Risk Analysis DOI: 10.1111/j.1539-6924.2010.01434.x

Intergenerational Considerations Affecting the Future of Nuclear Power: Equity as a Framework for Assessing Fuel Cycles

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Alternative fuel cycles are being considered in an effort to prolong uranium fuel supplies for thousands of years to come and to manage nuclear waste. These strategies bring with them different benefits and burdens for the present generation and for future generations. In this article, we present a method that provides insight into future fuel cycle alternatives and into the conflicts arising between generations within the framework of intergenerational equity. A set of intersubjective values is drawn from the notion of sustainable development. By operationalizing these values and mapping out their impacts, value criteria are introduced for the assessment of fuel cycles, which are based on the distribution of burdens and benefits between generations. The once-through fuel cycle currently deployed in the United States and three future fuel cycles are subsequently assessed according to these criteria. The four alternatives are then compared in an integrated analysis in which we shed light on the implicit tradeoffs made by decisionmakers when they choose a certain fuel cycle. When choosing a fuel cycle, what are the societal costs and burdens accepted for each generation and how can these factors be justified? This article presents an integrated decision-making method, which considers intergenerational aspects of such decisions; this method could also be applied to other technologies.

KEY WORDS: Breeder; intergenerational equity: nuclear fuel cycles; partitioning and transmutation; reprocessing; value

1. INTRODUCTION

Anthropogenic climate change caused by greenhouse gases and projected future energy demands pose serious challenges to future fossil fuel use. While some believe that we can meet this challenge by tapping renewable resources, others maintain that in the future nuclear energy will be indispensable. At present, nuclear energy accounts for approximately 6% of the global energy consumption and 16% of the global electricity production.(1, p. 138) A considerable growth of more than 30% by 2030 is foreseen.[3] Future growth predictions depend on how well nuclear plants operate, the cost of constructing new nuclear plants, the resolving of the nuclear waste disposal issue, proliferation concerns,

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[3] The joint report of the NEA and the IAEA (Red Book, 2007) foresees a low consumption and a high consumption scenario, varying from 372 GWe in 2007 to between 509 GWe (+38%) and 663 GWe (+80%) in 2030.(2) The Energy Information Administration of the U.S. government foresees a growth of approximately 33% going from 374 GWe in 2005 to 498 GWe in 2030.(1)

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international agreements concerning greenhouse gas reduction, and rising oil and natural gas prices. Nuclear energy also engenders controversy in public and political debates that may well prevent its expansion.

In this article, we propose a framework of *intergenerational equity*(3) in order to assess nuclear power production practices now and in the future. The "achievement of intergenerational equity" is one of the cornerstones of nuclear waste management(4) and one of the reasons for choosing geological repositories for the ultimate disposal of nuclear waste.(5) Many nations are currently considering alternative fuel cycle possibilities in order to prolong uranium fuel supplies and manage nuclear waste. These strategies bring with them benefits and burdens for present and future generations; the choice between existing fuel cycles has already come to be seen as a matter of intergenerational equity.(6) This article puts forward a way of assessing future fuel cycles in accordance with the intergenerational equity criteria presented as a broadly defined set of *moral* values built around the principle of sustainability. We characterize these values as moral values since they contribute to the environment and humankind's safety and security as well as an overall welfare of society in terms of sustainability; see in this connection Fig. 1.

We base our analysis on the future energy forecasts made primarily in the United States assuming that nuclear energy will play a part for at least another century. We do not, however, intend to make any normative claims regarding the desirability of nuclear power. We aim instead to provide a method that will allow every individual and stakeholder to be able to assess the future developments of nuclear technology on the basis of intergenerational equity criteria, that is, according to the distribution of benefits and burdens between generations. Even though we believe that a similar analysis could be made in order to address the consequences deriving from employment of other energy systems such as those involving coal or gas, this article presents an assessment of different nuclear fuel cycles, rather than a comparison between the nuclear option and other energy resources.

The article consists of two main parts in which a method is introduced that is subsequently applied to a fuel cycle. The following section first discusses the notion of values and why they are of relevance to our analysis. Section 2 further discusses the relationship between sustainable development and intergenerational equity. Values stemming from sustainability are then explored in Section 3, which lead to criteria of intergenerational assessment that are derived from these values. The remainder of the article focuses on the application of the method. In Section 4, the proposed criteria are applied to the once-through fuel cycle currently adhered to in the United States and to three possible alternatives. In Section 5, the four fuel cycles are compared on the basis of a scorecard that provides a summary of criteria and intergenerational assessments. The final section presents a number of concluding remarks.

2. SUSTAINABILITY AND INTERGENERATIONAL EQUITY

In this section, we focus on the questions of what values are, of how sustainability is considered as a value, and of what its relation is to the notion of equity between generations. We conclude the section by arguing why it makes sense to talk about intergenerational equity in discussions on nuclear power production.

