations are intended to reach this point.

It is only if these steps are taken that there can be an informed national discussion on the possible introduction of SMRs into Ireland's energy mix and issues such as safety and nuclear waste can be meaningfully discussed. If other better ways to achieve net zero energy without SMRs are found, then work on the above measures can be terminated before any commitment might be made to an SMR programme.

Whatever happens, Ireland will have some dependence on nuclear power. The choice to be made is whether we limit this dependence to nuclear capacity in Britain and France or whether we deploy SMRs in Ireland which would have the important added advantage of enhancing national energy security.

Ireland is a technology taker and, where other countries have gone in terms of renewables, Ireland is following, at times belatedly (notably in offshore wind and solar). It would be negligent if the country was not prepared if, ultimately, it becomes necessary to include SMRs in the energy mix in order to achieve a net-zero energy sector.

1 *Milestones in the Development of a National Infrastructure for Nuclear Power*, IAEA, 2015

1. INTRODUCTION

We need energy to provide services such as transport, heating and lighting, and to supply industry. At present, one-third of the energy we consume provides these services and the other two-thirds is not directly usable. Instead, it is released into the atmosphere as heat.[2] Most of this waste of energy occurs because of huge inherent inefficiencies in how energy is transformed into more useful forms - notably in power stations - and also from our dependence on machines and devices that are relatively inefficient.

Ireland's energy still comes, overwhelmingly, from fossil fuels and accounts for just over half of the country's GHG emissions. The *Climate Action and Low Carbon Development (Amendment) Act 2021* committed Ireland to halve greenhouse gas (GHG) emissions by 2030 and to reach net zero by 2050.[2]

For Ireland to become net zero by 2050, the energy sector will have to be fundamentally transformed and electricity will need to become the dominant energy vector.

This transformation involves two major sets of changes:

- Firstly, in electricity generation.
- Secondly, by the electrification of energy services (primarily heating and transport) which are, today, largely dependent on fossil fuels.

Changing how electricity is generated will, under current policy, require:

- Zero-carbon or net-zero renewable power capacity to meet all demand whenever sufficient wind and / or solar energy is available.[3]
- A fleet of assets (including *synchronous compensators* and batteries) to maximise the electrical energy which can be supplied from non-synchronous sources (wind, solar, and interconnectors).[4]
- Backup sources of power (interconnection and long-duration energy storage) and a backup fleet of zero-carbon generation assets operating on zero-carbon fuels which, combined, would be capable of meeting demand when there is insufficient wind or solar available.
- Strategic storage of green fuels (such as hydrogen or ammonia) with sufficient capacity to ensure security of supply for the backup fleet of zero-carbon generation assets for long periods.[5]

Achieving this will require the completion of multiple large infrastructure projects.[6] Such projects take time to deliver and the programme to achieve the above transformation must be completed in just 26 years.[7]

Ireland's path to net zero is set out in the annual *Climate Action Plan* and, in the case of the electricity sector, in EirGrid's *Shaping Our Electricity Future*. Neither of these important documents makes any reference to the possibility of nuclear generation in Ireland. This is unsurprising given that nuclear fission is expressly prohibited in Irish law.[8]

2 This is particularly well illustrated in the Sankey diagram depicting US energy flows in 2022 shown in *Appendix 3*.

3 As of January 2023, EirGrid *reported* installed generation capacity as follows (*Appendix 4*):
- Non-renewable: 6,370 MW; Renewable: 5,324 MW. By comparison to these installed capacities, the maximum all-time system demand was 5,544 MW.
- By 2050, the target for wind is not less than 46,000 MW (37,000 MW offshore and 9,000 MW onshore). For solar, the target is at least 8,000 MW. The 9,000 MW target for onshore wind and the 8,000 MW target for solar are to be achieved by 2030.

4 EirGrid is currently operating with a System Non-Synchronous Penetration (SNSP) level of up to 75% and has stated its objective to achieve a level of 100%: It is EirGrid and SONI's ambition to achieve operation at 100% SNSP with no conventional thermal generation online in the next decade (2030+), *Shaping Our Electricity Future*, Page 186.

5 The high-level analysis in *Appendix 1* suggests 30 days.

6 In addition to multiple large infrastructure projects to transform the generation sector, there will also need to be large programmes of projects to transform the transmission and distribution networks in the country. This report focusses solely on the generation sector.

7 The long time to complete energy infrastructure projects is exemplified by two projects nearing completion:
- Firstly, the 138 km long, 400 kV *North-South Interconnector* is due to enter service in 2027, 19 years after the need for it was first identified
- Secondly, the *Celtic-Interconnector*, which is due to enter service in 2026, will have taken 13 years to be completed from the time work commenced on preliminary feasibility studies.

8 The *Electricity Regulation Act 1999*, Section 18 (6), prohibits the Commission for the Regulation of Utilities from licensing a nuclear power station. The *Planning and Development Bill 2023*, Section 168, continues the existing prohibition of developments of nuclear power stations being authorised.

Elsewhere, EirGrid explicitly excludes nuclear from its scenario planning in *Tomorrow's Energy Scenarios 2023* because of this prohibition but does leave open the possibility of considering nuclear were Government policy to change:

> *We understand that some countries are considering development of nuclear power generators – this includes jurisdictions both with and without existing nuclear plant. Should policy develop that is supportive of nuclear power a future review may consider the potential for nuclear generation.*

At the core of Ireland's challenge to decarbonise the energy sector is the country's remote island location with exposed energy supply chains. Apart from the National Oil Reserves Agency's (NORA) 90 day stockholding of oil, Ireland does not have significant stores of energy to provide security of supply.[9] The gradual replacement of fossil fuels in Ireland's energy mix by renewables will increase the energy security challenge because of the new exposure the country will face from weather-related energy shortages.

One part of the solution to address this risk exposure could be the deployment of nuclear power plants, specifically SMRs.

Ireland's prohibition of nuclear power contrasts with the decision taken in December 2023 at COP28 calling on Parties to contribute to mitigation efforts by:

> *Accelerating zero- and low-emission technologies, including, inter alia, renewables, nuclear, abatement and removal technologies such as carbon capture and utilization and storage, particularly in hard-to-abate sectors, and low-carbon hydrogen production.*[10]

This call was qualified in the text by saying that this should be done … *in a nationally determined manner, taking into account the Paris Agreement and their different national circumstances, pathways and approaches.*

Ireland's circumstances and our pathways and approaches to decarbonisation warrant consideration of nuclear power generation by SMRs.

At COP28, also, 25 countries – including the UK and France - launched a declaration to triple aggregate nuclear generation capacity by 2050.[11] In circumstances where the two countries with which Ireland is planning to significantly increase grid connectivity are increasing their reliance on nuclear power, this option should also be considered in Ireland.

Notwithstanding that nuclear power is, along with wind and solar, among the safest and cleanest sources of energy (*Appendix 5*), there are deep public concerns about its safety. These concerns - compounded by the cost overruns and time delays on large nuclear projects - create formidable obstacles for public acceptance of SMRs in Ireland.[12, 13]

Although Ireland's GHG emissions are negligible in terms of their contribution to global emissions, it is important that the country achieves its net zero objective by 2050 to support the wider reduction by the EU and major nations (including China, the US and India) whose GHG emissions affect Ireland as a result of the global impact they have on climate.

The case for Ireland to consider SMRs is no different to that in many other countries. In the US, for example, the National Academy of Sciences addressed the case for SMRs in 2023 in Laying the Foundation for New and Advanced Nuclear Reactors in the United States. The opening paragraphs in the Preface to this book usefully mirror the viewpoint of the Irish Academy of Engineering:[14]

9 Stocks of coal, oil and biomass at a number of power stations provide some additional security of supply. However, natural gas is the predominant fuel in the power generation sector (47% in 2023) and there is no strategic store in the event that supply from the UK is curtailed or lost. Moreover, ESB is *planning* to convert Moneypoint from coal to Heavy Fuel Oil (HFO) and to operate, with limited run hours, from late 2024 until the end of 2029. One side effect of this development will be a further diminution in the country's energy security.

10 COP28, First global stocktake, *Draft decision, Section 28 (d).*

11 *Declaration to Triple Nuclear Energy, December 2023*

12 Windscale (1957), Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011)

13 Hinkley Point C (3.3 GW, UK), Flammanville (1.6 GW, France), Olkiluoto 3 (1.6 GW, Finland) and Vogtle (2.2 GW, US)

14 Laying the Foundation for New and Advanced Nuclear Reactors in the United States (2023) National Academy Press Washington *http://nap.nationalacademies.org/26630*

The world confronts an existential challenge in responding to climate change, resulting in an urgent need to reduce greenhouse gas emissions from all sectors of the economy. At the same time, there is growing concern throughout the world with ensuring energy security. In response, a rapid transition is necessary to reduce dependence on fossil fuels. While there will certainly be increased reliance on renewable energy, other low-carbon technologies will also likely play a significant role. The trajectory for this technology transition is very uncertain.

Nuclear power provides a significant portion of the world's low-carbon electricity, and it is widely recognized that the ongoing contribution from existing nuclear power plants will be essential to achieve carbon-reduction targets over the next decade or longer.

Many companies in the United States and around the world are pursuing development of advanced reactor technologies and targeting demonstration and deployment in coming years. The vendors claim that the new designs offer improved safety, lower cost, shorter construction times, and increased operational flexibility over existing reactors. For some technologies, there is also the potential for higher thermal efficiency, higher-temperature operation (opening opportunities for process heat applications), greater fuel utilization, stronger security, improved proliferation resistance, and reduced need for regulatory constraints on deployment. If achieved, these outcomes would be significant, with the result that advanced reactors could be an important component of our energy future.

All promoters of technologies to reduce GHG emissions make optimistic claims for the effectiveness and viability of what they are selling. The companies promoting SMRs are no different and, with this proviso in mind, it is useful to consider the technology and economic uncertainties of the energy transition and the approach to SMRs in other countries.

2. TECHNOLOGY AND ECONOMIC UNCERTAINTIES IN THE ENERGY TRANSITION

The central theme in this paper is the challenge to deliver transformational change in the power generation sector in a relatively short time against a background of considerable technological uncertainty and with no clarity of the implications for energy costs and for future electricity prices.

2.1 Technology uncertainties

Whereas renewables can meet most of the country's electricity requirements, intermittency means they cannot do it alone. Other sources of power will be needed. However, there is considerable uncertainty as to how this will be achieved including:

- Will it be technically feasible and economically viable to produce, transport and store large volumes of green hydrogen to be used to power zero-carbon generation plant to backup renewables?
- Will there be some other economically viable option (such as very large scale battery storage) which could store vastly greater quantities of electrical energy than seems conceivable today?
- Can Ireland depend on large scale interconnection with other grids to meet all, or a large part of, our energy needs when renewables are not available?
- Will the optimism of promoters of SMRs translate into the reliable delivery and operation of large numbers of SMRs in other countries whose experience Ireland can then learn from?

Unless one or more of the above options - or some other option altogether - can provide guaranteed zero-carbon backup for renewables, then the objective of creating a net zero energy sector will not be achievable.

It is clear that there are many uncertainties with SMRs. However, these uncertainties are mirrored by uncertainties in the other options that might be available to backup renewables:

- **Hydrogen** In a previous report (*Hydrogen as an Energy Carrier in the Irish Context*), the Academy identified a range of substantial challenges which need to be overcome if green hydrogen is to become the main source of zero-carbon backup generation capacity.
- **Long Duration Energy Storage (LDES)** The extent to which technologies to provide LDES (including batteries) need to develop is emphasised by what is considered to be long-duration.[15] There is considerable uncertainty about whether LDES technologies can evolve to the point where large scale projects to provide up to 30 days of backup could be delivered in Ireland by 2050. In the case of batteries, their use to provide long-duration energy storage would be unfeasibly expensive (*Appendix 1*).
- **Interconnection** Regardless of the capacity of interconnection that might be installed between Ireland and Britain and between Ireland and France, if the energy available to Ireland from these two grids is not sufficient at the times when it is most needed - and for the same reasons - then other sources of backup will be required.

To date, the direction of energy policy has been away from an electricity system comprising fossil-fuelled baseload and load-following generation plant towards a fully renewable generation system where the intermittency of renewables will be compensated for by zero-carbon backup generators.

If SMR technology delivers on the promises of its promoters, and if zero-carbon backup capacity for renewables cannot be provided to the extent implicitly assumed in current national policy, then the optimum solution for the country (from system reliability, energy security of supply and energy price perspectives) could include a significant proportion of baseload nuclear plant alongside large scale renewables with associated backup capacity.

