<u>Harnessing nuclear power to meet Croatia's energy needs</u>*

- Croatia should commission a Small Modular Reactor (SMR) as a pioneer of new types of nuclear power station

This short policy report considers the opportunities available to the Croatian government for the utilisation of new nuclear technology for domestically produced energy.

As other European countries struggle to balance their desire for a reliable energy supply with their contribution to climate change, recent advances in nuclear technologies present a solution.

Background

- Nuclear power has been demonstrated to be a safe, cheap alternative to fossil fuels
- Emphasis on sustainable economic development necessitates non-carbon energy providers

The global reliance on fossil fuels is a function of our energy needs, and although attempts to reduce demand (such as making internal combustion engines prohibitively costly to operate, or levying large taxes on air transport) may form part of the strategy, appropriate sources of supply still need to be defined.

Fossil fuels such as coal, oil and gas have the benefit of being **capable** of servicing our energy needs. However, they are a chief contributor to climate change. And as countries attempt to meet the Paris Agreement of keeping global temperature below 2º above pre-industrial levels, non-carbon energy sources are essential. Renewable sources such as wind or solar are **clean**, but intermittent, require an uneven geographical distribution, and are prohibitively expensive to fully replace the carbon pollutants.[1] Nuclear energy provides an opportunity on the grounds that it's capable *and* clean.

Nuclear power doesn't solve the issue of sustainability, literally, because there is only a finite amount of nuclear materials on earth. As West says, "energy produced by nuclear reactors is internal to the entire global system and consequently suffers from similar issues regarding the production of entropy and deleterious by-products." (2017, p.275). And as a member state of the EU Croatia is obliged to provide at least 20% renewable energy by 2020. However, renewable sources do not provide a complete solution, either. As Rooney (2018) says, "large-scale biomass is technically

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[1] Although renewable energy has demonstrated encouraging reductions in cost over time, they require massive amounts of land (or sea) which are not always close to the points of energy consumption. According to Eli Dourado there are no solar farms capable of operating at a similar scale to nuclear power stations, and just a single wind farm (in China, with a current output of 8 GW and planned output of 20 GW). See https://elidourado.com/blog/move-the-needle-on-progress/

renewable, but not necessarily sustainable – not without extremely tight safeguards and regulations" (p.21). An emphasis on sustainability, rather than renewability, is therefore an argument in favour of nuclear provision. Switching from unsustainable to fully renewable energy quickly is immensely costly and unnecessary. Making energy usage *more* sustainable is an alternative, realistic strategy. And nuclear power is much more sustainable than fossil fuels. For countries that are adopting an energy strategy that is (i) sustainable; (ii) low carbon; (iii) affordable; and (iv) safe; nuclear energy and renewables are complements, not substitutes. As Table 1 shows, nuclear power is a strong contender to form part of a countries energy needs.

	Sustainable	**Low carbon**	**Affordable**	**Safe**
Fossil fuels	×	×	✓	×
Renewables	✓	✓	×	✓
Nuclear	✓	✓	✓	✓

Table 1: Energy comparison

The major downside of nuclear energy is the waste products, but this may well be a price worth paying for a realistic means to meet climate change targets. The greater the concern about climate change, the more willing we must be to store nuclear waste. And as shall be discussed, technological advances can dramatically reduce the storage costs.

After the first nuclear power plant was built in 1956, steady growth saw the number exceed 100 in 1973, 200 in 1978, 300 in 1984, 400 in 1987, but has then remained under 450.[2] Power plants have evolved in four distinct "generations", summarised below.[3]

- Gen-I (1950-1970)
  The first generation of nuclear reactors were designed to provide electricity as well as plutonium for nuclear weapons programmes.
- Gen-II (1970-1990)
  The second generation delivered the majority of power stations in use today.
- Gen-III (1990-2030)
  The third generation are similar in design to Gen-II but with significant safety improvements following the notable accidents that occurred at Three Mile Island and Chernobyl.
- Gen-IV (2030-?)
  The next generation of power station designs over even greater benefits in terms of efficiency, proliferation resistance, and use of waste products.