2.1. Values, Valuers, and Value Systems

In conventional ethics and in discussions on human relations, terms such as "rights, justice,

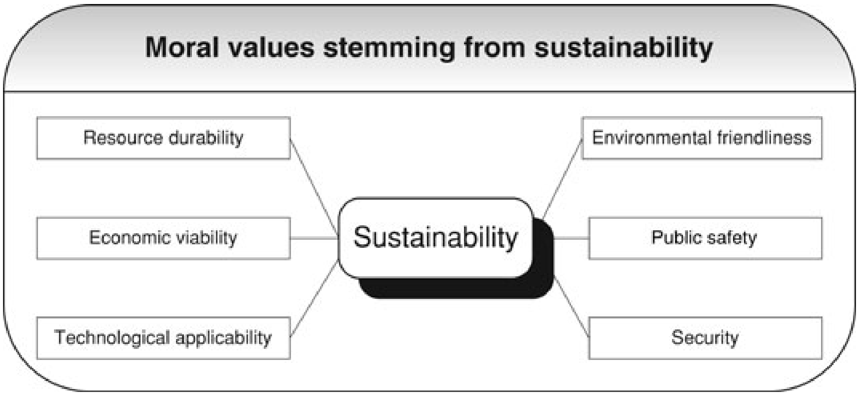

Fig. 1. The values stemming from equity and interpreted as different conceptions of sustainability.

beneficence and malificence, social contract [etc.]" are regularly used; here the fundamental term that will help to orient us is *value*, "it will be out of value that we will derive duty."(7, p. 2) The first important issue is to determine whether something is worth striving for because it serves a higher good or for its own sake. To put this in philosophical terms, we must establish whether something has *instrumental* value or *intrinsic* value and thus does not require further instrumental references.[4] This discussion gains serious relevance when it comes to the questions of how to value the environment and how to understand a human being's relationship with his natural world.[5] Generally, we can distinguish between two schools of thought: (1) those philosophers who believe that the environment only has an instrumental value to serve "human beings and the place it occupies in their lives,"(10) by emphasizing that "values always occur from the viewpoint of a conscious valuer"(11, p. 251)—this is referred to as *anthropocentric* or human-based ethics and (2) other philosophers who believe that nature has intrinsic value of its own,[6] also known as the *nonanthropocentric* view.(17, p. 20) In Section 3, we further elaborate on this issue and its relevance when identifying the values at stake.

Values are things worth striving for. However, we should not confuse values with the personal interests of individuals; values are general convictions and beliefs that people should hold paramount if society is to be good. This highlights the central challenge of defining values or, in other words, of how we can propose any broadly accepted set of moral values designed to serve the greater good of society. The inherent difficulty is that a value system one adopts should define a perception of moral values, describing a good way of life, and society: "there is no possibility ... to develop a single value or value system able to encompass the myriad strains of belief, commitments and attitudes that envelop people's relationship with their environment."(8) With nuclear technology it has been found that stakeholders' value systems largely define their acceptance of courses of action.(18)

We aim to present a set of broadly defined and *intersubjectively*[7] formulated values; by intersubjective, we mean that different individuals and stakeholders could relate to these values, regardless of their subjective value systems. A stakeholder's attitude toward risk acceptance relates more to the way values are prioritized and traded off against one another, rather than to how an isolated value is perceived.

2.2. Sustainability and Equity: A Two-Way Road

Widespread concerns about the depletion of the earth's natural resources and environmental damage have invoked discussions on the equitable sharing of benefits and the burdens between generations so as to meet "the needs of the present without compromising the ability of future generations to meet their own needs," commonly referred to as the Brundtland definition.(19, p. 43) As this definition implies, the equitable distribution of goods across generations is what underlies the notion of sustainability. In the following section, different interpretations of sustainability will be presented in terms of moral values; the conflicts arising from the interests of different people in relation to these values will be clarified and elaborated by using the notion of equity between generations.

Equity, as a principle in environmental policy making, was first officially incorporated into the Rio Declaration on Environment and Development of 1992(20) and it was reiterated in the same year during the UN framework convention on climate change when it was stated that we should protect future

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[4] When something has an intrinsic value, it has a value in itself. Instrumental values are on the other hand ascribed to things that have no value as such or no intrinsic value; an instrumental reference is then needed here.

[5] Valuing nature is a long and still ongoing subject in environmental philosophy. Rolston-III gives in his book, *Environmental Ethics*, a comprehensive account of the notion of value. He distinguishes (in Ch. 1) between different categories of values such as life-support value, economic value, scientific value, aesthetic value, etc. and deals with the fundamental question of whether we have obligations to the natural world.(7) See also *Values and the Environment*(8) and *Valuing Nature*.(9)

[6] Among the latter, we can also distinguish between those who defend *ecocentrism* or *biocentrism* by asserting that nature's value is independent of humans and animals(12) and those who believe that nonhuman animal interests should be given equal consideration.(13,14) Some people argue that it is a form of "human chauvinism" to reduce environmental justice purely to human interests.(15) DesJardiens gives in his book *Environmental Ethics* an accessible overview of this discussion.(16, Ch. 7) These discussions have already gone beyond philosophical considerations regarding animals' right and have entered the reality of policy making. Recently, a "Party for the Animals" was established in the Netherlands and even got into the Dutch Parliament. This political party's primary concerns are "animal welfare and the respectful treatment of animals"; see, for more information: http://www.partyfortheanimals.nl/.

