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van de Poel, Ibo; Taebi, Behnam; de Wildt, Tristan

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Societal and ethical issues associated with nuclear energy should be taken into account, recognizing that they may well change over time.

Engineering and Social Responsibility

Accounting for Values in the Development and Design of New Nuclear Reactors

Ibo van de Poel, Behnam Taebi, and Tristan de Wildt


Ibo van de Poel


Behnam Taebi


Tristan de Wildt

According to a recent report of the Intergovernmental Panel on Climate Change (IPCC 2018), nuclear energy will play an important role in all scenarios in which global temperature rise is limited to 1.5°C above pre-industrial levels. One scenario even anticipates a sixfold increase in nuclear energy by 2050. These projections raise questions about the types of nuclear energy and nuclear reactors that might help achieve this goal.

Proposed new reactor designs either incrementally improve existing Generation II light water reactors or are based on radically differently designs that aim, for instance, for small-scale production of nuclear energy (e.g., Lovering and McBride 2020). Others explore alternatives such as molten salt as a nuclear fuel and coolant (e.g., Meserve 2020).

Ibo van de Poel is the Antoni van Leeuwenhoek Professor in Ethics and Technology, Behnam Taebi is an associate professor in climate and energy ethics and scientific director of Delft Safety and Security Institute, and Tristan de Wildt is a postdoctoral researcher, all at Delft University of Technology.

Table 1 Values for nuclear energy (Taebi and Kadak 2010; Taebi and Kloosterman 2015). Sustainability may be seen as an overarching value, particularly for the last three rows in this table.

Value	Explanation
Economic viability	Affordability of investments for developing, building, maintaining, operating, and decommissioning nuclear reactors as well as affordable energy prices
Safety	Protection of people from accidental and unintentional harm over the reactor life cycle (e.g., including storage of nuclear waste)
Security (including nonproliferation)	Protection of people from intentional harm due to nuclear energy production (e.g., arising from weapons proliferation, theft or sabotage of nuclear materials, cybersecurity threats)
Resource durability	Continued availability of natural resources for nuclear energy production or the ability to regenerate such resources
Environmental benevolence	Protection of the environment from harm (including climate change, thermal pollution, or other emissions)
Intergenerational justice	Protection of the well-being of future generations (in particular related to nuclear waste and greenhouse warming)

New reactor designs often spring from specific value considerations. Apart from CO_2 reduction and climate change more broadly, considerations of cost and safety play a role in choices among nuclear options (Ingersoll et al. 2020). We argue that, for a full picture of the societal and ethical issues associated with nuclear energy, additional values should be taken into account, recognizing that they may well change over time.

Values in Nuclear Energy

In addition to economic viability, safety, and CO_2 reduction, various other values are at play in nuclear energy and in choices among nuclear options (table 1). One such value is nonproliferation: the development and use of civil nuclear energy should not contribute to the (further) spread of either nuclear weapons or the knowledge and materials needed for these weapons. Nonproliferation has been an important value since the start of civil nuclear energy after the Second World War.

More recently, other security concerns have become more prominent. Whereas the value of safety is in preventing unintended harm (e.g., from a reactor accident), security concerns protection from intentional harm. Nuclear reactors and other nuclear facilities may be the target of terrorist or cyberattacks or theft of nuclear materials. The Nuclear Security Summits initiated by President Barack Obama aimed to limit these and other security concerns associated with nuclear materials and installations.

Sustainability

The current emphasis on CO_2 reduction is part of a broader value concern that can perhaps best be categorized as sustainability, which encompasses different types of more specific values. It is usually defined following the definition of sustainable development by the Brundtland committee: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 41).

While sustainability is often used in a dichotomous mode in public debate about whether certain energy technologies are sustainable or unsustainable, it is a rich notion that could enable serious ethical assessments of energy technologies, including nuclear (Kermisch and Taebi 2017).

The broad definition of sustainability also encompasses values such as environmental benevolence and resource durability. Environmental benevolence refers to concerns related to climate change and CO_2 reduction as well as other possible environmental effects—positive or negative—from the use of nuclear reactors (e.g., thermal pollution). Resource durability refers to the continued availability or regeneration of nuclear energy resources, such as uranium. Uranium is abundantly available in the Earth's crust and in seawater, but its economically affordable availability depends on the price of extraction. Resource durability may be a reason to look for other fissile materials such as thorium, or for ways to regenerate fissile materials through reprocessing (although this may also lead to additional proliferation concerns).

In the Brundtland definition, sustainability refers not only to environmental concerns but also to issues of intragenerational and intergenerational justice. The latter is a particularly important value in nuclear energy deployment and waste management.