There are currently 449 nuclear power plants in the world, and the biggest producers of nuclear energy are the United States (805 TWh), France (379 TWh) and then China (less than 250 TWh), Russia (less than 200 TWh), South Korea (less than 150

[2] See https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx
[3] This overview relies heavily on Rooney, 2018, p.24

TWh), and then Canada, Ukraine, Germany, UK, Sweden, and Spain all produce between 50 TWh and 100 TWh.[4]

The most fascinating part of the French emphasis on nuclear power is that it preceded global concerns about climate change. From 1978 to 1998 France's embrace of nuclear energy permitted a reduction in their use of fossil fuels from 55% of electricity production to 10%.[5] This has been referred to as "*the most successful rapid decarbonisation on record.*"[6]

As of 2014 Ukraine satisfied 49% of its electricity requirement from nuclear power, Bulgaria had 34% and Romania 18%. Europe is the main global market for nuclear energy with several countries gaining more than 20% of their energy needs from nuclear sources (Finland, Sweden, Switzerland, the UK, Spain, Hungary, Czech Republic, Slovakia, Slovenia).[7]

During the 1990s around 16%-18% of global electricity production came from nuclear sources. However this has steadily fallen, to just over 10% in 2015.[8] In part this is due to the rise of renewable energy, which has risen from just under 20% in the 1990s to 23% in 2015. But it's clear that renewable sources are not sufficient, especially since global energy needs are rising.

Nowhere is this better demonstrated than in Germany, where a decision to completely phase out nuclear power by 2022 has prompted a move back to coal production to meet energy needs.

The German case is a curious one, with a general public particularly averse to nuclear power. And yet it's clear that the sudden abandonment is a result of the Fukushima disaster on March 11th 2011. While it may be understandable that multiple meltdowns that occurred caused *Japan* to reassess its nuclear strategy, the relevance for Germany is less clear. The Fukushima disaster occurred because the Tohoku earthquake delivered a 14m high tsunami that breached the plant seawall. This is not an argument against nuclear power per se, but should prompt a reflection on whether building them on remote sea front locations, without sufficient wave protection, is wise. It is certainly not an argument against nuclear power in *Europe*, where the threat of earthquakes and tsunamis is minimal.

There is evidence to suggest that public concerns over nuclear power are a reflection of ignorance, rather than underlying danger. For example, Americans that live closer to nuclear power stations are *more* likely to have a favourable opinion of the nuclear industry.[9] This may well reflect a greater financial reliance (e.g. the families of people who earn their livelihood from nuclear power), but also

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[4] See https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx
[5] See https://twitter.com/laydgeur/status/1232667445246222338?s=20
[6] https://twitter.com/mattyglesias/status/1233715610477105152
[7] See https://ourworldindata.org/grapher/nuclear-energy-electricity-production/. Accessed June 9th 2020.
[8] https://ourworldindata.org/grapher/nuclear-versus-renewables-as-share-electricity-production
[9] See Rooney, 2018, p.37.

demonstrates that when people understand the benefits they are much more willing to educate themselves on the risks.

Clearly the impact of Fukushima was to reinforce in the mind of the public (and policymakers) the idea that nuclear power is inherently dangerous. Links were immediately made with the Chernobyl disaster and Three Mile Island.[10] And yet nuclear power is demonstrably safer than alternatives.

Markandya and Wilkinson (2007) present data on the safety records of alternative sources of energy supply. These include acute and chronic effects of pollutants as well as cancer-related deaths attributable to nuclear power.[11] As Figure 1 shows, nuclear power is significantly safer than all listed alternatives.