[7] We do not claim that moral values are *objectively* to be defined; therefore we adhere to the notion of intersubjective values.

people's interests "on the basis of equity."(21) Equity has also been very influential in discussions linked to nuclear waste management: in 1984, the Nuclear Energy Agency[8] (NEA) first expressed "a desire for equity" in radioactive waste disposal.(22) Partly on the basis of this desire and discussions about sustainable development, the International Atomic and Energy Agency (IAEA) laid down certain principles for radioactive waste management, one of which states that nuclear waste should be managed in such a way that it "will not impose undue burdens on future generations,"(23, p. 7) in conjunction with the idea that the generation enjoying the benefits of an undertaking should manage its consequences (in other words, the waste).(5)

Sustainability and intergenerational equity are closely intertwined. Nigel Dower argues that "the commitment to sustainability is a moral commitment to sustaining the conditions in which human well-being can be achieved, not only now and in the near future but also into the more distant future."(24, p. 401) Dower distinguishes between two ways of understanding justice toward future generations, namely: (1) sustaining justice in the way it is perceived now and (2) achieving intergenerational justice in terms of what we leave for our descendants. "If the next generation had enough resources to distribute at that time fairly but half what the current generation had, then the sustainability of justice is achieved but not intergenerational justice."(24, p. 401) In this article, we consider intergenerational equity or justice[9] as presented in terms of Dower's second interpretation, to the effect that the present generation's primary concern should be with what it bequeaths to future generations.

The distribution of benefits and burdens between generations could be divided into three different categories: (1) future benefits versus future burdens (as in Dower's first interpretation of intergenerational equity), (2) current benefits versus current burdens, and (3) current benefits and burdens versus future benefits and burdens. In this article, we will not enter into discussion about the first category, as already stated in the preceding paragraph. The second category deals with the question of who among our contemporaries are receiving the benefits and who are bearing the burdens, referred to as *intragenerational* equity.[10] Besides intergenerational equity, discussions about the distribution of wealth between contemporaries (and the problem of global poverty) remain the cornerstones of sustainable development as originally proposed by the Brundtland commission.(26) Even though we acknowledge the moral relevance of the discussions, our main focus in this article has to be on *temporal equity*, or equity considerations pertaining to nuclear power production (the third category) between generations.

2.3. Why do We Consider Intergenerational Equity?

Let us focus for a while on the question of why it makes sense to view this problem in terms of generations and why it amounts to a problem of fairness? We follow here Stephen Gardiner's discussions of "The Pure Intergenerational Problem" (PIP)(27) in which he imagines a world of temporally distinct groups that can asymmetrically influence each other: "earlier groups have the power to impose costs on later groups . . . , whereas future groups have no causal power over them." Each generation has access to a diversity of commodities. Engaging in activity with these goods culminates in present benefits and potential substantial future cost, all of which pose the problem of fairness. This also holds for nuclear energy: the present generation will mainly enjoy the benefits by depleting resources. In addition, the production of nuclear waste, and its longevity in terms of radioactivity, also creates future cost and burden issues.

We relate the PIP to the production of nuclear power and follow the widest definition of future generations by defining them as "people who by definition will live after contemporary people are dead."(28, p. 138) This definition of a generation

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[8] The Nuclear Energy Agency (NEA) is the OECD agency (Organization for Economic Cooperation and Development) that is specialized in nuclear energy.

[9] Justice, fairness, and equity are used interchangeably in the relevant literature sources. Many philosophers are concerned about what is *fair* with respect to the future and fairness seems to be subsumed under the heading *justice*. *Equity* relates to the equal distribution of goods. In this article, it is not our intention to go into great depth on these philosophical discussions. *Intergenerational equity* or *justice* are referred to here as the equitable distribution of risks and burdens across generations.

[10] For example, questions pertaining to who are enjoying the benefits of nuclear energy production and who are bearing its burdens within a country are interesting to be examined within the framework of equity as well; see, for more discussions on intragenerational equity: Duties to Future Generations, Proxy Consent, Intra and Intergenerational Equity: The Case of Nuclear Waste.(25)

approximately corresponds to 100 years;[11] we consider 100 years to be the cut-off point when distinguishing between Generations 1 and 2. Obviously, the real-world cases are not always as temporally distinct as those presented in the PIP and a certain degree of overlap might well change a few of these arguments or make them less compelling. We do, however, believe that this overlap will not substantially change the intergenerational nature of this problem.[12]

In this section, we elaborated on the notion of sustainable development and its philosophical relationship to intergenerational equity. We shall now continue, in the next section, by identifying the values that contribute to sustainable development.