15 EirGrid, *A Call for Evidence on the Market Procurement Options for Long Duration Energy Storage (LDES)* Page 19, October 2023: Although there is no agreed definition of what constitutes LDES, it is generally seen as, and for the purpose of this call for evidence, being storage with a minimum duration of 8 hours.

2.2 Economic uncertainties

In addition to the technology uncertainties, there are also major uncertainties about the economics of the different generation technologies that could contribute to achieving a net-zero power sector.

When standalone comparisons are made between the cost of renewables and the cost of other sources of power, nuclear appears to be particularly uncompetitive.

For example, in its World Energy Outlook 2023, the IEA summarised the technology costs it used in modelling an Announced Pledges Scenario (**Table 1**) to project worldwide Total Energy Supply levels in 2050 (**Table 7** in *Appendix 1*).

The contrasts between nuclear and solar in capital cost per kW of capacity ($4,500 versus $410) and in LCOE ($110 per MWh versus $30 per MWh) in 2050 are striking. On the face of it, it does not appear that SMRs could possibly be competitive with solar and with other renewables.

	Capital Costs (USD / kW)			Capacity factor			LCOE (USD / MWh)		
	2022	2030	2050	2022	2030	2050	2022	2030	2050
Nuclear	6,600	5,100	4,500	70%	80%	80%	155	120	110
Coal	2,000	2,000	2,000	30%	n/a	n/a	220	n/a	n/a
Gas CCGT	1,000	1,000	1,000	25%	10%	n/a	220	270	n/a
Solar PV	990	600	410	14%	14%	14%	65	40	30
Wind onshore	1,750	1,650	1,570	29%	30%	30%	60	55	50
Wind offshore	3,420	2,200	1,540	50%	56%	59%	75	45	30

Table 1: Technology costs in the European Union in IEA's Announced Pledges Scenario
Source: Table B.4b, *World Energy Outlook 2023*, IEA

However, the above comparisons are of limited use because the additional costs arising, firstly, due to the intermittency of renewables and, secondly, because renewables are non-synchronous, need to be considered as part of the cost of renewables:

- Firstly, nuclear generation can provide firm and dispatchable power. Renewables, on the other hand, require there to be a backup source of zero-carbon generation when wind or solar are not available at the required power levels. This is a very significant additional cost which the market, and ultimately, the consumer must bear.
- Secondly, nuclear generation is synchronous and can provide grid services which renewables cannot and which, in a grid approaching 100% SNSP, will have to be purchased from other sources with the cost, again, being passed onto consumers.[16]

These differences are partly recognised by IEA in its explanation of the assumptions behind the costs in **Table 1:** *Solar PV and wind costs do not include the cost of energy storage technologies, such as utility-scale batteries.*[17]

In contrast to the IEA estimates for 2050, one SMR developer, TerraPower, suggests that once it has moved beyond the demonstration phase, its 345 MW Natrium SMR plant will have a construction cost of about $1 billion (equivalent to $2,800 per kW) and an LCOE in the range $50 to $60 per MWh.[18]

Beyond the above comparisons, and for the same reasons, nuclear will also appear expensive by

16 SNSP: System Non-Synchronous Penetration (see explanation in the Glossary)

17 *World Energy Outlook 2023, Page 304.*

18 TerraPower *website*

comparison to renewables based on strike prices in auctions and other procurement processes run by national governments / energy regulators.

As power markets develop, major project investments are increasingly being facilitated by the price certainty which strike prices incorporated in contracts for difference (CFDs) provide. For example, the ORESS1 auction accepted four bids for an aggregate capacity of 3,074 MW at an average strike price of €86.05 per MWh.[19]

Just as IEA's LCOE estimates are not directly comparable between renewables and other power sources, so also the strike prices for offshore wind are not directly comparable with the strike price for nuclear projects, the most notable example being the gigawatt scale Hinkley Point C.

In the case of Hinkley Point C, the original strike price agreed for the project was £95.20 per MWh at 2012 prices. This is equivalent to about €139 in 2023 prices after indexation.

It would be wrong, for the reasons set out above, to compare €86 with €139 and conclude that nuclear is uncompetitive and should not be considered.

The variability of strike prices for renewables, both between different technologies and over time, is large as exemplified by the recent publication of parameters for the UK's Allocation Round 6.[20] These parameters included Administrative Strike Prices which set the maximum strike price that a project can receive. The level (at 2012 prices) was £73 per MWh (€85 per MWh) for offshore wind, and £176 per MWh (€206 per MWh) for floating offshore.

The energy security needed to provide reliable power in a zero or net-zero generating system in 2050 will come at a cost, and the price of electricity paid by consumers will be a function of the mix of different sources of power including not only those shown in **Table 1** but also zero-carbon backup generation plant powered by stored green fuels.

Against this background of deep uncertainty, the economics of SMRs compared to other technologies cannot be meaningfully or sensibly assessed. It is important, therefore, that any decision today to exclude SMRs as an option is based on more than a perception that nuclear generation might be too expensive.

Electricity costs in Ireland for large industrial consumers are already the highest in the EU - and are almost two-thirds higher than the EU average (*Appendix 6*) – and it is possible that SMRs could be a more viable option for zero-carbon electricity than, for example, the combination of renewables and backup generation using green hydrogen.

19 *ORESS1 Final Auction Results*, EirGrid, June 2023

20 *R6 Core Parameters, Contracts for Difference (CfD): Core Parameters for the sixth allocation round, 2024,* UK Department for Energy Security and Net Zero, November 2023.

3. THE POTENTIAL OF SMRS

3.1 SMRs compared to traditional gigawatt scale nuclear reactors

Nuclear reactors have been used for power generation for over 70 years and, in 2022, 437 reactors (with an aggregate capacity of 394,000 MW) generated 2,545 TWh in 32 countries (*Appendix 2*). In addition, small nuclear reactors (20 MW to 60 MW) have been used to power ships (including icebreakers and in military applications) for many decades and, today, over 160 ships are powered by more than 200 small reactors.[21]

Traditional nuclear power plants are large, expensive and take a long time to construct:

- The average capacity of the world's fleet of 439 nuclear power reactors is 900 MW but recent projects are much larger (typically 1,600 MW per reactor).
- The 3,200 MW Hinkley Power Point C project will cost in the order of €38 billion at 2015 prices. (The actual cost will be significantly higher than this nominal amount).
- The median time to complete large nuclear power plant projects is over seven years. The Olilakutu 3 project in Finland took *18 years*.[22]

In contrast, SMRs are being developed to provide zero carbon baseload power generation capacity without the megaproject shortcomings of traditional gigawatt scale nuclear power plants.

The SMR approach to nuclear generation is intended to:

- Allow power plants to be constructed on a small land area particularly where there are existing grid connections.
- Facilitate the modular production of main components in factory environments as a means of improving speed, quality and construction cost efficiencies.
- Reduce project risks (cost over-runs and delays).

SMR technology, as now proposed, is an emerging option based, both on tried and tested technologies - notably PWRs - and on newer advanced reactor types.

Given the pressures to decarbonise generation, if SMRs prove themselves to be viable, they will likely be deployed in large numbers (by comparison to gigawatt scale reactors) within ten to fifteen years. This could happen, most relevantly from Ireland's perspective, in the UK.

21 *World Nuclear Association*

22 *World Nuclear Performance Report 2023*, World Nuclear Association, Page 11. WNA measures construction periods from start of construction of the reactor building to grid connection.

3.2 The approach to SMRs in the UK

The UK has five large existing nuclear power plants in operation with an aggregate capacity of 5,985 MW. Additionally, another two – each with a capacity of 3,260 MW – are either in construction or close to starting construction **(Table 10** in *Appendix 2*).

The UK Government established *Great British Nuclear* (GBN) to oversee the delivery of 24,000 MW of nuclear capacity by 2050.[23] This includes both large gigawatt scale plants - such as Hinkley Point C and Sizewell C - and SMRs. The emphasis on SMRs is far greater than on gigawatt scale plants.

GBN is running what it describes as *a competitive technical selection process to select the SMR technologies most likely to achieve a FID* [Final Investment Decision] *by 2029 and deliver operational projects in the mid-2030s.*

In 2023, it announced a list of six companies whose technologies had passed a first stage in this process (**Table 2**).

OEM	Brand	MEC	Type	Website
EDF	NUWARD SMR	2 x 170 MW	PWR	*link*
GE Hitachi	BWRX-300	300 MW	BWR	*link*
Holtec	SMR-300	300 MW	PWR	*link*
NuScale Power	VOYGR SMR	77 MW	PWR	*link*
Rolls Royce SMR	Rolls Royce SMR	470 MW	PWR	*link*
Westinghouse	AP300 SMR	300 MW	PWR	*link*

Table 2: Six SMR companies selected by GBN in 2023

GBN has described its process to develop SMRs as follows:[23]

- Tenders will be sought, and contracts awarded, to progress proposed technologies through to regulatory approval and finalisation of designs.
- In doing this, the six companies shown in **Table 2** will be reduced to four.
- Access to sites for SMRs - notably ten sites with redundant nuclear plants (**Figure 4** in *Appendix 2*) - will be secured.
- The technologies of these companies will be matched to specific sites such that individual sites can support the deployment of multiple SMRs of a given technology.
- GBN will identify development companies capable of delivering SMR projects.
- Tenders to develop up to three SMRs at selected sites will be sought with the potential to deploy more SMRs in subsequent development phases at these sites in the future.
- GBN's target is to have the first SMR project reach Final Investment Decision stage by 2029.

23 In addition to its nuclear targets, the UK has set ambitious targets to increase its already large (14 GW) installed offshore wind capacity: *We have the ambition to deploy up to 50 GW by 2030, with up to 5 GW coming from floating offshore wind. The project pipeline of around 77 GW across 80 projects offer significant, new investment opportunities around the whole offshore value chain.* *Offshore Wind Net Zero Investment Roadmap*, March 2023.

3.3 SMRs in other countries

In January 2023, Ontario Power Generation signed a contract with GE Hitachi to deploy the first of four planned BWRX-300 SMRs at its Darlington site in Canada.

What is happening in the UK and in Canada is also happening in other countries. Most notably, construction of the Linglong One 100 MW SMR at Changjiang by the China National Nuclear Corporation is underway. This is the first SMR to be approved by the IAEA.

Recently, following the Nuclear Energy Summit in Brussels in March 2024, 32 countries committed to fully unlock the potential of nuclear energy *… as a key component of our global strategy to reduce greenhouse gas emissions from both power and industrial sectors, ensure energy security, enhance energy resilience, and promote long-term sustainable development and clean energy transition.* These 32 countries included 14 EU Member States and the UK.[24]

3.4 Advanced SMRs

The types of SMRs that could be considered in Ireland will be determined by what happens in other countries. In the first instance, this suggests designs based on PWR and BWR technologies.

However, it also possible that more advanced reactor types might be viable, and these could become an option for Ireland in due course. Current examples include:

- TerraPower's 345 MW Natrium sodium fast reactor under development in the US
- Terrestrial Energy's proposed 392 MW integral molten salt reactor in Canada
- The 210 MW high temperature gas-cooled pebble-bed reactor being developed in China

However, just as there is uncertainty about the ultimate viability of, for example, large scale hydrogen storage for zero-carbon backup generation, so also there is uncertainty about the viability of these more advanced SMR designs and, indeed, of the designs based on PWR and BWR technologies.

This uncertainty was exemplified in November 2023 when NuScale announced the termination of a project to deliver a six-reactor 462 MW project for the Utah Associated Municipal Power Systems (UAMPS) by 2030.

3.5 Ireland's changed circumstances for nuclear power

The most significant difference between traditional gigawatt scale nuclear power plants and the SMRs now being proposed is the scale of SMRs by comparison with the size of the grid in Ireland.

Among the reasons for ESB opting not to proceed with a nuclear plant in Ireland in the 1970s was its capacity compared to the level of demand. In the early 1980s, maximum demand – which today is in excess of 5,500 MW - was in the order of 2,000 MW and the nuclear power plants being considered at that time had a capacity of 500 MW.[25]

This factor was again considered by ESB in 2017:[26]

> *Apart from the legal position, the minimum size of nuclear power plant currently available is over 1,000 MW. This is too large relative to the peak load on the electricity system in Ireland to permit reliable operation. Therefore nuclear power is not included in the roadmap in Chapter 5 as this is based on current technologies. The expected development of small modular reactors (SMRs) with smaller size and greater flexibility may make nuclear power more feasible in the future. Should this happen, it would be appropriate to reconsider nuclear power as an option.*

Where a single nuclear reactor in the 1980s would have had a capacity equivalent to 25% of maximum demand, the equivalent figure in 2050 would be 3%.[27]

24 The 14 EU Member States are: Belgium, Bulgaria, Croatia, Czech Republic, Finland, France, Hungary, Italy, Netherlands, Poland, Romania, Slovakia, Slovenia and Sweden.