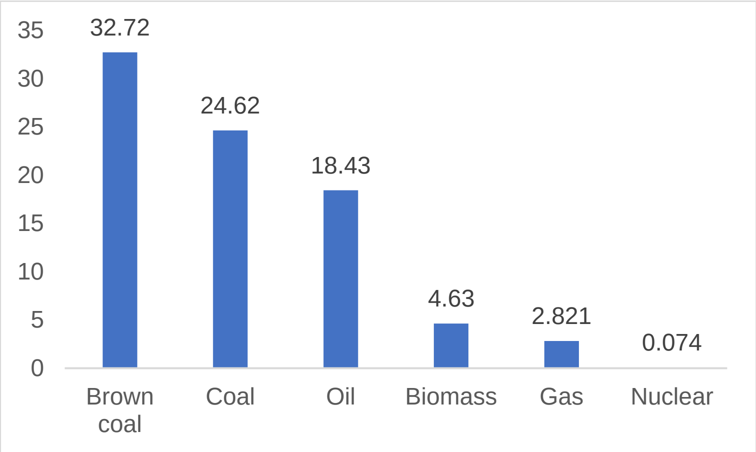

Figure 1: Death rates from energy production per twh. Source: Markandya and Wilkinson (2007).

Sovacool et al (2016) collate accidents from a range of energy production sources, counting 686 separate accidents that have resulted in over 180,000 human casualties. They conclude that wind energy produces the most accidents and hydroelectric are most fatal.[12]
An advantage of this study is that it includes a Fukushima disaster, and yet nuclear power still has a very low number of human casualties. Indeed, it's worth dwelling on how resilient the power station was. The earthquake caused Japan's main island to move a full 8 feet eastward, and the tsunami killed 18,000 people. According to

[10] the focal point of Schlosser (2014)'s account of nuclear accidents is when an air force repairmen dropped a wrench while maintaining a US nuclear warhead, in Arkansas in 1980. The damage prompted a leaking fuel tank which, when ignited, killed one person, injured 21 others, and catapulted the payload out of the silo and into off base woodland. This remarkable event constitutes a near miss but it's important to point out that the weapon didn't detonate. Despite the disastrous circumstances, the safety features of the bomb itself *worked*.
[11] https://ourworldindata.org/grapher/death-rates-from-energy-production-per-twh
[12] They present a set of risk profiles, namely "high" risk of accidents (nuclear, hydro, and wind energy); "moderate" accident risk (hydrogen, biofuels, and biomass); and "low" risk (solar and geothermal). The key reason for the risk assigned to nuclear is the fact that nuclear accidents tend to be more expensive than other accidents. Although this is a valid concern, it paints a false impression of the risk of nuclear energy in terms of human health. Also, any study that attempts to assess the safety record of alternative energy sources will systematically misrepresent industries that the greatest scope for technical innovation. Records of past accidents should be revised by improvements (and expected future improvements) in safety protocols.

Rosling (2018, p.115), 1,600 people died in the course of fleeing the reactor site, but as of 2020 just one death has been attributed to radioactive contamination.[13]

Nuclear power is one of the safest forms of energy provision, and supported by the International Energy Agency (IEA) and Intergovernmental Panel on Climate change (IPCC) as part of the required energy mix.[14]

Impact

- Croatia's reliance on energy imports is rising, with over half the energy needs coming from outside domestic production.
- Croatia is already a leader in non-fossil fuel energy. Most domestic energy production is provided through hydro or thermal power plants.
- It is estimated that 15%-20% of Croatia's energy needs are met by the Krško Nuclear Power Plant, a joint venture between the Slovenian and Croatian government. However, this is due to be decommissioned in 2023.

From 1995 to 2005 the total primary energy supply has increased across all major sources. As Figure 2 shows, Croatia is heavily reliant on oil and natural gas.