Trade-Offs

Current reactors produce waste that remains radiotoxic for several hundred thousand years and therefore requires very careful storage over a very long period. This obviously raises questions about the level of protection owed to future generations. At the same time, nuclear energy offers possibilities to reduce greenhouse gas emissions and associated global warming, benefiting future generations. For these reasons, it is appropriate to recognize that different nuclear fuel cycles and nuclear waste management options might affect the interests of short- and long-term future generations differently (Kermisch and Taebi 2017).

The choice for a (future) nuclear fuel cycle or reactor may best be considered in terms of important values at stake. Sometimes values support each other (e.g., the economic viability and resource durability of uranium), in other cases they may conflict. Systematically accounting for values in the design of new technologies requires the adoption of an approach such as value-sensitive design.

Value-Sensitive Design

Value-sensitive design was developed in the 1990s to better take into account values of moral importance in the design of computer systems (Friedman and Hendry 2019). Since then, variations have been developed (e.g., design for values); more specific methods and tools have been proposed; and applications have expanded to a variety of engineering domains, including software development, architecture, water engineering, energy systems, biotechnology, nanotechnology, and nuclear technology (van den Hoven et al. 2015).

At the core of value-sensitive design is a tripartite method of empirical, conceptual, and technical investigations:

- Empirical investigations involve mapping relevant stakeholders and inquiring into the values that they consider important and how they understand these values.
- Conceptual investigations involve a further definition and conceptualization of the values at stake (think, for example, of the Brundtland definition of sustainability), considering tensions between values and possible ways to address them (e.g., through trade-offs between them).
- Technical investigations seek to (i) discover value concerns in current technical choices and designs and (ii) translate relevant values into technical features so that the new technology design respects these values.

These three types of investigations require different types of expertise. Generally speaking, technical investigations primarily require engineering and scientific expertise, empirical investigations require expertise in social science, and conceptual investigations mainly draw on philosophical and legal expertise. Moreover, the three types of investigations are not just phases of the design process that can be done separately: they require interaction and iteration in an interdisciplinary approach.

There are at least three ways that values can play a role in nuclear energy. First, they may be translated into design heuristics and requirements to guide the design and development of new technology (van de Poel 2013). For example, nonproliferation may be specified in the (design) requirement that a nuclear reactor not produce materials that can be used to manufacture nuclear weapons or that those materials not be easily separable. In a pebble bed reactor, for instance, plutonium is produced by fissioning U235, but this plutonium cannot be easily (and efficiently) separated from the silicon-coated pebbles, so this reactor better meets the value of nonproliferation (Taebi and Kloosterman 2015).

Second, values may be used in development and design choices as criteria to compare and choose between options. Different fuel cycles (Taebi and Kadak 2010) and proposed reactor designs (Taebi and Kloosterman 2015; table 2) have been assessed for how well they meet a range of values.

Third, values may inspire new areas of research or new design approaches. For example, when the first risk assessments of nuclear reactors were done, there was no

Table 2 Three future reactor designs scored on four important values: safety, security, sustainability, and economic viability
(Taebi and Kloosterman 2015). GFR = gas-cooled fast reactor; HTR-PM = high-temperature reactor pebble bed module; MSR = molten salt reactor

	HTR-PM	GFR	MSR
Safety	++	–	+
Security (mainly nonproliferation)	+	–	–
Sustainability (mainly resource durability)	–	+	++
Economic viability	+	0	–