3. MORAL STANDING OF SUSTAINABILITY: VALUES AT STAKE

Up until now, there has been no consensus among scientists on how to apply the notion of sustainable development to nuclear power. Some perceive of sustainability as "affordable, reliable electricity" that does not put "the earth's climate in jeopardy,"(29) while by referring to the same notion, the safety of plant operation as well as proliferation concerns are also addressed.(30–33) Some stakeholders in these discussions believe that under certain conditions "there is a basic case for treating nuclear energy as a contribution to sustainable development"(30, p. 149) at least in a "transitional role towards establishing sustainable energy systems"(34, p. 151) and others state that nuclear power is inherently "unsustainable, uneconomic, dirty and dangerous."(35)

In this article, we do not pretend to answer the controversial question as to whether nuclear energy is—or could possibly be—sustainable. We argue that in order to understand this question, we need to interpret sustainability and address the conflict of interests between people belonging to different generations. To this end, we identify values that contribute to different interpretations of sustainability and provide an account of our intersubjective set of values.

Before spelling out these values, let us just discuss one more issue, namely, that of how these values are grounded in principles of intergenerational justice. Elsewhere, we have argued that a requirement of justice is that the overall range of opportunities open to future generations should not be narrowed; this corresponds to Barry's principle of egalitarian justice.(36) We should thus safeguard equal opportunities for posterity. The two temporal duties proposed to comply with this principle are these: (1) we should not endanger the vital interests of future generations, which is a fundamental condition if they are to enjoy equal opportunity, and (2) we should safeguard the opportunity for welfare.[13] In other words, we should sustain the environment and humankind's safety and security and we should seek to sustain human welfare. These two principles are here below linked to the relevant contributing values.

3.1. Sustaining the Environment and Humankind's Safety and Security

Sustainability could be seen as the process of preserving the status of nature and leaving it no worse than we found it: the value we relate to this notion is *environmental friendliness*. Another interpretation is to perceive of sustainability as the protecting of public safety and security or, as defined by NEA, the providing of "the same degree of protection" for people living now and in the future.(22) The IAEA articulates these concerns in its safety principles when it states that nuclear waste should be managed in such a way that "predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today."(23, p. 6) The value we link to these concerns is *public safety*, which pertains to the exposure of the human body to radiation and the subsequent health effects of radiation.

Depending on which school of anthropocentric or nonanthropocentric ethics we follow, "environmental friendliness" and "public safety" could be merged. Some scholars argue in favor of this standpoint by stating that we should protect nature for future generations in order to respect *their* equal opportunity to make use of the environment. This is allegedly a more appropriate and convenient

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[11] It should be noted that Avner de-Shalit, whose definition is cited here, abides by the common definition of generation as being a time span of 30 years. If we, however, adopt his definition of future generations and define the immediately following generation as everyone who is now alive, including the infants born in the last couple of moments, then it will be a much longer period of time—namely, the length of people's average life expectation—before the current generation ceases to exist and we can speak of a future generation.

[12] Gardiner discusses a few counterarguments and concludes that even in overlap cases the main rationale of the PIP is not undermined.(27)

[13] This claim is discussed in the introduction section of "Nuclear Power and Justice Between Generations."(37)

notion in environmental policy than that of ascribing environment an intrinsic value.(38, p. 5) The latter also corresponds to the way in which the UN Framework on Climate Change perceives of nature as it proposes protecting the climate system "for the benefit of present and future generations of humankind."(21, Ar.3)

IAEA[14] seems, on the other hand, to ascribe an intrinsic value to the environment. By defining "safety" as "the protection of people and the environment against radiation risks, and the safety of facilities and activities that give rise to radiation risks,"(39, p. 173) IAEA implies that the environment should be spared, but not necessarily for the sake of human beings. Safety in terms of the "Fundamental Safety Objective"—introduced by a few leading organizations in nuclear technology—is referred to as the protection of "people and the environment from [the] harmful effects of ionizing radiations."(40, p. 4) In this article, we define "public safety" as the protecting of people from the accidental harmful effects of ionizing radiation.

We do not find it necessary to take a stand in the discussions but we present instead in this section "environmental friendliness" as a separate value in order to broaden our set of values and give every stakeholder in this discussion the opportunity to relate to them. In our analysis in the following sections, we do, however, consider the two values of "environmental friendliness" and "public safety" in combination as they both refer to the same radiation hazards. The latter should not be seen as a normative statement; it is merely a way of facilitating and simplifying the analysis. Besides, stakeholders are at all times free to separate these two values and discuss the related concerns separately.