In the case of Italy – which closed the last of its nuclear plants in 1990 – the Government established a National Platform for Sustainable Nuclear Energy in September 2023 to define a path aimed at the possible resumption of the use of nuclear energy.

25 *The History of the ESB*, Page 206, Maurice Manning and Moore McDowell, Gill and McMillan, 1984

26 *Ireland's low carbon future - Dimensions of a solution*, Page 31, ESB , July 2017

27 Based on a reactor capacity of 350 MW and a maximum demand of 12,000 MW.

The system reliability challenges posed by decarbonising generation by 2050 are greater than the security of supply challenges which were to the forefront of energy policy in the 1970s. The response taken in the 1970s was to develop the expertise needed to introduce nuclear power if that were the decision ultimately taken. These preparations included the establishment of the Nuclear Energy Board in 1973. This subsequently became the Radiological Protection Institute of Ireland in 1992 before being subsumed into the EPA in 2014.

An equivalent approach to that taken in response to the second oil shock of the 1970s is needed and the Academy recommends that the necessary steps be taken to develop the institutional capacity in Ireland to evaluate the case for SMRs over the next decade and, if appropriate, to oversee their introduction into the country's energy mix.

In taking these steps, it will be important that there is an active public discussion so that, whatever decision might ultimately be taken, it is well-informed. For example, the environmental and major accident concerns many people have with nuclear energy will need to be considered against the impacts of climate change. They will also have to assessed alongside the environmental and other risks which, for example, a large scale reliance on ammonia as a fuel for zero-carbon generation would pose.[28]

3.6 How might SMRs be deployed in Ireland

Unlike the UK, Ireland has no redundant nuclear facilities which provide grid-connected sites for possible future SMRs.

However, Moneypoint was originally identified as a potential nuclear site but was, instead, developed for coal fired generation in the 1980s. It is currently being converted to heavy fuel oil prior to its planned shutdown in 2029. The Moneypoint site is large and it could conceivably be repowered with SMRs, possibly reusing the existing steam turbines, cooling water systems, alternators, site utilities and HV transmission infrastructure.

Some of the SMRs being developed could replace a portion of future planned renewable capacity together with their related backup capacity. Other SMR designs are intended to complement renewables by not only providing baseload capacity but also providing energy storage which can backup renewables.

For example, TerraPower's 345 MW Natrium SMR is a sodium fast reactor coupled with a molten salt energy storage system which, it is claimed, can boost power output to 500 MW for more than five hours at a time. This storage capacity would be equivalent to 44% of the storage capacity which Turlough Hill provides.

TerraPower recently *announced* that it had applied for a construction permit to the U.S. Nuclear Regulatory Commission for a demonstration project at a former coal fired power station at Kemmerer, Wyoming. A similar approach could be imagined at Moneypoint.

Another rationale for considering SMRs in Ireland would be to meet the power requirements of data centres and other new technology loads.

In its *Ten-Year Generation Capacity Statement 2023–2032* , EirGrid projects that data centre demand in Ireland will reach 13 TWh by 2032, equivalent to 30% of all demand. However, the demand for grid connections from data centres is already greater than EirGrid can accommodate and, beyond that, conflicts are emerging between policy targets to reduce GHG emissions in the energy sector and industrial policy targets to support the growth of data centre and other new technology industries. The nature of data centre loads suits baseload generation plant and an annual demand of 13 TWh could be met by five or six SMRs.[29]

The compatibility of data centres with zero-carbon nuclear baseload power sources was highlighted recently in the US when Amazon Web Services *acquired* the 960 MW Cumulus data centre campus in northeast Pennsylvania. The deal included a ten-year power purchase agreement with the 2,700 MW Susquehanna nuclear power station.

The coincidence of the growth in demand from data centres with the need to decarbonise the electricity sector is creating policy target conflicts which are not easily resolvable. The inclusion of SMR baseload plant in Ireland's future energy mix could reconcile these conflicts.

28 Of the three main options for storing hydrogen - as a pure substance in gaseous or liquid form (H_2), within green methanol (CH_3OH), and as green ammonia (NH_3) - the ammonia option is arguably the most proven method albeit that ammonia comes with significant risks in the event of a major accident. Recently, Bord Gáis Éireann *announced* the signing of an MOU with Mitsubishi Power Europe to explore the development, construction, and operation of what they described as Europe's first ever ammonia-fired power plant at BGE's Whitegate CCGT power station.

29 In forecasting future demand, EirGrid assumes data centres have a flat demand profile across the day, with a gradual ramp throughout the year to their forecasted demand. This has been observed in real time data. *Ten-Year Generation Capacity Statement 2023–2032*, EirGrid, Page 49.

4. PAST AND FUTURE CHANGES TO IRELAND'S GENERATING MIX

Building on the possibility that SMRs might prove themselves to be viable, the question of how much SMR capacity Ireland might need will arise.

One of the extraordinary features of the energy transition will be a huge increase in thermal generation capacity and overall electricity consumption as indicated in **Table 3.**

		2022[30]	2050	% change
Power	Non-renewable	6,370 MW		+88%
	Zero-carbon		12,000 MW[31]	
	Renewable	5,324 MW	54,213 MW[32]	+918%
	Total	**11,694 MW**	**66,213 MW**	**+466%**
Energy	Non-renewable	19.4 TWh	-	-100%
	Renewable / Zero-carbon	12.9 TWh	80 TWh	+520%
	Total	**32.3 TWh**	**80 TWh**	**+148%**

Table 3: Comparison of existing generation capacity and electricity consumption with indicative levels in 2050

There have been previous large changes in both the scale and the composition of Ireland's generation sector, albeit over a much longer period. *Appendix 7* shows the changes from 1920 to 2014.[33]

Over almost a century, as power generation capacity grew exponentially, Ireland's energy security deteriorated to the point where we now have a critical dependence on gas interconnectors to Scotland with a single point of connection into the British gas network at *Moffat* in Scotland.

Moreover, there have been notable failures of market auctions for new gas turbine capacity in recent years leading to the procurement by EirGrid of 653 MW of emergency generation capacity.[34]

Where Ireland has been fortunate that the lack of strategic gas storage has not left the country exposed to date, we are now, as a matter of policy, moving to a situation where we will have to provide strategic zero-carbon energy stocks as a buffer against the certain disruptions that would otherwise happen to our energy supply because of weather events once we have made the step towards 100% renewable generation.

The average size of the ten largest generating units in the country is 378 MW (*Appendix 4*). With an indicative requirement for 12,000 MW of zero-carbon backup generation capacity in the country by 2050, more than thirty units of this size could be needed.

30 Source: *EirGrid*. See *Appendix 4* for the composition of the country's generation assets.

31 Based on the high-level analysis in *Appendix 1*.

32 Based on stated targets in the Climate Action Plan for onshore wind and solar to 2030 and for offshore wind to 2050 plus 213 MW of hydro (which generated 0.9 TWh in 2023).

At capacity factors of 28% (9,000 MW onshore), 50% (37,000 MW offshore) and 11% (8,000 MW solar), the total potential annual renewable energy could be 193 TWh per annum.

33 *A 100 year review of electricity policy in Ireland (1916–2015)*, Gaffney, Fiac; Deane, John Paul; Ó Gallachóir, Brian P.; 2017

34 *Generation Capacity Statement 2023–2032*, Eirgrid, Page 11: *EirGrid have procured two Separate tranches of emergency generation units in Dublin (Northwall and Huntstown), Offaly (Shannonbridge) and Kerry (Tarbert) with a combined capacity of 653 MW that are due to be operational and available to EirGrid, the Transmission System Operator in 2023/24.*

In this context, the deployment of one or two SMRs would have little impact. If SMRs were to provide a significant proportion of the country's zero-carbon baseload generation capacity, then a sizeable fleet of them would be required.

Identifying the optimum size of an SMR fleet can only be done when the costs of SMRs and the costs of alternative backup approaches are known with reasonable certainty.

The Academy has long been concerned at the lack of a high-level plan showing how Ireland will achieve the required transformation of the energy sector. Such a plan is needed to:

- Provide a summary of the projects and programmes that will transform the country's generation, transmission and distribution systems by 2050.
- Identify other assets needed for the future including long duration energy stores, synchronous compensators and interconnectors.
- Estimate the overall costs of these investments and their likely impact on the price of electricity for consumers.
- Analyse the combined effect of these electricity prices and improved energy efficiencies on consumers' energy costs.

The very large renewables targets in current policy do not constitute a plan. Completing the energy transition will depend on societal acceptance of the developments that will be required including multiple large power generation and transmission line projects. It will also require considerable investment by businesses, households and individuals in building upgrades and heat pumps. A clear national plan with broad political support is an essential prerequisite.

5. SUMMARY AND CONCLUSIONS

1. In 2022, 53% of Ireland's GHG emissions were energy related. If the net zero target for 2050 is to be met, then the energy sector will have to be transformed and, in doing this, electricity will become the dominant energy vector.

2. This could require a sixfold increase in renewable electrical energy from 12.9 TWh in 2022 to 80 TWh in 2050.

3. Current Government targets envisage the installed capacity of renewable generation increasing tenfold from 5.4 GW in 2023 to 54.0 GW by 2050.

4. Ireland's energy security exposure increased substantially as the Kinsale gas field was depleted and as our dependence on imported natural gas grew. Fortunately, this exposure hasn't resulted in major disruptions to the country's energy supply.

5. In 2050, however, the dependence on renewables for 100% of our energy supply will expose the country to the certain risk of energy shortages when large weather systems result in simultaneous and protracted periods of calm over Ireland and much of north-west Europe, particularly in winter. These periods can range from several days to several weeks.

6. To cater for these situations, Ireland will need a second set of zero-carbon generation assets with an aggregate dispatchable capacity in the order of 12 GW to backup the planned 54 GW of renewable capacity which would not be able to meet our needs at such times. By comparison, the aggregate capacity of the existing fleet of non-renewable generation assets is 6 GW implying a doubling in thermal generation capacity in just 26 years.

7. These zero-carbon backup generation assets will need strategic stocks of green fuels. The focus in national energy policy to provide green fuels is on hydrogen. A 30-day stock would equate to 13.2 TWh. This could be achieved by storing 0.4 million tonnes of hydrogen (or, alternatively, 2.5 million tonnes of ammonia). To the extent that other LDES technologies or interconnection can contribute to the zero-carbon backup capacity needed, the figures of 12 GW and 13.2 TWh would reduce.

8. There are many uncertainties as to whether a backup strategy based on green hydrogen can be delivered by 2050 and there are, as yet, no estimates of the potential capital costs.

9. Given the risk that the domestic renewables options currently being considered might not be capable of providing the reliability (or security of supply) the country needs, the only other source of backup energy is from interconnection with other grids, notably Britain and France.

10. However, it is likely that these grids will not be able to meet Ireland's requirements for energy imports at times when our own renewables are not sufficient. The completion of ongoing analysis by EirGrid is needed to definitively assess this risk.

11. Elsewhere, small modular nuclear reactors (SMRs) are being developed with a generating capacity similar in size to that of the largest generating units in the country currently (378 MW).

12. The SMR approach has its own uncertainties but plans underway in the UK, Canada, the US and in many other countries will address these uncertainties over the coming decade and, by the mid-2030s, we will know whether SMRs can deliver on their promise or not. This is similar to the likely timescale to commercialise floating offshore wind.

13. If they can - and if it turns out that SMRs would be a worthwhile accompaniment to renewables - then we will only have 15 years to introduce SMRs at scale in Ireland. If the country isn't prepared to deploy SMRs by the mid-2030s, then the attainment of the net zero energy objective by 2050 might not be possible.

14. Against this background - and notwithstanding the prohibitions in law on nuclear fission in Ireland - it is important that work commences now to,

    - Evaluate the potential of SMRs,
    - Inform a national discussion on the possible introduction of SMRs into the energy mix and, if approved at a policy level,
    - Prepare for the possible deployment of SMRs at scale.