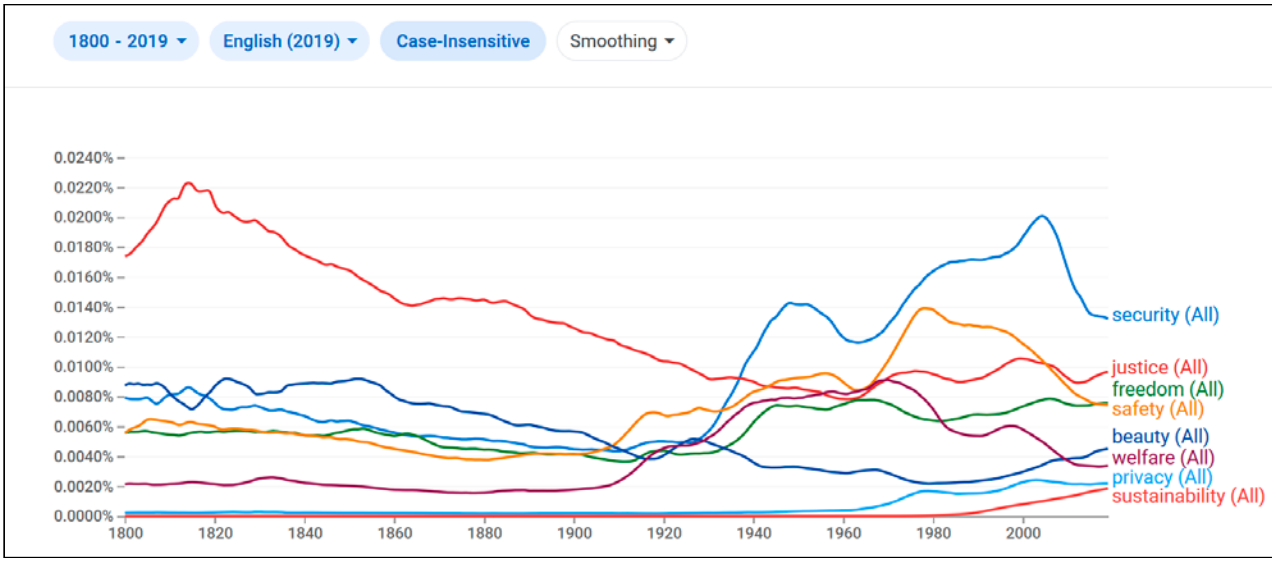

FIGURE 1 Societal value changes in security, justice, freedom, safety, beauty, welfare, privacy, sustainability, 1800–2019. The analysis was done August 13, 2020, with Google Books Ngram viewer (https://books.google.com/ngrams).

full-fledged theory of reactor operation and historical accident data were not available. This triggered the development of probabilistic risk assessment (PRA), a method for estimating risks that was first applied in the so-called Rasmussen study (NRC 1975). While PRA has not eliminated the large uncertainties in safety risk estimates for nuclear reactors (van de Poel 2015), it has become an important assessment and design tool inspired by the value of safety.

Changing Values

One issue that is particularly important in the design of technologies with long life cycles is that values may change over time (van de Poel 2018) and in different contexts, such as, in the case of nuclear energy, society as a whole, societal debate about nuclear energy, scholarly literature on nuclear energy, and the day-to-day operation of nuclear reactors.

For society as a whole, figure 1 provides a rough indication of changes in the relative importance of societal values over time. One interesting development is the emergence of the value of sustainability, which has gained traction since the late 1980s. Although references to what is now called sustainability can be found going back to antiquity (Du Pisani 2006), the value became prominent only in the late 20th century because of increasing environmental degradation and the need to balance economic development with environmental protection. These general developments have also influenced the field of nuclear energy. For example, there is a growing emphasis on the role of nuclear energy in reducing CO_2 emissions.

Societal debate about nuclear energy reflects broader societal developments (e.g., the rising interest in sustainability since the 1980s) as well as other dynamics. For example, the emphasis on safety in this context is driven partly by the large nuclear accidents at Three Mile Island (TMI; 1979), Chernobyl (1986), and Fukushima (2011). Moreover, nuclear energy raises its own specific moral problems, like nuclear waste and proliferation, which means that the values in this context will not be exactly the same as in general society.

An important question is how the societal discussions affect the scientific nuclear community and the direction of technical research and design. Figure 2 shows the percentage of scientific articles on nuclear energy that address a specific value: safety, security, sustainability, economic viability, and intergenerational justice. The figure is based on a topic model that traces both explicit and latent or implicit discussions of a value in documents (de Wildt et al. 2018, 2020).

Figure 2 shows a number of interesting things. First, the growing attention to safety reflects, at least in part, societal discussions and concerns in the wake of the three large nuclear accidents. However, other factors played a role as well.

Concern about the risk of accidents led to a shift from active to passive safety systems, which rely on natural laws,