"[T]he same degree of protection," alluded to by NEA(22) not only refers to the health and safety of people, but also to security concerns such as the unauthorized possession or theft of radioactive material to either cause sabotage or be used in the creation of nuclear weapons; *security* is the next value that will be addressed in this analysis. In the IAEA's safety glossary, sabotage is defined as "any deliberate act directed against a nuclear facility or nuclear material in use, storage or transport which could endanger the health and safety of the public or the environment."(39, p. 133) One can argue that "security" as defined here also refers to the safety considerations discussed above. We shall, however, keep the value of "security" separate in this analysis so as to be able to distinguish between unintentional and intentional harm; the latter also relates to extremely relevant proliferation considerations such as the use and dispersal of nuclear technology for destructive purposes. We define "security" as the protecting of people from the intentional harmful effects of ionizing radiation resulting from sabotage or proliferation.[15]

3.2. Sustaining Human Welfare

So far, we have presented three values for sustaining the environment and humankind's safety and security. In other words, the right side of Fig. 1 represents the sustaining of human and nonhuman life as well as the status of nature. Another aspect of sustainability links up with the sustaining of human welfare;[16] some economists state that "a development is sustainable if total welfare does not decline along the path"(41, p. 419) and that "achieving sustainable development necessarily entails creating and maintaining wealth."(41, p. 420) We argue that sustaining welfare as a minimum requirement relates to the availability of energy resources, which is why we distinguish between the three values of: (1) resource durability, (2) economic viability, and (3) technological applicability. These three values are presented as moral values since they gain relevance in relation to each other and in aggregate they contribute to human welfare in terms of sustaining resources.[17]

Resource durability has to do with the availability of natural resources for the future. Brian Barry

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[14] The United Nation's specialized agency in nuclear technology.

[15] The overlap between the value of safety and security allows for different interpretations. It must be noticed that some scientists would rather subsume sabotage concerns under public safety and interpret it as preventing and mitigating both accidental and sabotage release; security in this line of reasoning only refers to proliferation concerns, in which the importance of the latter is emphasized. We follow here the IAEA safety glossary by referring to security as "any deliberate act against a nuclear facility or nuclear material in use, storage and transport"(39, p. 133) and believe that it is better to see sabotage as a security concern. Such a definition enables us to draw a distinction between unintentional harm (safety) and intentional harm (security).

[16] *Welfare* and *wealth* are used interchangeably not only by this author but also elsewhere in the literature. We prefer to stick to the notion of welfare because it more relates to health and happiness; wealth has a more monetary connotation. Also the notion of *well-being* is sometimes used in this context.(24)

[17] One can also argue that the availability of resources and technology have no independent moral relevance, which means that resource durability and technological applicability are rather conditions that make it possible to achieve other values or objectives. We owe this suggestion to Frans Berkhout.

Table I. The Presented Nuclear Fuel Cycle Values and Their Definitions as Understood in This Article

Value	Explanation
Environmental friendliness	Preserving the status of nature leaving it no worse than we found it
Public safety	Protecting people from the accidental and *unintentional* harmful effects of ionizing radiation
Security	Protecting people from the *intentional* harmful effects of ionizing radiation arising from sabotage or proliferation
Resource durability	The availability of natural resources for the future or the providing of an equivalent alternative for the same function
Economic viability	Embarking on a new technology at a certain stage and ensuring its continuation over the course of time
Technological applicability	The scientific feasibility of a certain technology as well as its industrial availability

presents the theory of intergenerational justice as the appropriate consumption of nonrenewable natural resources across time. In relation to nonrenewable resources, "later generations should be left no worse off . . . than they would have been without depletion."(42, p. 519) Barry proposes compensatory action or recompense for depleted natural resources such as oil and gas and for all the side effects of this depletion, such as climate change. Edward Page suggests that the most obvious example of such compensation lies in technological improvement such as that seen in heightened energy efficiency.(43, p. 55) Following this line of reasoning, we argue that technological progress could also lead to energy efficiency or to the deployment of new natural resources for energy production.[18] We therefore present here *technological applicability* as one of the interpretations of sustainability, which is defined as the *scientific feasibility* of a certain technology in combination with its *industrial availability*. In particular, industrial availability depends very much upon *economic viability* and competitiveness with respect to the various alternatives.

To recapitulate, the three values are defined as follows: "resource durability" is the availability of the natural resources required for the future or the providing of an equivalent alternative for the same function, "technological applicability" is the scientific feasibility and industrial availability of a specific technology. Finally, "economic viability" is the economic potential to embark on a new technology at a certain point in time and to safeguard its continuation.

Let us illustrate this with an example. As thorium is a naturally very abundant resource, its deployment as an alternative to uranium has been considered since the early days of nuclear power production.(46) Its "scientific feasibility" was revealed in the 1950s, but its "industrial applicability" is still far from a reality. Technological impediments as well as serious proliferation concerns—due to the production of ^{233}U—are the challenges posed to a thorium fuel cycle. The adopting of thorium as a realistic alternative will require decades of R&D investments(47) and additional nuclear facilities will have to be built once this fuel cycle is finally ready to be used at industrial level. To conclude, by the time thorium becomes technologically applicable and economically viable, we may well be able to argue that it enhances resource durability.

4. INTERGENERATIONAL ASSESSMENT OF FUEL CYCLES

In the preceding section, we introduced six central values that contribute to sustainable development (see Table I). We shall continue in this section by looking at different nuclear power production processes in terms of fuel cycles. If we assert that the fuel cycle choice should be evaluated on the basis of the stipulated values and the impact that each fuel cycle has on different generations, we can *operationalize* the central values by relating them to their burdens and benefits for different generations. The emerging operationalized values are what we call the *value criteria* for an intergenerational assessment of fuel cycles.