15. This work should inform the preparation of a national plan showing how the country's generation, transmission and distribution systems will be transformed by 2050. This plan needs to detail the technical options and their scales, the aggregate capital investment required, and the key environmental and major accident risk exposures, so that an informed decision can be taken as to how Ireland will backup its renewable energy sector at times when renewable sources are not available. Critically, also, this work must estimate the likely future price of electricity and the overall costs for consumers of energy services, notably heating and transport.

16. In addition to a range of technical uncertainties, there are also large uncertainties about the economics of all of the approaches to deliver a net zero energy sector. It is important, therefore, that the SMR option is not rejected at this stage based on a perception that nuclear might be too expensive. When all of the costs of the energy transition are known, it might not be.

APPENDIX 1 - ENERGY AND POWER REQUIREMENTS IN IRELAND IN 2050

The thinking and analysis behind the commentary in this report is set out below under seven headings:

- Energy in Ireland, 2022
- IEA World Energy Report, 2023
- Security of Energy Supply
- Projection of energy and power requirements in Ireland to 2050
- Additional electricity demand for backup by green hydrogen
- Limitations of current battery technology for LDES
- Conclusions

Energy in Ireland, 2022

In 2022, Primary Energy Requirement (PER) in Ireland was 167.0 TWh and Total Final Energy Consumption (TFEC) was 140.3 TWh (**Table 4**).

	ktoe	TWh	% of PER
Primary Energy Requirement	**14,365**	**167.0**	**100%**
Oil	6,911	80.4	48%
Natural Gas	4,471	52.0	31%
Wind	964	11.2	7%
Other renewables	899	10.5	6%
Coal	727	8.5	5%
Peat	223	2.6	2%
Non-Renewable Waste	148	1.7	1%
Electricity	22	0.3	0%
Total Final Energy Consumption	**12,069**	**140.3**	**84%**

Table 4: Summary Energy Balance 2022, SEAI

In 2022, electricity generated from renewable sources accounted for only 7.7% of Primary Energy Requirement – 12.9 TWh from the total of 167.0 TWh (Table 5).

Renewable source	Energy	% of PER
Wind	11.2 TWh	6.7%
Solar	0.01 TWh	0.0%
Hydro	0.7 TWh	0.4%
Other Renewable	1.0 TWh	0.6%
Total renewable electricity	**12.9 TWh**	**7.7%**

Table 5: Electricity from renewables in 2022, EirGrid

In terms of Total Final Energy Consumption, electricity accounted for 21.9% with the major part generated from fossil fuels (**Figure 1**).

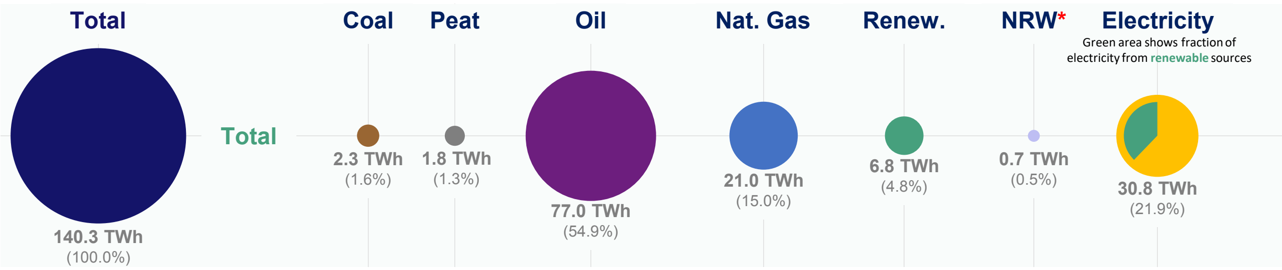


Figure 1: Summary of Final Energy Consumption by energy source 2022, SEAI

Ireland's energy related GHG emissions are a function of the country's Primary Energy Requirement.

Achieving net zero by 2050 will require the electrification of many activities, notably heating and transport. Because of the greater efficiencies of, for example, heat pumps and electric vehicles (by comparison to conventional fossil fuel boilers and petrol / diesel vehicles), electrification will reduce energy demand.

Energy demand will also be reduced by the elimination of energy transformation losses (22.5 TWh in 2022) as fossil fuel generation capacity is replaced by renewables.[35]

However, there will be drivers which will increase energy demand (**Table 6**).

Drivers that will decrease Primary Energy Requirement	Drivers that will increase Primary Energy Requirement
▶ Renewable generation ▶ Electrification of heating ▶ Electrification of transport ▶ Modal shift to public transport ▶ Insulation	▶ More data centres ▶ Population growth ▶ Production of hydrogen for backup generation

Table 6: Drivers of future changes in Ireland's Primary Energy Requirement

35 This accounts for most of the difference of 26.7 TWh between PER and TFEC shown in Table 4.

IEA World Energy Report, 2023

In its *World Energy Report 2023*, the IEA projected future energy requirements in 2050 based on a number of scenarios including what it termed an Announced Pledges Scenario. This scenario assumed that all national energy and climate targets made by governments are met in full and on time.

One insight from this analysis is that Total Energy Supply in many parts of the world - notably in Europe, the US and China - will reduce significantly between 2022 and 2050 as renewables replace fossil fuels and as energy services are electrified (**Table 7**).

TWh	2022	2050	% change
World	175,556	173,028	-1%
European Union	15,611	10,556	-32%
Europe	21,722	16,000	-26%
United States	26,056	19,556	-25%
China	44,361	36,917	-17%
India	11,667	16,750	+44%

Table 7: Change in Total Energy Supply under IEA's Announced Pledges Scenario
Source: Adapted from data in Annex B, *World Energy Outlook 2023*, IEA

It is reasonable to assume that Ireland's PER in 2050 will be lower than it was in 2022 for two reasons:

- The preponderance of the drivers in **Table 6** point towards a decrease in PER.
- Ireland is following energy policies similar to those of other EU member states.

Security of energy supply

Ireland's energy security of supply has been a risk since the foundation of the State.[36] This was recognised in energy policy, in particular, in 1978 but, with the major exception of NORA's strategic petroleum storage (and, to a lesser extent, fuel stocks in coal, oil and biomass power stations), the country has been exposed to a significant strategic risk for half a century. [37] Moreover, the increasing dependence on gas increased the country's strategic risk exposure.[38]

By 2050, however, Ireland will have to decisively address the security of supply risk exposure in order to ensure that electricity can be generated at all times, particularly when wind and solar energy are not available. Whereas the country has been fortunate that the security of supply exposure has not been critical over the past fifty years, it is certain that there will be instances of critical exposure post 2050 if energy stores of sufficient scale are not developed. This is well explained by EirGrid in *Shaping Our Electricity Future*.[39]

Beyond this, EirGrid has also recognised the need to consider what derating factor should apply to interconnectors when assessing system adequacy. In its *Generation Capacity Statement 2023–2032, EirGrid* uses a 60% de-rating factor for the East-West Interconnector (Wales), the Moyle Interconnector (Scotland) and the future Celtic Interconnector (France).

EirGrid has noted that, in future, the methodology underpinning adequacy analysis in its Generation Capacity Statement will focus on the risk of low renewable energy periods and times of low interconnector support.[40]

Given the planned move to having no fossil-fuelled thermal plant, and Ireland becoming mainly dependent on a combination of renewables, stored renewables and zero-carbon generation, it will be essential to understand the extent to which interconnection with Britain and France can be relied on to meet our energy needs when required.

A simple view, based on Dunkelflautes covering Ireland, Britain and France simultaneously, would be that Ireland will need to be able to meet 100% of its electricity generation requirements exclusively from dispatchable national resources when required. A similar view was taken by The Royal Society in 2023 and expressed in the following terms:[41]

36 Review of Energy Supply Security in Ireland 1920-2020 - Gerry Duggan - December 2020 (*link*)

37 ENERGY-IRELAND, Discussion Document on some Current Energy Problems and Option, *Oireachtas Library*.

38 Gas Networks Ireland *reported* that natural gas generated 47% of total electricity in 2023 versus 48% in 2022.

39 Page 69, 5.3 *Long term adequacy*

40 *Generation Capacity Statement 2023–2032*, Eirgrid, Page 147.

41 *Large-scale electricity storage*, Page 19, The Royal Society, September 2023

… the weather in different parts of Europe is linked. Imports to GB are vulnerable to pan-European wind droughts and cold periods, water shortages, and (potentially) political factors. It would therefore be wise to design a GB system that would cope when imports are not available. Contributions from interconnectors are therefore not included in the modelling in this report.

The variability of wind speeds over time was exemplified in 2021 when wind speeds over Ireland, the UK and much of northwest Europe were, from July to September, consistently and significantly lower than they had been in the previous 30 years.[42]

Projection of energy and power requirements in Ireland to 2050

Making projections as far into the future as 2050 with any level of certainty is challenging but in order to assess what contribution SMRs might make to Ireland's energy mix, it is important to have some sense of the scale of the challenge the country is facing.

In this paper, we have used projections from EirGrid's *Tomorrow's Energy Scenarios 2023* report which show demand levels in 2050 ranging from 71.5 TWh to 86.2 TWh (excluding electrolysis) under four scenarios (**Figure 2**).[43]

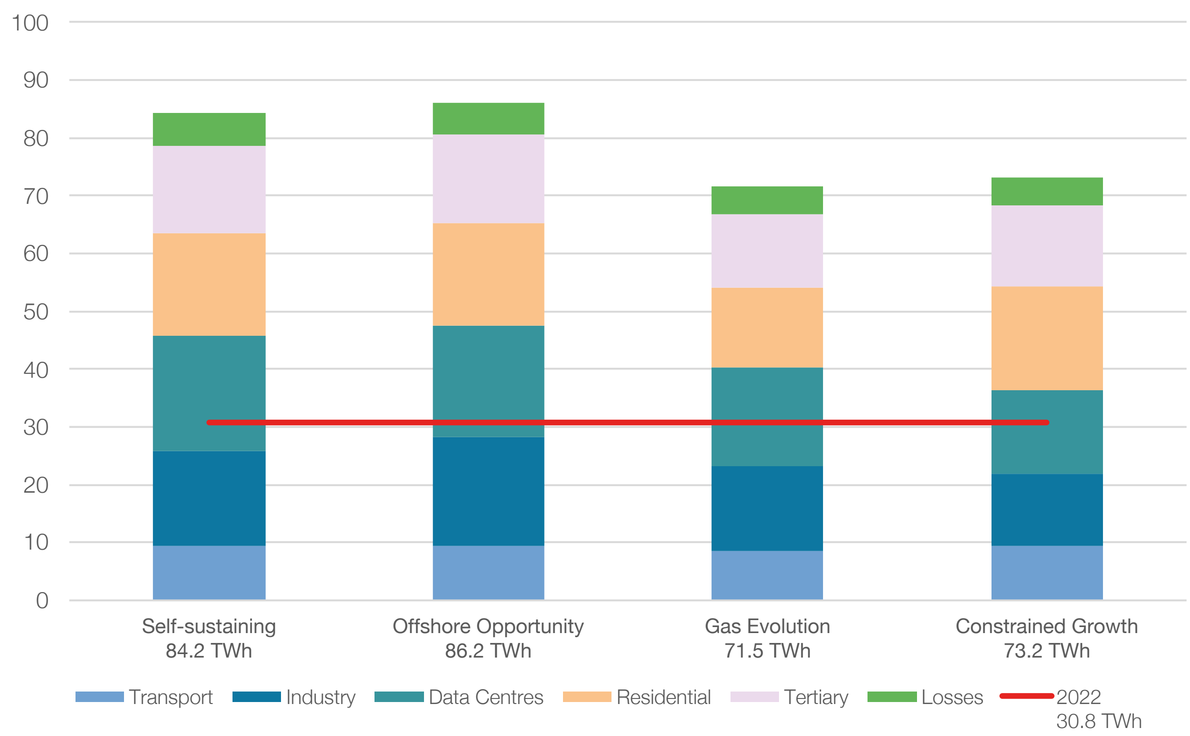


Figure 2: Projections by EirGrid of Annual Total Electricity Requirement in 2050 under four scenarios

42 *Low winds | Copernicus*

43 The four scenarios - *Self-Sustaining; Offshore Opportunity; Gas Evolution; Constrained Growth* - are described on Page 35 of *Tomorrow's Energy Scenarios 2023.*

EirGrid, additionally, projected peak demand out to 2050 (Figure 3) in a range from 11.3 GW to 12.9 GW.