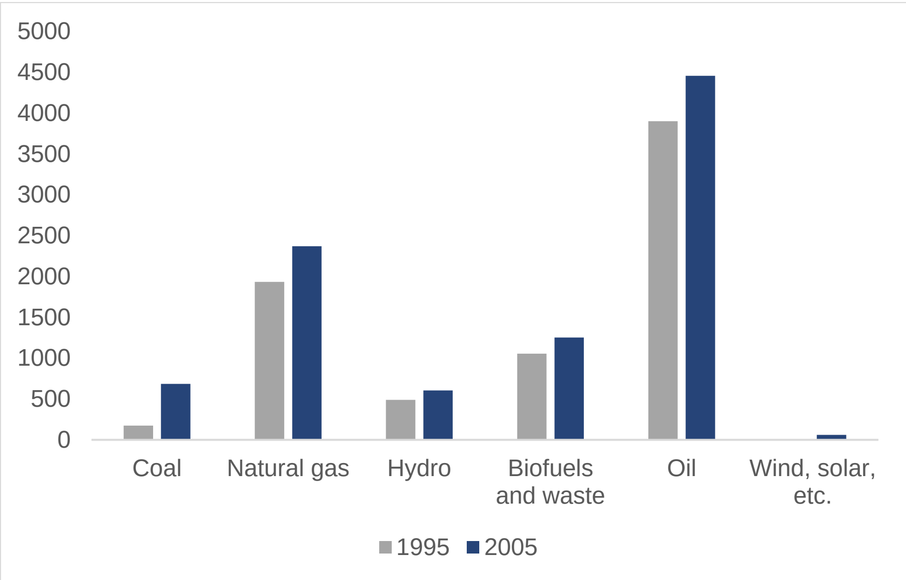

Figure 2: Total primary energy supply (ktoe). Source: IEA World Energy Balances 2009

[13] This underlines the disjoint between public perception and actual nuclear risks. More lives would have been saved had people not fled the scene. Similarly, although much of the blame for the 1986 Chernobyl disaster can be attributed to the lack of safety procedures and culture of secrecy within an authoritarian system (in other words such an accident is highly unlikely in a modern democratic country), once the meltdown began the severe health impacts were a result of the attempted cover up and lack of information rather than the radioactive material. Around 70% of the fallout landed in Belarus and yet it took over three years before the public learnt about the what had happened. By 1992 there had been a 40% increase in congenital defects in new-born children, and 333 cases of thyroid cancer in children were attributed to the radiation. See Marples (1996, p.106).

[14] See Rooney, 2018, p.23.

In terms of production, the majority of Croatia's domestic energy supply comes from hydro power and fuel wood and biomass. Figure 3 shows the split as of 2018.

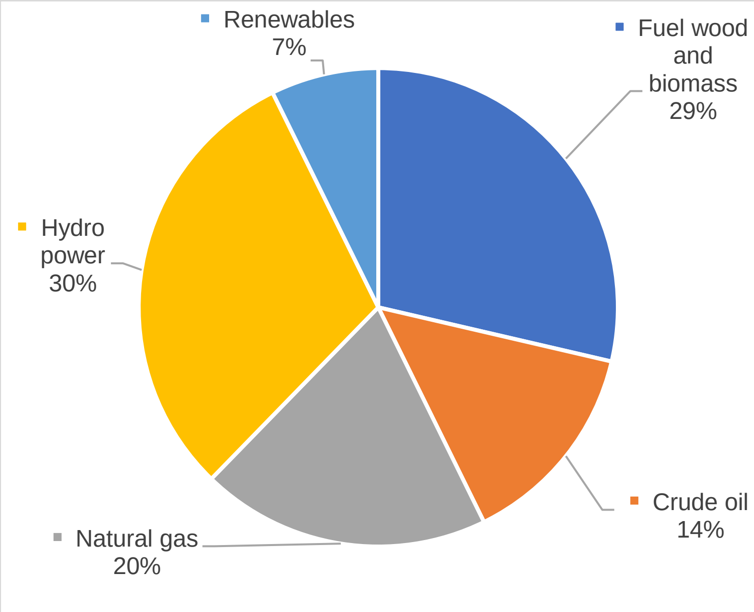

Figure 3:Primary Energy Production, 2018 Source. Energy in Croatia 2018

The composition has changed over time, with production from renewable energy growing at an average annual rate of 16 percent since 2013. Over the same period natural gas fell by 7.4 percent (from 63.11pj to 43.07pj) and hydro power declined 4.6 percent (from 84.92pj to 66.98pj).[15]