The nuclear fuel cycle consists of several major elements starting with the mined uranium ore and continuing with irradiation in a reactor (front end phase) and the optional spent nuclear fuel treatment required after irradiation before finally finishing with the disposal of waste (back end phase); see Fig. 2. Uranium is currently deployed in most operational energy reactors or light water reactors (LWR).

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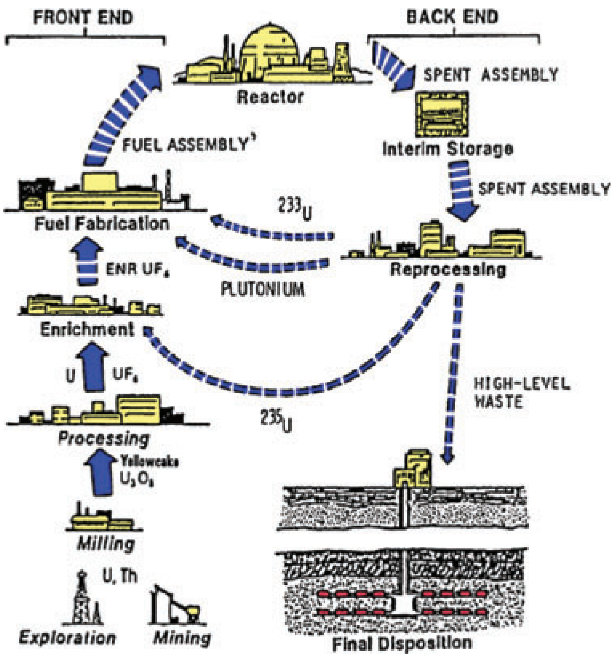
[18] Here, we need to make an important assumption, namely, that natural energy resources can be substituted by human-made resources. So the loss of exhaustible energy resources should be compensated by technological progress or other energy resources;(44) see also Skagen-Ekeli(45) on this issue.



Source: Website of the U.S. National Regulatory Commission.

Fig. 2. Nuclear fuel cycle, from uranium ore to final disposal.

Naturally occurring uranium contains different constituents (isotopes) in the form of the minor fissile ^{235}U that is present in less that 1% and the major ^{238}U isotopes (>99%). The former isotope is *fissile*, meaning that neutrons in a LWR can fission it; most energy production from existing LWRs comes from uranium that is enriched in the isotope ^{235}U.[19] The major uranium isotope (^{238}U) is not fissile, but as it is a *fertile* nuclide, which captures neutrons and produces other isotopes, some of which can be fissile such as Plutonium-239 (^{239}Pu). ^{239}Pu provides a substantial amount of energy in a typical LWR core toward the end of the operating cycle of the fuel element.[20]

In a once-through fuel cycle, *enriched* uranium (with increased ^{235}U concentration) will be irradiated once in a reactor and the spent fuel (SF) from the reactor will then be disposed of as waste. Spent fuel contains short-lived and long-lived radioactive materials; the latter, in particular uranium, plutonium, and other actinides, dominate the period of radiotoxicity, demanding long-term isolation from the biosphere for up to 1 million years, a period commonly known as the waste life-time.[21]

The once-through fuel cycle currently adhered to in the United States is the first fuel cycle we will discuss in this section. We include a variant of the once-through cycle in the context of giving future generations an option to deal with whether the spent nuclear fuel is a waste or a resource. The second major option is to adopt *reprocessing*, involving the extraction of fissile material from spent fuel, which can then be reused as fuel. Reprocessing therefore prolongs the supply of uranium. Plutonium and uranium can be extracted from the spent fuel and recycled in LWRs as mixed oxide fuel (MOX), which is what is currently practiced in France. The use of MOX extends the supply of uranium by approximately 15% and reprocessed waste in a vitrified form reduces the volume of high-level nuclear waste that needs to be disposed of. The third alternative fuel cycle option is to introduce fast reactors (FR) in combination with the reprocessing method, which enables us to *consume* or eliminate radioactive constituents. By using fast reactors in the "burn" mode, some long-lived actinides can be fissioned (consumed) while others are transmuted into isotopes that have shorter waste life-times while also diminishing long-term radiotoxicity of waste.

The same fast reactors could also be used in *breeder* configurations (in combination with recycling) to produce (or breed) more fuel during operation. Breeders need an initial start-up core of plutonium or enriched uranium. This core is surrounded by a "blanket" of fuel assemblies containing ^{238}U, which is used to capture neutrons producing ^{239}Pu.