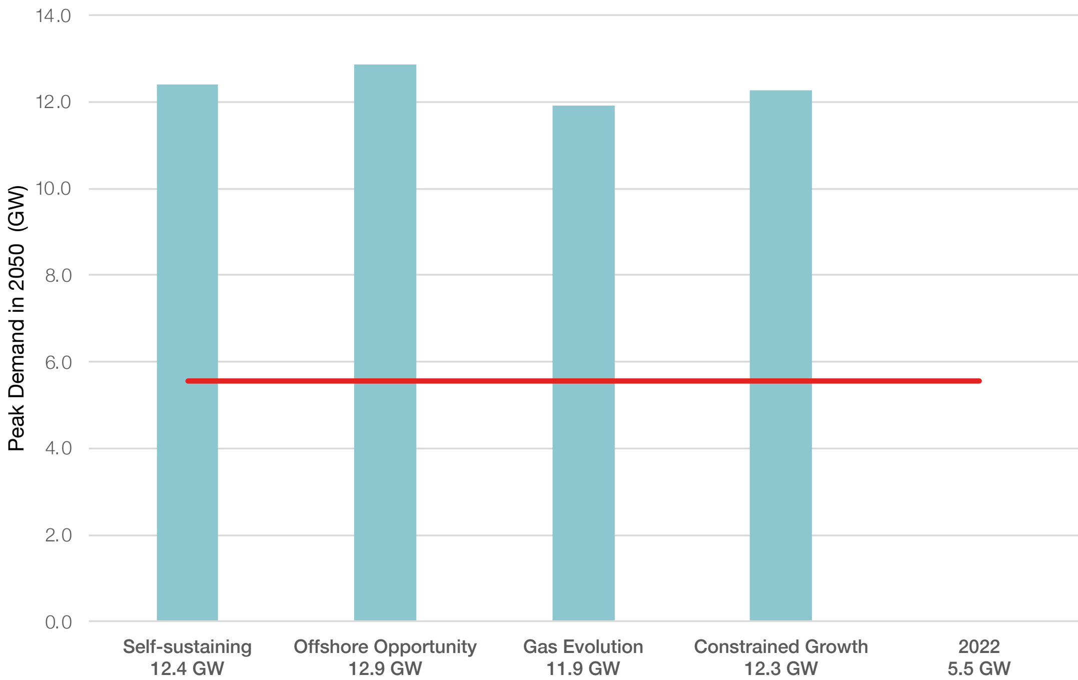


Figure 3: Projections by EirGrid of peak demand in 2050 under four scenarios

Using these projections by EirGrid, the commentary in this report is based on an assumed electrical energy demand of **80 TWh** (before electrolysis) and a maximum power demand of **12 GW**.

If the 80 TWh of demand is reached, the electricity sector in Ireland will have to generate six times more renewable electricity by 2050 than it currently does.

However, this is only part of the challenge because there would be an additional requirement for high capacity stores of zero-carbon fuels for backup generation.

In order to assess the possible benefits of SMRs, it will be necessary to estimate the scale of the energy storage that will be required without SMRs and compare it to what would be required with SMRs.

A few more simplifying assumptions suggest an energy storage requirement of up to **13.2 TWh** would be needed without SMRs:

- EirGrid's assessment of the adequacy of interconnectors concluding that interconnectors could not be relied on during protracted periods of calm over north-west Europe.
- Battery technology not developing to the extent required to provide long duration energy storage and high power delivery capacity.
- 80 TWh of electrical energy required per annum.
- Strategic storage of zero-carbon fuels needed to generate electricity for up to 30 days.
- Energy stored as green hydrogen or as a derivative (ammonia) [44]
- 50% average efficiency of zero-carbon generation plant.

To put the figure of 13.2 TWh into context, *NORA* currently holds a minimum of 1.6 million tonnes of refined product - with an energy content of 18.8 TWh - to meet 90 days of demand.

44 If stored as hydrogen (with a lower heating value of 33.3 kWh per kg), 13.2 TWh would equate to 0.4 million tonnes. As ammonia (5.2 kWh per kg), it would equate to 2.5 million tonnes.

Additional electricity demand for backup by green hydrogen

In a previous report, the Academy noted that the economics of using green hydrogen to provide backup capacity for renewables are challenging because of the successive efficiency losses at each stage of the hydrogen supply chain.[45] For every one unit generated by an OCGT fuelled by green hydrogen, between 4.4 units (optimistic) and 6.0 units (more realistic) would be consumed.

If intermittency required 10% of the 80 TWh to be generated from stored green hydrogen over the course of a year, then overall electricity demand would be at least 107 TWh instead of 80 TWh.

Limitations of current battery technology for LDES

Lithium-ion batteries are increasingly being deployed to enhance power system stability. For example, ESB recently commissioned a 75 MW / 150 MWh battery in Poolbeg in Dublin to provide, in ESB's words, *fast-acting energy storage to help provide grid stability and deliver more renewables on Ireland's electricity system.*

Batteries do not, currently, have the capacity to enhance system reliability by providing long-duration energy storage. In the context of this report, long-duration is taken to mean 30 days and the amount of energy that might need to be stored, if it were to be stored in batteries, would be in the order of 6.6 TWh. This would require 44,000 units with the capacity of the Poolbeg unit.

The extent to which battery technology would have to be developed to meet Ireland's long-term LDES requirements can be seen by imagining meeting this requirement with lithium-ion batteries.

In 2023, the National Renewable Energy Laboratory (NREL) in the US published cost projections for utility-scale battery storage out to 2050.[46] The most optimistic NREL projection for the reduction in the capital cost of battery storage capacity is from $482 per kWh in 2022 to $159 per kWh in 2050 (at 2022 prices).

At this price, the capital cost of 6.6 TWh of battery storage would be €976 billion (at 2022 prices).

Between now and 2050, battery technologies (including iron-air batteries and vanadium flow batteries) will continue to develop. However, whether they can develop sufficiently to deliver viable LDES solutions at the scale required in an all-renewable grid in Ireland is highly uncertain.

Conclusions

The analysis above suggests the following:

- Ireland's electricity demand for energy services (i.e. excluding electrolysis) in 2050 could be in the order of **80 TWh**.
- **13.2 TWh** of energy stored in green fuels could be required (assuming an average thermal efficiency of 50%).
- **12 GW** of zero-carbon generation capacity might be needed.
- There could be an unacceptably high risk of low or even zero availability from interconnectors with Britain and France at times coinciding with there being low or no availability from renewables in Ireland.
- It will not be viable to use grid scale batteries to provide long duration energy storage (30 days).

45 *A Commentary on the Medium Term Prospects for Ireland's Hydrogen Economy*, Irish Academy of Engineering, August 2023, Page 21.

46 *Cost Projections for Utility-Scale Battery Storage: 2023 Update,* Wesley Cole and Akash Karmakar National Renewable Energy Laboratory.

APPENDIX 2 – BACKGROUND TO NUCLEAR POWER

Many types of nuclear reactors can be designed using a variety of fuels, coolants and moderators.

The World Nuclear Association (WNA) summarises the world nuclear fleet of power generation reactors across seven types of reactors as shown in **Table 8**. [47]

Reactor type [48]	Fuel	Coolant	Moderator	Number	%	Aggregate capacity GW	Average reactor MW
PWR	Enriched UO_2	Water	Water	310	71%	296.5	956
BWR	Enriched UO_2	Water	Water	60	14%	60.9	1,015
PHWR	Natural UO_2	Heavy water	Heavy water	48	11%	25.0	521
LWGR	Enriched UO_2	Water	Graphite	10	2%	6.5	650
AGR	Natural U (metal), enriched UO_2	CO_2	Graphite	8	2%	4.7	588
FNR	PuO2 / UO_2	Liquid sodium	None	2	0%	1.4	700
HTGR	Enriched UO_2	Helium	Graphite	1	0%	0.2	200
			Totals	**439**	**100%**	**395.3**	**900**

Table 8: Summary of reactor types and capacities as of May 2023

In its *World Nuclear Performance Report 2023*, the WNA reported that 437 reactors - with an aggregate capacity of 394 GW - generated 2,545 TWh in 2022 (implying an aggregate capacity factor of 74%).

Table 9 shows the installed capacities and the electrical energy generated by nuclear plants in the UK, France and the US in 2022.

Nuclear power makes a large contribution to domestic electricity generation in both the UK (15%) and in the US (17%). In France, the contribution is much higher and, notwithstanding plant availability problems in France in recent years (which resulted in a low aggregate capacity factor of 55% in 2022), nuclear power still generated 62% of all electricity generated in France.[49]

47 Source: *World Nuclear Association*

48 PWR - Pressurised water reactor; BWR - Boiling water reactor; PHWR - Pressurized heavy water reactor; LWGR - Light water graphite reactor; AGR - Advanced gas-cooled reactor; FNR - Fast neutron reactor; HTGR - High temperature gas-cooled reactor

49 The World Nuclear Association *reports* that: In 2022 France's reactor fleet produced 282 TWh, well below the ten-year average of 395 TWh. Output rose in 2023 to 320 TWh as reactors returned to service following inspections and repairs. EDF estimates output of 315-345 TWh for 2024, and 335-365 TWh in both 2025 and 2026.

	UK	France	US
Capacity (MW)	5,883	61,370	94,770
No. of reactors	9	56	93
Average reactor capacity (MW)	654	1,096	1,019
Total generation (TWh)	324	475	4,502
Nuclear generation (TWh)	48	295	772
Nuclear %	15%	62%	17%
Average capacity factor	93%	55%	93%

Table 9: Nuclear power capacity and generation in selected countries, 2022

PWR and BWR reactors account for more than four-fifths of the world nuclear fleet.

By the end of the decade, all of the UK's nuclear reactors will be PWR's (**Table 10** and **Figure 4**).[50]

Station	Type	Commenced	Due to close	Capacity
Hartlepool	AGR	1983	2024	1,185 MW
Heysham 1	AGR	1983	2026	1,155 MW
Heysham 2	AGR	1988	2028	1,230 MW
Torness	AGR	1988	2028	1,190 MW
Sizewell B	PWR	1995	2035	1,198 MW
			Total	**5,985 MW**
Hinkley Point C	EPR[51]	Under construction		3,260 MW
Sizewell C	EPR	FID not yet made[52]		3,260 MW
			Total	**6,520 MW**

Table 10: Summary of Civil Nuclear Sites nuclear power plants in Britain

50 *CIVIL NUCLEAR: ROADMAP TO 2050*, Department for Energy Security & Net Zero, January 2024