Croatia has 17 hydro power plants and 7 thermal power plants. Wind and solar energy are typically generated through private providers.[16]

Figure 4 shows that Croatia's dependency on imports to satisfy energy needs has risen from 46% in 2009 to 53% in 2018.[17] According to rough estimates this amounts to around 12 billion kuna.[18]

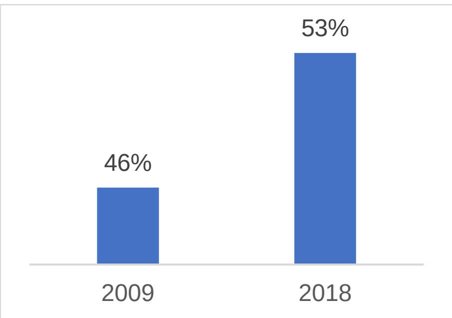

Figure 4: Energy imports dependency. Source: Eurostat.

[15] See Energy in Croatia 2018.
[16] https://www.expatincroatia.com/croatia-energy-sources/
[17] See http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_ind_id&lang=en
[18] https://www.expatincroatia.com/croatia-energy-sources/

Most imports are crude oil and other petroleum products and the vast majority of exports are petroleum products. Figure 5 shows the breakdown.

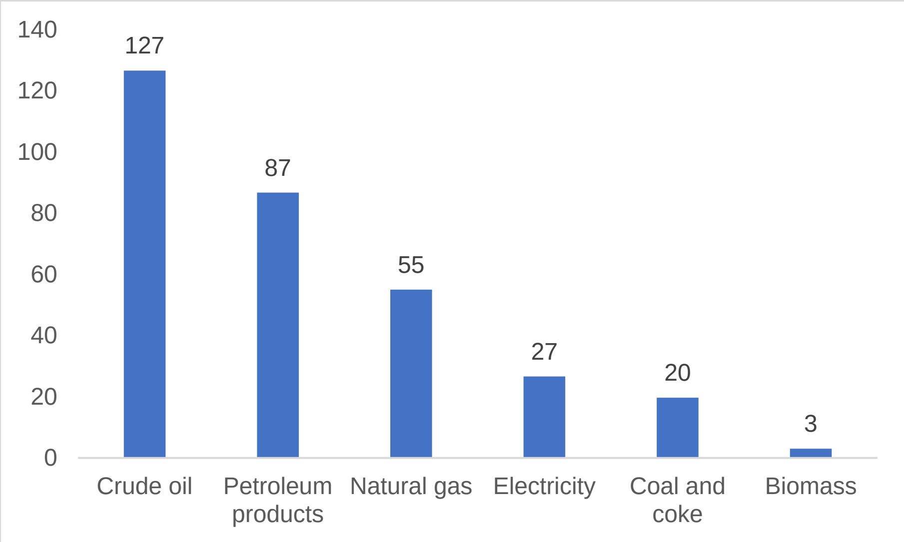

Figure 5: Energy imports (PJ). Source: Energy Report 2018

Croatia does currently produce and utilise nuclear power. The Croatian government has joint ownership of the Krsko nuclear power plant, located in Slovenia.[19] 28% of Slovenia's average energy needs are provided by the single nuclear reactor at Krisko.

According to some sources, the Krsko plant provided 15%-20% of Croatian energy needs as of 2010.[20] At that point discussions were being made for Slovenia to have sole ownership of an upgraded plant, and for Croatia to develop its own in Eastern Slavonia. However official statistics report zero domestic nuclear production, and no imports of nuclear generated power.[21] So although Croatia doesn't produce nuclear energy in Croatia, it has existing nuclear reliance and capabilities.