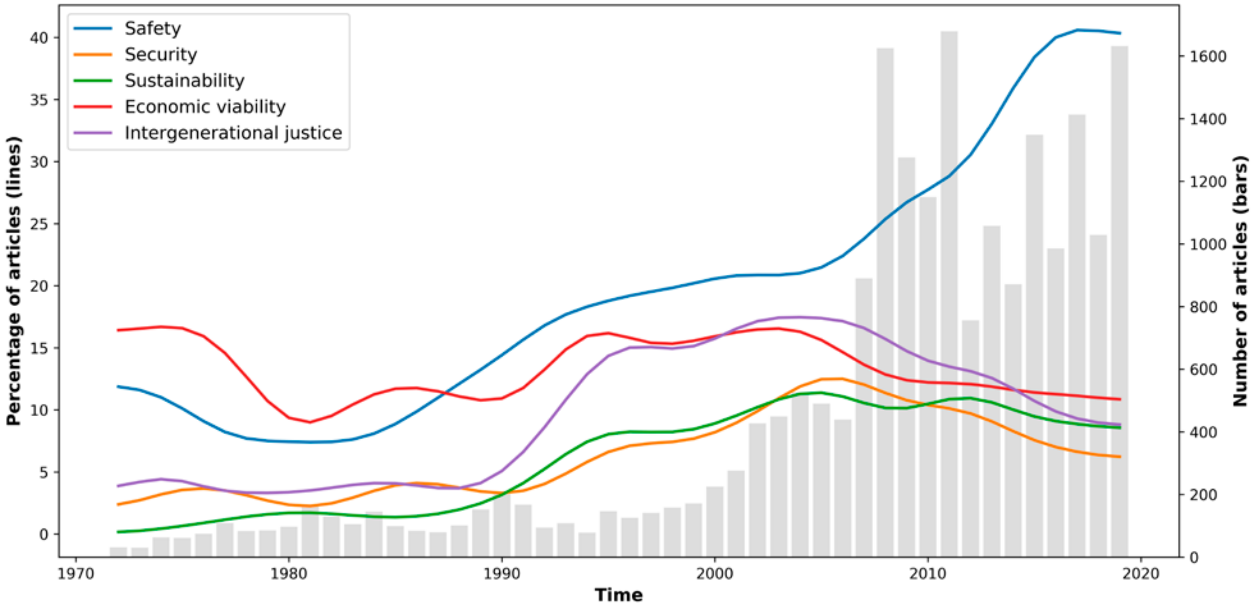

FIGURE 2 Percentage of 21,731 scientific articles addressing both explicit and latent values for nuclear energy over time (1972–2019). See de Wildt et al. (2020).

such as the law of gravity to help water flow to the reactor core if the temperature increases. The most advanced safety conceptualization is inherent safety that relies on design choices that eliminate certain risks altogether. A high-temperature reactor pebble bed module (table 2) is designed—in terms of the size and shape of the reactor and the reactor fuel (silicon-coated pebbles)—so that it can never reach temperatures at which its core could melt. The move toward passively safe reactors was mainly an attempt to guarantee public acceptance, especially for small-scale reactors that could be built closer to residential areas, with the benefit of energy provision in urban areas (Taebi and Kloosterman 2015).

What is further remarkable in figure 2 is the relatively low emphasis on security, which also reflects nonproliferation concerns. Such concerns have played a role in the choice between open and closed fuel cycles in some countries. The infrequent mentions might be because scientific articles that address security are a function of the extent to which this value can be addressed through innovation and hence requires technical and scientific research. Most of the literature on which figure 2 is based discusses technical and scientific issues and (far) less governance and policy issues, which would include security. (In contrast, safety may be relatively overrepresented in the technical literature as much research focuses on it.)

Value changes in the previous context may have an effect on nuclear reactor operations in both the short and long term. Take the increased emphasis on safety due to large nuclear accidents. In the short term, this has, in each case, led to some operational changes or smaller design changes that can be implemented in existing reactors to increase operating safety (e.g., design proposals to incrementally improve light water reactors).

The long-term effect mainly concerns the shift to passive safety and the development of new generations of nuclear reactors based on passive rather than active safety systems, as well as a shift in thinking about the governance of (global) nuclear safety (Taebi and Mayer 2017). These latter effects, however, may take quite long to be effected at the level of operational nuclear reactors as the time from the proposed development of a new reactor through its design, political and regulatory approval, construction, and actual operation is typically several decades.

Designing for Changing Values

A main upshot of this discussion is that there may be discrepancies and time lags between values that are given priority in the different contexts and at different times. This means that if new reactor designs are based on values currently deemed important in the nuclear scientific community (figure 2), there may be a mismatch with societal priorities (although there is no clear evidence of such a mismatch). Another potential problem is that by the time research and design efforts have materialized in new operating reactors, values in society and the nuclear engineering community may have changed so that the new reactors reflect past value priorities. Both issues could give rise to serious ethical problems.

How, then, to account for changing values in current nuclear reactor research and design? This is difficult, but there are at least two possibilities.

First, one can try to anticipate value change. Not all value changes are predictable, but it may be possible to detect signs of future change. One interesting hypothesis, that requires further research and testing, is that value changes may first manifest at the societal level and then, over time, affect the nuclear scientific community. If so it may be possible to develop methods to anticipate value change at the societal level.

We are exploring the possibility of finding latent values and value changes in texts with the help of topic modeling (de Wildt et al. 2018, 2020). In the same vein, one could ensure that societal value changes translate more quickly into priorities at the level of research and design of new reactors, for example by monitoring societal value changes or involving societal stakeholders in setting research priorities. This would also seem desirable for other societal as well as ethical reasons; it fits well with the idea of responsible research and innovation aimed at better aligning research and development (R&D) with the values and needs of society (European Commission 2014).

A second possibility may be to build more flexibility and adaptivity into nuclear reactor design and related R&D trajectories, so that changing values can be better accommodated. For example, modular designs (such as those discussed in Lovering and McBride) might allow the replacement of parts and subsystems, rather than the construction of entirely new systems, to deal with value change.

Another option is to deliberately allow for competing technologies and technological trajectories. While this may be costly in the short term, it increases future possibilities to adapt to changing values.

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