51 The European Pressurised Reactor (EPR) is a Generation III+ PWR reactor (**Table 11**)

52 Final Investment Decision

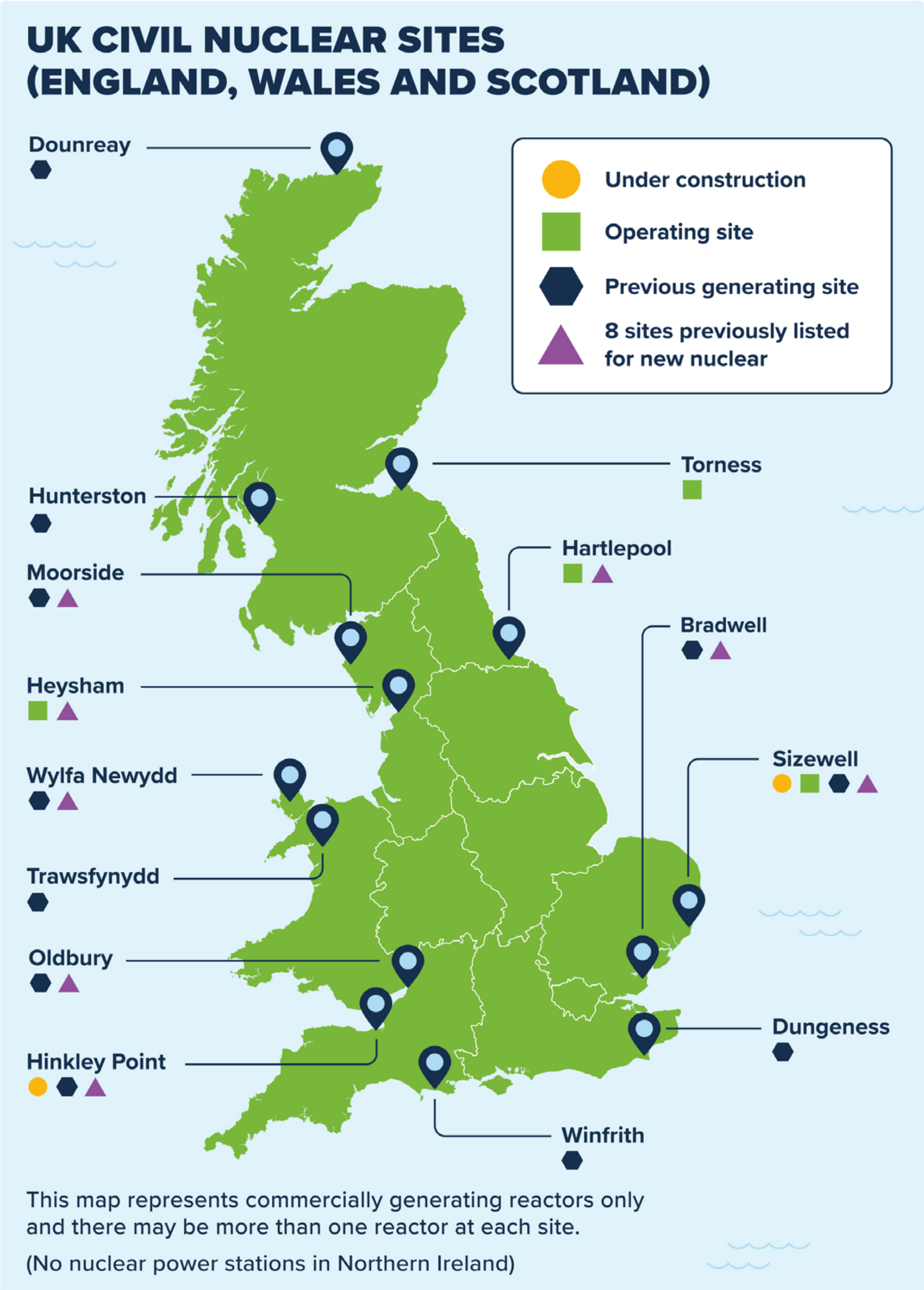


Figure 4: Location of Civil Nuclear Sites nuclear power plants in Britain

The main components of a PWR reactor are shown in **Figure 5**.

The small reactor pressure vessel - 4.3 metres high with a diameter of 3.0 metres (for the 1,100 MW Westinghouse AP1000) – and the steam generator are housed inside a large concrete and steel containment structure and output high pressure steam to a turbine which drives an alternator. Light water is used as both the moderator and coolant and operates at a pressure of 155 Bar.

The fundamental difference between a nuclear power plant and other types of steam turbine power plant is how the heat to produce steam is generated.

In steam turbine power plants in Ireland (such as in Moneypoint and Tarbert), coal or heavy fuel oil (HFO) is combusted in a boiler. The energy released is about 8.1 kWh / kg for coal and 10.8 kWh / kg for HFO. In a nuclear power plant, nuclear fission produces in the order of 23,000,000 kWh / kg of fuel.

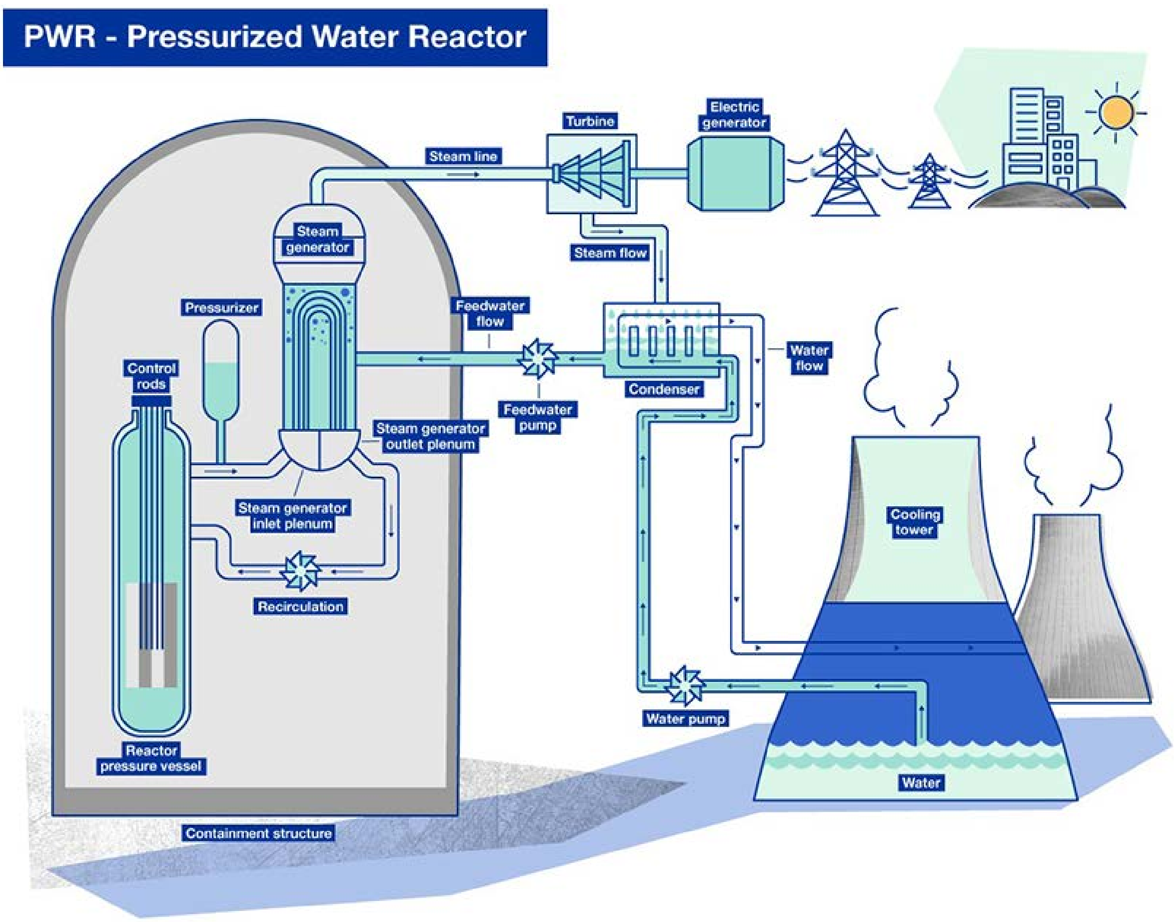


Figure 5: Schematic of a pressurised water reactor, *IAEA*

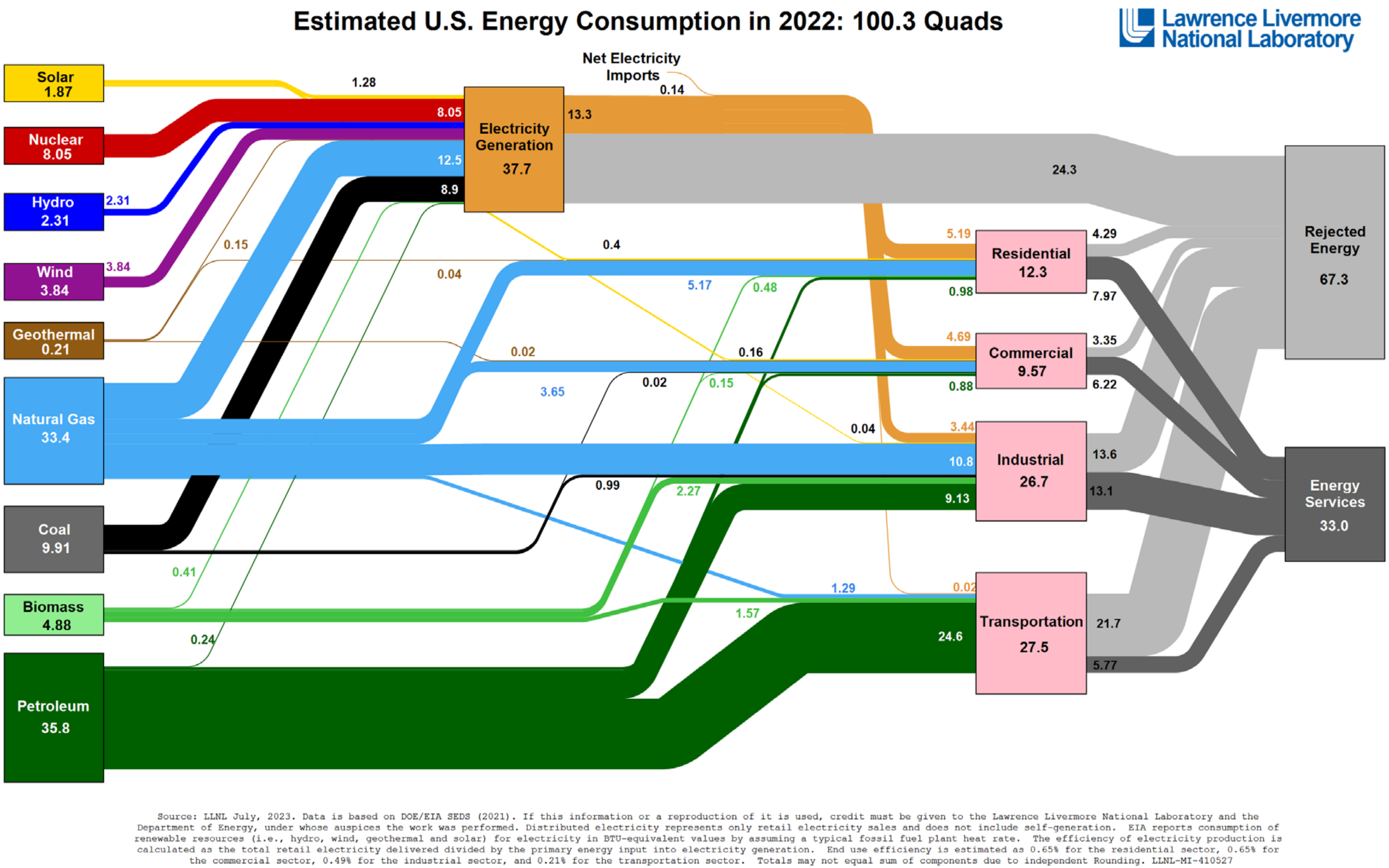
Commercial nuclear reactors for power generation have been operating since the 1950s and, over the past 70 years, there have been distinct generations of reactor type and design as usefully categorised in a Policy Briefing published by the Royal Society (**Table 11**).

	Description	Examples
Generation I	Early prototype reactors.	Calder Hall-1, Shippingport, Dresden-1.
Generation II	Commercial power reactors designed for a typical lifetime of 40 years. Comprised the majority of the world's commercial PWRs and BWRs (over 400) – typically referred to as light water reactors (LWRs).	Pressurised water reactors (PWR), CANada Deuterium Uranium reactors (CANDU), boiling water reactors (BWR), advanced gas-cooled reactors (AGR).
Generation III	Evolved Gen II designs. Improvements include fuel technology, thermal efficiency, modularised construction, safety systems, and standardised design. Planned lifespan of 60 years.	Advanced boiling water reactors (ABWRs), Westinghouse 600 MW advanced PWR (AP600), Enhanced CANDU 6.
Generation III+	Improved Gen III designs, mainly regarding safety. Gen III+ reactors incorporate passive safety features that do not require active controls. Further improvements to fuel efficiency and waste production.	Advanced CANDU reactor (ACR-1000), AP1000, Economic simplified boiling water reactor (ESBWR), European pressurised water reactor (EPR e.g. Hinkley C).
Generation IV	Currently in R&D phase. Mainly comprised of small modular reactor (SMRs) or advanced modular reactors (AMRs), designs. The advantages of Gen IV reactors include high temperatures, less waste per generated output, use of waste and increased variety of viable fuels.	Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), High-temperature or Very Hightemperature Reactor (HTR / VHTR).
Small Modular Reactor (SMR)	Small modular reactors are nuclear fission reactors producing up to 300 MW of electrical power. They can be largely built in factories as modules to minimise costly on-site construction. Their designs can be based on Generation III or Generation IV reactor designs. The term is used by the UK Government to refer to small Generation III reactor designs.	
Advanced Modular Reactor (AMR)	The term used by the UK Government to describe small modular reactors based on new Generation IV designs.	
Fusion reactor	All Generation I to IV reactors are fission reactors that produce energy from splitting atoms. A fusion reactor produces energy from combining atoms. Research is ongoing around the world to develop fusion reactors e.g. ITER.	