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[19] An exception to this rule is the Canadian deuterium uranium reactors or, the CANDU reactors. This type of reactor uses heavy water as a moderator and light water as a coolant; this combination makes it possible to use natural uranium (instead of enriched uranium) as fuel.(48, p. 5)

[20] It is important to distinguish between fissile and fissionable nuclides. A fissile isotope can be fissioned by slow neutrons in an LWR. The main uranium isotope (^{238}U) is a fertile material (but not fissile in a thermal spectrum) and but it can be fissioned in a fast reactor.(49, p. 67)

[21] The 1-million-year time period was established by a U.S. National Academy of Science report,(50) which suggested that for Yucca Mountain, the design of the repository should be capable of handling the analyzed period of peak dose, which occurs at roughly 750,000 years. Also the Environmental Protection Agency follows this period in its final rule for setting radiation protection standards for the Yucca Mountains.(51) Other nations may choose different lengths of time for their periods of concern, all depending on the design of their repositories. It is also noteworthy that 1 million years is not based on the radiotoxicity of spent fuel. This radiotoxicity decays after approximately 200,000 years to the levels below the radiotoxicity of natural uranium, which means that peak doses occurring after this period have less impact in terms of radiotoxicity; therefore, the period of necessary care for spent fuel is defined by some scientists as 200,000 years.(52, p. 5)

This plutonium isotope is then reprocessed and recycled in the core. Breeding ratios as high as 1.3 are possible, which means that the reactor can produce 30% more fuel than it consumes, thus extending uranium supplies for power production for thousands of years by using multiple reprocessing and recycling steps. The breeder fuel cycle is the last alternative that will be discussed.

In the following subsections, all these fuel cycles will be assessed on the basis of the value criteria to be introduced. Precisely how the value criteria will change is mapped out in the burden/benefit charters where the once-through fuel cycle will serve as the default situation. An integral analysis of these fuel cycles is presented in the following section.

4.1. Current Practice: The Once-Through Cycle

In a once-through fuel cycle enriched uranium is irradiated once in an LWR and spent fuel is kept in interim storage above ground for a few decades, pending final disposal in deep geological repositories. Fig. 3 provides a chart of the operationalization of the values or value criteria in which the burdens and