Around 55 nuclear reactors are under construction across the world, including Mochovce 3 in Slovakia and Mochovce 4 in Slovenia. However, the key opportunities come from new types of nuclear reactor.
There are three main innovations worth monitoring closely.

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[19] The operating company, Nuklearna Elektrarna Krsko (NEK), is owned by GEN Energija, (a subsidiary of the Slovenian state-owned Elektro-Slovenija (ELES)), and the Croatian state-owned company Hrvatska Elektroprivreda (HEP).

[20] See "Approval sought for new Slovenian reactor", World Nuclear News, January 29th 2010. https://www.world-nuclear-news.org/Articles/Approval-sought-for-new-Slovenian-reactor.

[21] Having said this, some sources neglect Slovenian imports entirely. This implies that Slovenia consumes all of the nuclear production at Krsko, compensating Croatia in a way that doesn't show up as a Croatian export. According to one website, in 2018 Croatia imported 40% of crude oil (from Russia, Azerbaijan, Iraq, Libya and Nigeria), 27% of petroleum products (from Russia, Azerbaijan, Iraq, Libya and Nigeria), 17% of natural gas (from Russia), 8% of electricity (from Hungary and Bosnia and Hercegovina), 6% of coal and coke (from Columbia) and 1% of biomass. See https://www.expatincroatia.com/croatia-energy-sources/

(i) Small Modular Reactors

A disappointing aspect of the French nuclear experience is the failure of economies of scale in production. Ordinarily one should expect that building more nuclear reactors would reduce the future per unit costs, due to factors such a learning by doing, but according to Grubler (2010) the costs went up. Rooney (2018) points to three main reasons for this:

- Increased safety requirements
- Increased build durations
- Frequent design changes

Although there's an inevitable element of cost overruns being typical of any large public infrastructure project, it's clear that "large nuclear power plants were more likely to go over budget and by a greater percentage than any other electricity generation technology" (Rooney 2018, p.26). But it seems that a reasonable compromise can be made. There remains scope for government to take a lead on such projects, given that "the places where nuclear power has thrived have been where the Government has taken an active role in a large-scale deployment programme through the use of a national champion" (Rooney 2018, p.26). The nuclear industry has high regulatory requirements, there are national interests in energy security, and economies of scale are prevalent. However, that doesn't necessitate the massive projects that have characterised nuclear power stations thus far.

Small Modular Reactors (SMR) are pre-fabricated units that can be assembled onsite. Over the last 5 years SMR's have emerged as a means to provide nuclear power at much lower costs than traditional reactors. They are:

- Compact (they fit on the back of a trailer and only require a small power station to run)
- Affordable
- Quick to construct
- Portable

The US and UK governments have made SMR's part of their energy strategy (in 2020 Rolls Royce announced plans to build 15-20 SMRs in the UK). China and Russia have plans to build SWRs and Canada is investigating 3 sites.

In a detailed account of the potential for SMR's, published by the UK think tank *policy Exchange*, Matt Rooney advocates the funding of SMR design studies that judge alternative plans based on (i) simplicity of the design; (ii) potential for reducing costs; (iii) deployment speed; and (iv) all without compromising safety.[22]

A key problem facing SMR's are the licensing and regulatory system that is geared towards incumbent reactors. Any government that establishes an energy policy that is forward looking and compatible with emerging technologies will have a major advantage.

[22] Rooney, 2018, p.10

In work presented at the *International conference on Climate Change and the Role of Nuclear Power*, Tomsic et al (2019) showed several scenarios relating to the utilisation of SMRs. They used the PLEXOS simulation tool to establish that the capital expenditure for each successive SMR would benefit from learning by doing (or what they call "factory learning effects"). The critical findings here is that Croatia's utilisation of renewable energy such as hydropower is not a reason against the need for nuclear power, but demonstrates that alongside investment in nuclear energy Croatia could plausibly achieve zero CO_2 emissions by 2050.