Table 11: Categorisation of the generations of nuclear reactors, The Royal Society.[53]

53 *Nuclear cogeneration: civil nuclear energy in a low-carbon future,* Policy Briefing, The Royal Society, 2020

APPENDIX 3 – ENERGY FLOWS IN THE US, 2022 [54]



54 Source: Lawrence Livermore National Laboratory. Energy units are Quads (where 1 Quad = 10^{15} BTU = 293 TWh).

APPENDIX 4 – GENERATION ASSETS, IRELAND, SEPTEMBER 2023 [55]

All generation assets

Nov 2022 to Oct 2023	MEC
Transmission connected non-renewable	6,028 MW
Distribution connected non-wind / solar	342 MW
Wind	4,675 MW
Solar	436 MW
Hydro	213 MW
Total	**11,694 MW**
Non-renewable	6,370 MW
Renewable	5,324 MW
Total	**11,694 MW**

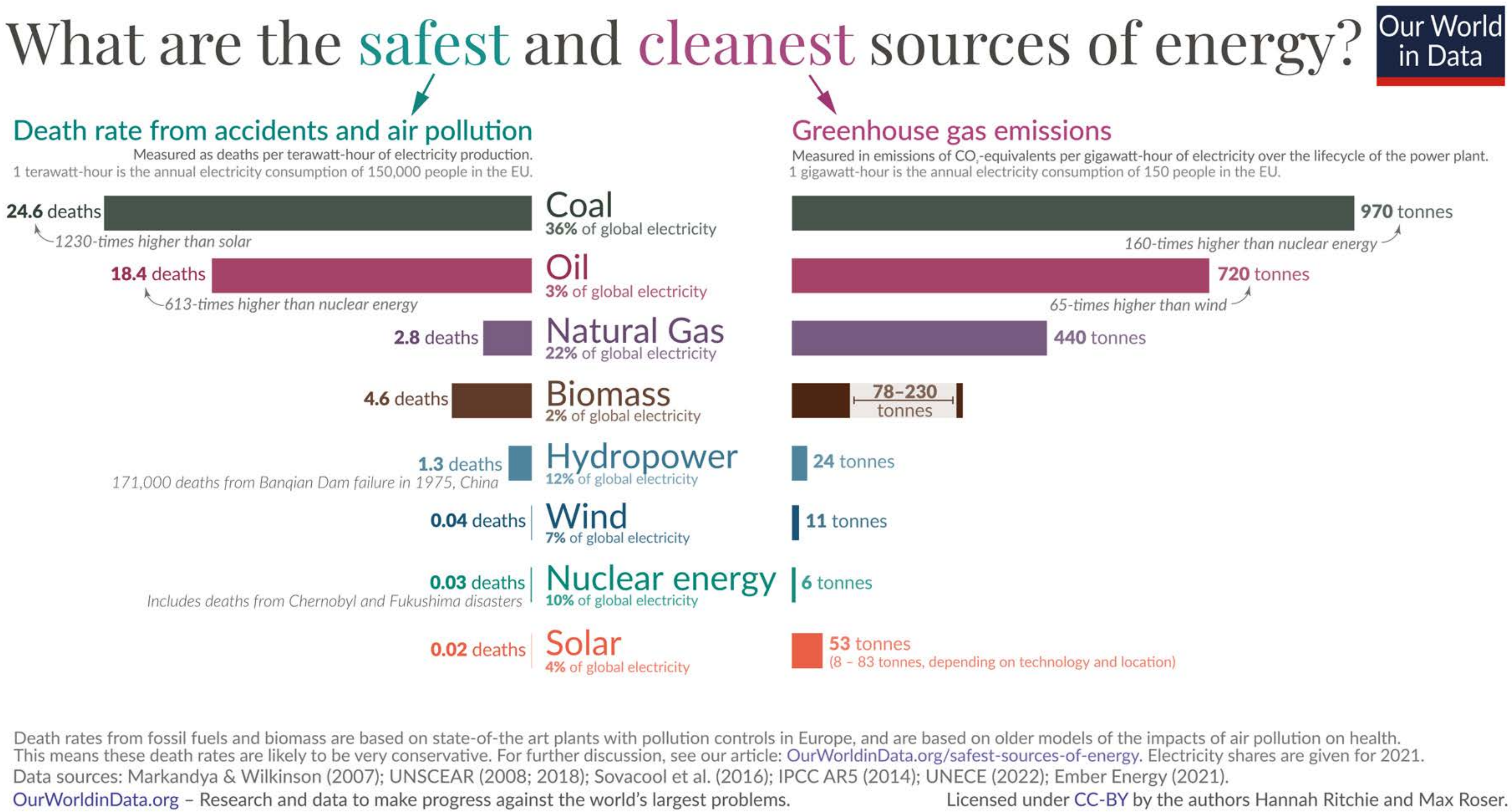
Transmission connected non-renewable generation assets

	Generator	Fuel / type	MEC	Connection Date
1	Poolbeg	Gas / DO	463 MW	Pre 2000
2	Whitegate	CCGT	445 MW	2010
3	Aghada CCGT	CCGT	431 MW	2010
4	Dublin Bay Power	Gas	415 MW	2002
5	Huntstown (2)	Gas	412 MW	2007
6	Tynagh	Gas	404 MW	2006
7	Huntstown (1)	Gas	352 MW	2002
8	Moneypoint (1)	Coal	287.5 MW	Pre 2000
9	Moneypoint (2)	Coal	287.5 MW	Pre 2000
10	Moneypoint (3)	Coal	287.5 MW	Pre 2000
11	Tarbert (3)	HFO	240.7 MW	Pre 2000
12	Tarbert (4)	HFO	240.7 MW	Pre 2000
13	Great Island CCGT	CCGT	216 MW	2014
14	Great Island CCGT	CCGT	215 MW	2014
15	Aughinish Alumina	CHP	162 MW	2005

55 Source: *EirGrid*

	Generator	Fuel / type	MEC	Connection Date
16	West Offaly Power	Peat	141 MW	2005
17	Edenderry Power	Peat	121.5 MW	Pre 2000
18	Edenderry Peaking	OCGT	116 MW	2010
19	North Wall (5)	Gas / DO	109 MW	Pre 2000
20	Lough Ree Power	Peat	94 MW	Pre 2000
21	Aghada (11)	Gas / DO	90 MW	Pre 2000
22	Aghada (12)	Gas / DO	90 MW	Pre 2000
23	Aghada (14)	Gas / DO	90 MW	Pre 2000
24	Tarbert (1)	HFO	54 MW	Pre 2000
25	Tarbert (2)	HFO	54 MW	Pre 2000
26	Tawnaghmore Peaking 1	OCGT	52 MW	2003
27	Tawnaghmore Peaking 2	OCGT	52 MW	2003
28	Rhode PCP (1)	Distillate	51.8 MW	2004
29	Rhode PCP (2)	Distillate	51.8 MW	2004
30	Kelwin (KZ3)	Diesel	2 MW	Jul-18
		Total	**6,028 MW**	

APPENDIX 5 – COMPARISON OF SAFETY AND GHG EMISSIONS FOR DIFFERENT SOURCES OF ENERGY [56]



56 Source: Report by Hannah Ritchie and Pablo Rosado published by *Our World in Data*

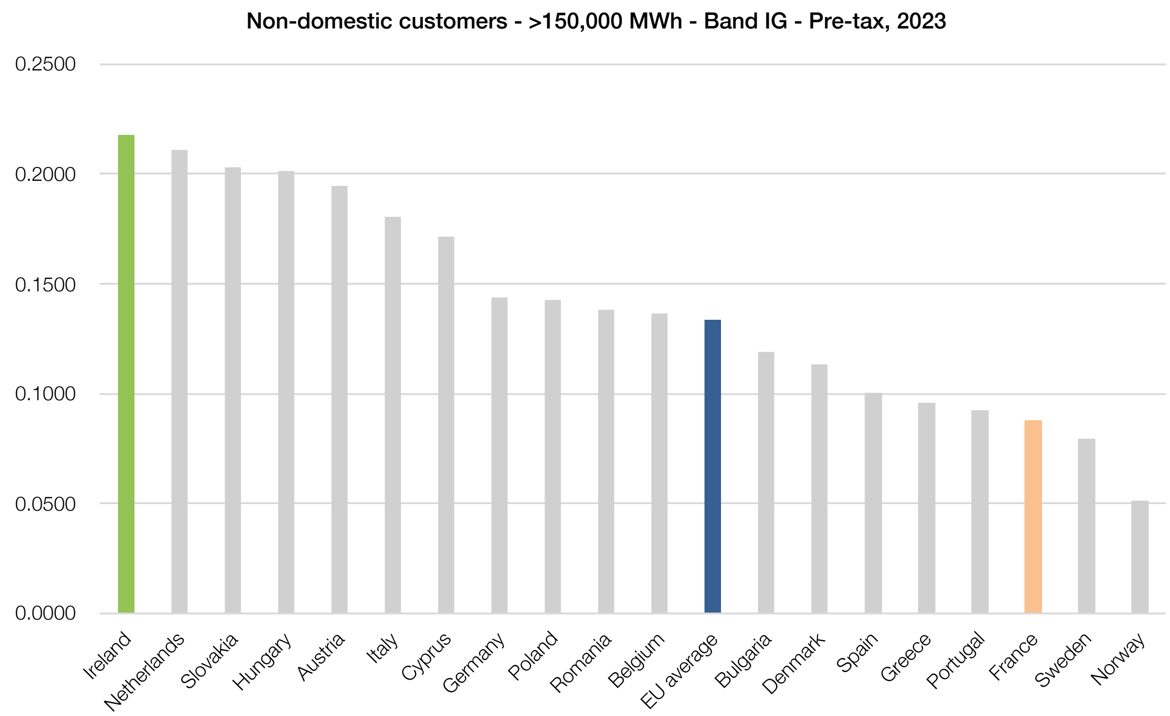
APPENDIX 6 – ELECTRICITY COSTS FOR LARGE ENERGY USERS IN EU MEMBER STATES [57]

Comparison in 2023 (€ per kWh)

	2023-S1	% of cost in Ireland
Ireland	0.2175	100%
Netherlands	0.2108	97%
Slovakia	0.2031	93%
Hungary	0.2013	93%
Austria	0.1944	89%
Italy	0.1807	83%
Cyprus	0.1715	79%
Germany	0.1440	66%
Poland	0.1424	65%
Romania	0.1381	63%

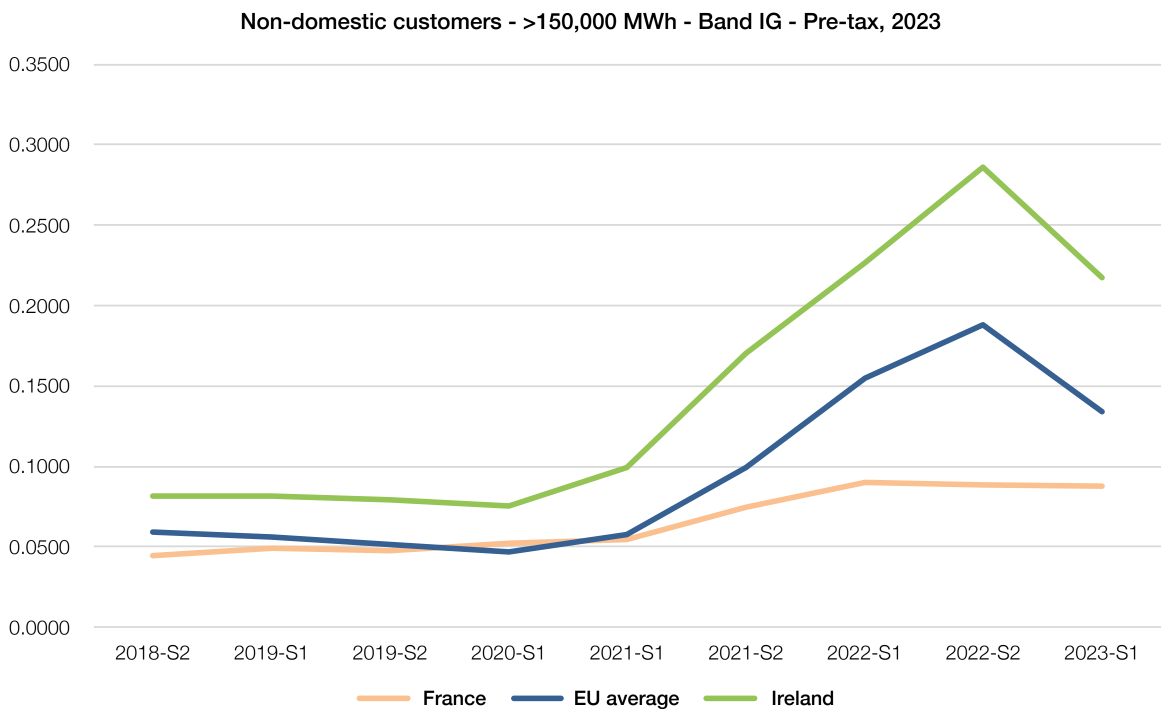
	2023-S1	% of cost in Ireland
Belgium	0.1363	63%
EU average	0.1338	62%
Bulgaria	0.1188	55%
Denmark	0.1133	52%
Spain	0.1003	46%
Greece	0.0961	44%
Portugal	0.0927	43%
France	0.0881	41%
Sweden	0.0796	37%
Norway	0.0515	24%