(ii) Thorium Reactors

Current nuclear reactors use either uranium or plutonium as a fuel source. An alternative would be to use thorium.[23] Liquid Fluoride Thorium Reactors (LFTR), have several distinct benefits:

- Availability of supply – thorium is 3-4 times more abundant than uranium with 6.2 million tonnes of known resources. Around 846,000 tonnes are located in India, 632,000 in Brazil, 595,000 in Australia and the US each, 380,000 in Egypt, and 374,000 in Turkey. It is most easily recovered from the rare earth phosphate mineral monazite, with contains around 6% thorium on average, but is commonly found when mining for any rare earth metal.[24]
- It is safer – it doesn't rely on an electrical power supply to remove fissile material, and thus wouldn't lead to the types of explosive meltdowns that occurred at Three Mile Island, Chernobyl, or Fukushima. Because the reaction occurs at atmospheric pressure large cooling towers and containment structures aren't necessary.
- Generates less nuclear waste – an LFTR reactor generates 300 times less waste than a standard uranium reactor, and that waste is 83% spent within 10 years (Cooper 2011, p.6238).
- Harder to weaponise – thorium itself cannot be directly converted into a weapon.[25]

(iii) Fusion Reactors

Standard nuclear reactors rely on fission, which occurs when one atom is split into smaller fragments. Fusion occurs when a gas is separated into ions and electrons. This is the process by which the sun releases energy, and is much more powerful than either a chemical or fission reaction. Lockhead Martin have a development program for compact fusion reactors which would fit on the back of a single truck.[26]

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[23] Thorium is not directly usable in a nuclear reaction but transmutes into uranium which is. It therefore still requires a driver, which can only be uranium (233 or 235) or plutonium (239). In other words, thorium isn't a complete alternative to using conventional elements, but can dramatically reduce the utilisation of them.
[24] https://www.world-nuclear.org/information-library/current-and-future-generation/thorium.aspx
[25] Ashley et al, 2015, argue that thorium production still contains some risk of proliferation.
[26] See https://www.lockheedmartin.com/en-us/products/compact-fusion.html

Implementation

Progress is being made in the nuclear power industry and offers a capable, clean, and safe way of achieving sustainable energy independence. It satisfies the criteria set out by Eli Dourado for what can "*move the needle of economic progress*", namely:

- An economically significant sector
- With lagging productivity
- And a plausible path to improved productivity

A 2011 study estimated that a LFTR program would cost $1bn over 5-10 years (Cooper 2011, p.6238). A joint exercise with countries further along with their LFTR program would reduce the need for development costs

Much of the technology is transferable and several companies are seeking new sites. The main constraints are regulatory, and dramatic growth potential is available for countries that find a way to integrate nuclear power in their existing energy strategy, ensuring that the regulatory framework permits innovation and that incumbent firms share the proceeds of growth.

Croatia is capable of supporting the nuclear industry. Croatia's support scheme for energy-intensive companies, containing a €10m annual budget, was approved by the European Commission in June 2020.[27] This was deemed compatible with EU state aid rules and supports existing measures that a funded by electricity consumers.

The Energy Act 2012 harmonised Croatian energy policy with EU directives, and the 2016 Act on Renewable Energy Sources and High-Efficiency Cogeneration introduced measures to reduce reliance on fossil fuels.

A new energy policy, focused on new nuclear technologies, can turn Croatia into a European leader in this developing market.

Proposed action:

- Commission a study to estimate costings – including estimates of energy usage and costs related to alternative supply sources.
- The creation of a new energy panel to seek private sector partners for construction and operation.
- Form strategic alliances with other state subsidisers to share best practice and reap economies of scale.

[27] See Pavlova, I., "EU Commission approves Croatia's support scheme for energy-intensive firms" https://renewablesnow.com/news/eu-commission-approves-croatias-support-scheme-for-energy-intensive-firms-701876/

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