Comparison from 2018 to 2023 (€ per kWh)

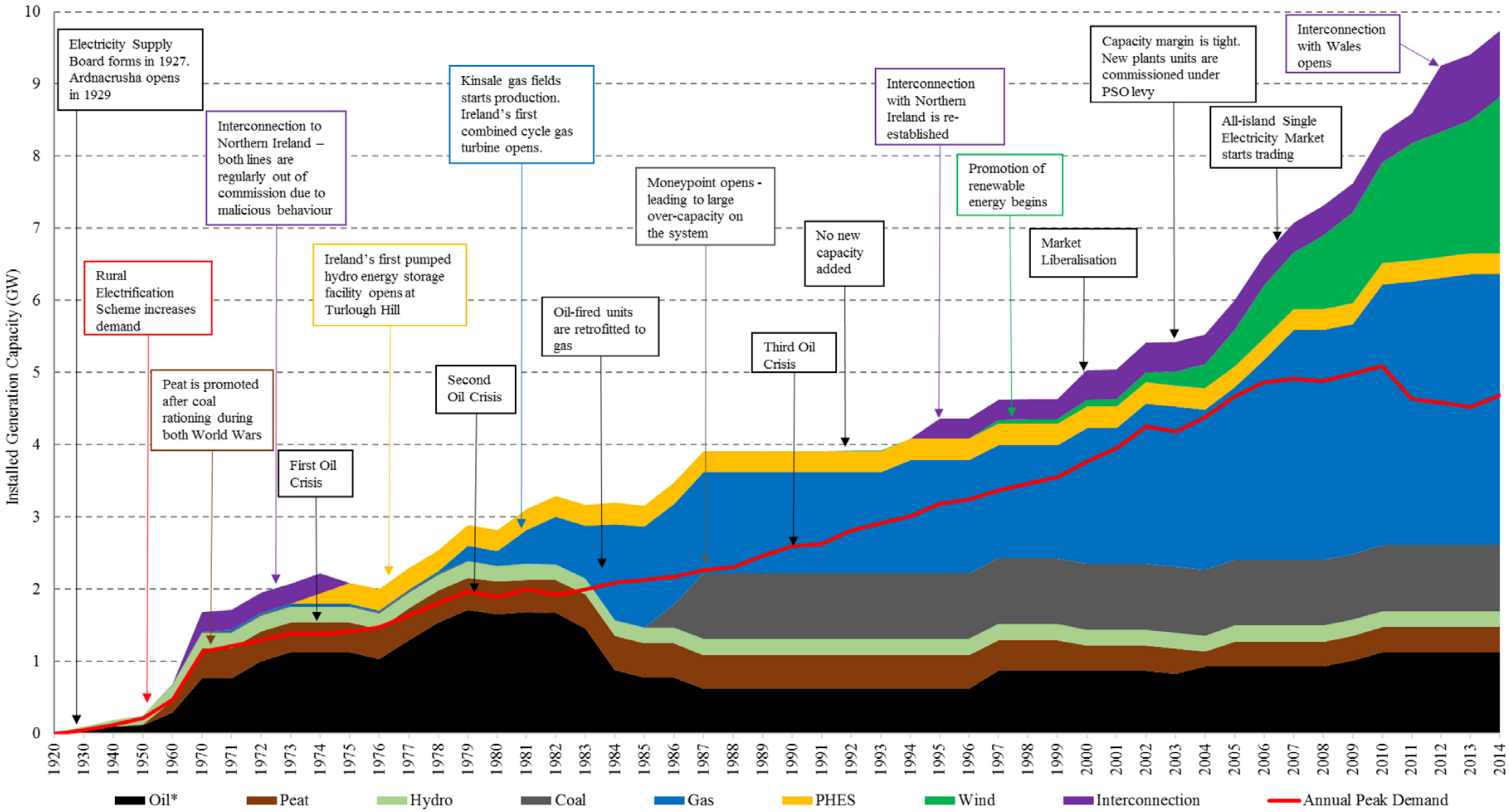


57 Source: *Eurostat* - Non-domestic customers - >150,000 MWh p.a. - Band IG - Pre-tax

	France	EU average	Ireland
2018-S2	0.0446	0.0590	0.0814
2019-S1	0.0494	0.0559	0.0816
2019-S2	0.0479	0.0514	0.0790
2020-S1	0.0524	0.0467	0.0757
2021-S1	0.0543	0.0580	0.0993
2021-S2	0.0745	0.0993	0.1703
2022-S1	0.0900	0.1551	0.2270
2022-S2	0.0883	0.1880	0.2861
2023-S1	0.0881	0.1338	0.2175



APPENDIX 7 – GROWTH IN POWER GENERATION CAPACITY IN IRELAND [58]



* Early oil-fired units could also operate on coal – which was preferred until the 1960's

58 A 100 year review of electricity policy in Ireland (1916–2015), Gaffney, Fiac; Deane, John Paul; Ó Gallachóir, Brian P.; 2017

GLOSSARY

Term or abbreviation	Description
BWR	Boiling Water Reactor
Capacity factor	A 10 MW generator running for 8,760 hours in a year would generate 87,600 MWh and would have a capacity factor of 100%. In practice generators run fewer hours in the year and not always at their maximum capacity. Their capacity factor is, therefore, less than 100%. In 2022, EirGrid reported that Ireland's installed wind capacity of 4,527 MW generated 10,895 GWh giving a capacity factor of 28%.
CCGT	Combined cycle gas turbine.
CFD	Contract for difference. Investors in large energy projects require reasonable revenue certainty in order to be able to raise finance. This has been achieved in Ireland, and in other countries, by guaranteeing the unit energy price projects will earn over a defined period (typically 20 or 25 years). CFDs provide this certainty by ensuring that if the price received from wholesale markets is lower than an agreed strike price, then the difference will be made up by a supplementary payment. However, at times, wholesale markets will yield prices higher than the agreed strike price and, in these circumstances, projects are required to refund the difference. The net cost of supplementary payments and refunds is borne by customers.
CRU	Commission for Regulation of Utilities
Dunkelflaute	EirGrid describes a Dunkelflaute as: *…a German word which translates as 'cold, dark doldrums'. In such conditions, it is essential to have indigenous resources that can supply electricity over a multi-day, rather than multi-hour, period.*
FID	Final Investment Decision
GBN	Great British Nuclear is the renamed British Nuclear Fuels Limited (BNFL). GBN has been given the responsibility to drive delivery of new nuclear projects in the UK, notably SMR projects.
GHG	Greenhouse gases
Gigawatt scale	Large nuclear reactors typically have a power capacity in excess of 1,000 MW (1 GW).The term gigawatt scale usefully differentiates these large traditional nuclear plants from the small power output SMR class of nuclear reactors with power capacities up to 500 MW.
GW	Gigawatt. 1 GW = 1,000 MW.
HFO	Heavy fuel oil
IAE	Irish Academy of Engineering
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ktoe	kilo tonnes of oil equivalent. This is a unit of energy where 86 ktoe = 1 TWh. Using ktoe can be useful as it allows energy quantities to be visualised in terms of recognisable physical quantities. For example, the energy content of 1,000 tonnes of diesel is very close to 1 ktoe.

Term or abbreviation	Description
LCOE	The Levelised Cost of Energy is a measure of the average cost of producing energy over the lifetime of a generation asset, discounted to current prices. Its calculation incorporates a range of costs including capital investment cost, fuel cost, fixed and variable operating and maintenance costs, finance costs, and an assumed capacity factor. It provides a basis to compare the cost of generation by different technologies. For example, nuclear has a very much higher LCOE than, for example, solar. LCOE, however, has its limitations. Most electricity customers do not buy power from generators. Reliable power, available 24/7/365 is purchased from a power system. The price of electricity from the power system will be determined by the mix and usage of generation plant on the system. Use of simple LCOE comparisons can be misleading when considering the future price of electricity.
LDES	Long Duration Energy Storage
MEC	Maximum Export Capacity. The maximum power (MW) allowed to be exported to the grid.
MW	Megawatt is a measure of the power output of a generator (or the power demand of a load, such as a factory, a town or a data centre). In power systems, the total power capacity is typically in the thousands of MW and GW is often used instead. 1 GW = 1,000 MW. Steam powered generators (including nuclear, coal and oil fired units) generate electricity at an efficiency in the order of 35% to 40%, i.e. 60% to 65% of the energy in the fuel is transformed into heat and is mostly wasted. Sometimes the output of a nuclear plant is stated in MW_e to clarify that it is the electrical output that is being referred to. In this report, wherever MW (or GW) is used, it refers to electrical output.
NORA	National Oil Reserves Agency
OCGT	Open Cycle Gas Turbine
ORESS1	ORESS is an abbreviation for the Government's Offshore Renewable Electricity Support Scheme. ORESS1 refers to the first auction run under this scheme. The final results of this auction were announced by EirGrid in June 2023.
PER	Primary Energy Requirement is the combination of the energy content of the fuels (oil, gas and coal) imported into or sourced in the country (gas, peat, waste) and of the energy generated by renewables or imported via interconnectors. Some fuels (notably gas and coal) are, for the most part, used to generate electricity and much of their energy content is lost in this transformation. PER in Ireland in 2022 was 167.0 TWh or 14.4 ktoe.
PWR	Pressurised Water Reactor
SMR	Small Modular Reactor

Term or abbreviation	Description
SNSP	System Non-synchronous Penetration. In traditional AC grids, all generation capacity came from AC generators driven by various types of turbines (steam, gas and water). In such generators, the momentum (or inertia) of the rotating turbines and generators can provide energy over very short periods to counteract disturbances on the system and, in this way, contribute to the maintenance of system frequency, voltage and stability. In recent years, there are sources of DC power increasingly being connected to the grid, notably batteries and solar PV arrays. These cannot contribute to system stability. Moreover, for technical reasons, long-distance transmission in undersea cables is DC with the AC at the sending end changed (rectified) to DC and the DC at the receiving end changed (inverted) to AC. Finally, although wind turbines have AC alternators, the AC must be changed to DC first and subsequently back to AC at grid frequency. In all of these four cases the sources of power are non-synchronous and cannot contribute to grid stability. The proportion of such sources of power in the system is referred as System Non-synchronous Penetration.
TFEC	Total Final Energy Consumption is the energy required to provide services such as transport, heating, lighting and for industrial process (including cement manufacture, factories and data centres). TFEC in 2022 was 140.3 TWh or 12.1 ktoe.
TWh	Terawatt-hour is a unit of energy. 1 TWh = 1,000,000 MWh (megawatt-hours) and 1 MWh = 1,000 kWh (kilowatt-hours). Also, 1 TWh = 86 ktoe.
Zero-carbon	In this report, the term zero-carbon refers to thermal generation plant fuelled by hydrogen or ammonia or conventional generation plant fuelled by, for example, natural gas but with carbon capture and storage (CCS).

PREVIOUS REPORTS OF THE ENERGY & CLIMATE ACTION COMMITTEE OF THE IRISH ACADEMY OF ENGINEERING

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2	Response to Energy Security Report	Oct-22	*link*
3	Europe's Energy Crisis – Implications for Ireland	May-22	*link*
4	Restoring confidence in Irish energy supply	Nov-22	*link*
5	National Energy and Climate Plan - The Challenge of High Levels of Renewable Generation in Ireland's Electricity System	Mar-21	*link*
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9	Natural Gas - Essential for Ireland's Future Energy Security	Jul-18	*link*

Disclaimer

The members of the Taskforce and the contributors participated in extensive discussions in the course of a series of meetings, and submitted comments on a series of draft reports. This report represents the collective view of the Academy , and its recommendations do not necessarily reflect a common position reached by all members of the Taskforce and do not necessarily reflect the views of individual members of the Taskforce, nor do they necessarily reflect the views of the organisations to which they belong.

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