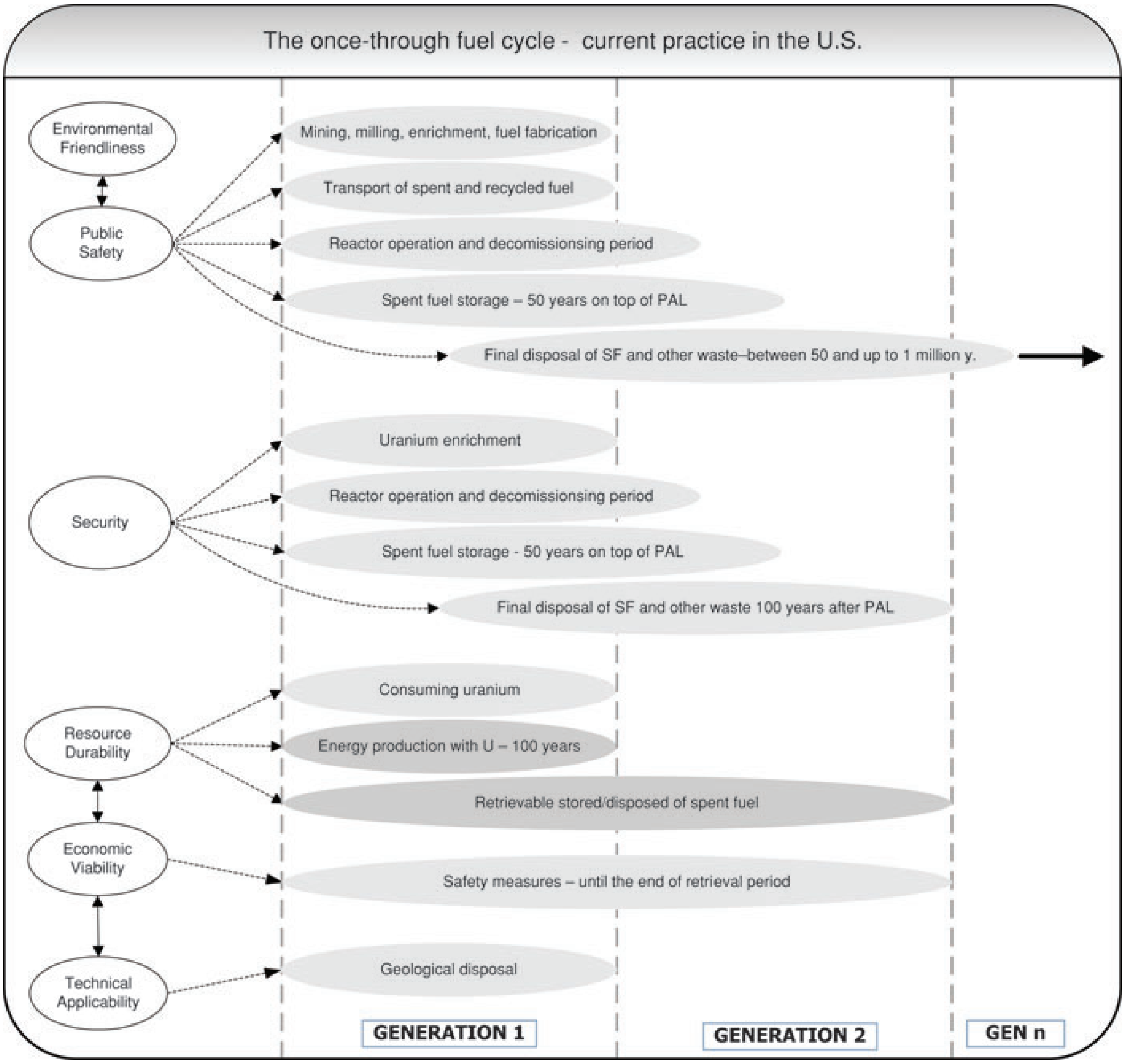

Fig. 3. Relating moral values to concrete consequences and to the associated *Period in which the Activity Lasts* (PAL) as seen in a once-through fuel cycle or the current practice in the United States. The light and dark gray ellipses represent the respective burdens and benefits. The horizontal black arrow depicts a projection of certain considerations extending into the future and far beyond the time frame of the charts.

benefits emanating from the production process are specified and related to the different generations that experience them.

In our analysis, we make the explicit assumption that nuclear power will remain in use for a period of 100 years; we call this period the *Period in which the Activity Lasts* (PAL). Some concerns continue for the duration of the PAL, for instance, the safety concerns surrounding the front end of the once-through fuel cycle related to the mining, milling, enrichment, and fuel fabrication processes. Other concerns like, for example, the power plant's decommissioning and its safety and security considerations, outlive the activity period. Finally, with some activities, the period of concern starts at a later stage and ends at a time that is independent of the PAL. For instance, the spent fuel derived from a once-through fuel cycle must be disposed of underground a few decades after the operation has started and concerns will last for the duration of its radiotoxicity or its waste lifetime (1 million years).

The lengths of the ellipses given in Fig. 3 are not intended to correspond to the actual durations of these periods; they merely serve to indicate the relative difference. A horizontal black arrow, like, for instance, the one given in front of the public safety concerns linked to final disposal, depicts a projection of these considerations extending into the future and far beyond the time frame of the charts. In our figures, we can distinguish between two types of ellipses: the light-gray ones and the dark-gray ones representing all the respective burdens and benefits.

We also distinguish between generation 1 (Gen. 1) and generations 2 and beyond (Gen. 2–n). On the basis of the most recent estimations, there will be sufficient reasonably priced uranium available for approximately another 100 years for the purposes of once-through fuel cycle usage.(2) The benefits of uranium deployment for Gen. 1 are illustrated by means of the dark-gray ellipse given in front of the resource durability indications. We immediately see here the problem of fairness that arises between Gen. 1, which benefits from the energy production while bearing some of the burdens, and future generations that will mainly bear the safety and security burdens accompanying long-term nuclear waste disposal. Fig. 3 gives a graphical illustration of the temporal behavior of burdens and benefits on current and future generations.

There is a further interesting tradeoff regarding the retrievability of spent fuel. Retrievable spent fuel is designed to give future generations an equal opportunity to benefit from the potential energy advantages underlying fissionable materials in spent fuel,[22] but at the same it gives rise to additional safety and security concerns during the same period. In other words, in order to respect a next generation's freedom of action to use spent fuel for energy purposes, we need to impose more safety and security burdens on that generation.[23]

4.2. Once-Through Cycle with Direct Underground Storage/Disposal

This is a new option being considered for the United States by researchers at Massachusetts Institute of Technology (MIT)[24] to address the dilemma of the long-term storage of spent fuel at many reactor locations or in similarly vulnerable above ground open central storage sites. In this scenario, spent fuel, after five years of storage in spent fuel pools, will be shipped and stored underground in facilities that could be used both for storage and ultimately for disposal purposes. This fuel cycle is a derivative of the first fuel cycle in that instead of the repository closing when full it remains open as a long-term storage facility so that the next generation can determine whether the resources preserved in the form of spent fuel are used for energy production or not.(55) In this way, the next generation's freedom of action is simultaneously safeguarded. The key to this option lies in assuring that the spent fuel is retrievable, which, in turn, affects the design of the repository.

This cycle considerably reduces security concerns for Gen. 1 as SF is stored underground in ventilated tunnels. The U.S. Nuclear Waste Technology Review Board has conducted thermal analysis showing that with long-term ventilation such a system is feasible.(56) With this proposal the facility would be designed as a repository but initially licensed as an underground storage place. Should it be decided that the spent fuel is indeed waste, then the disposal

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[22] Besides the matter of future economic value, retrievability has other purposes too; the two most important ones are: (1) to be able to take remedial action if the repository does not perform as expected and (2) to give future generations the possibility to render waste harmless with new technology. See, in this connection, the section entitled "Equal opportunity: retrievable disposal" in "A Challenge to geological disposal."(53)

[23] Lars Löfquist deals in his Ph.D. dissertation with this tradeoff.(54, pp. 254–257)

[24] This is one of the fuel cycles discussed in the forthcoming MIT study on the future of nuclear power in the United States, to which this article is a contribution; one of the authors of this article (Kadak) is a co-editor of this study.

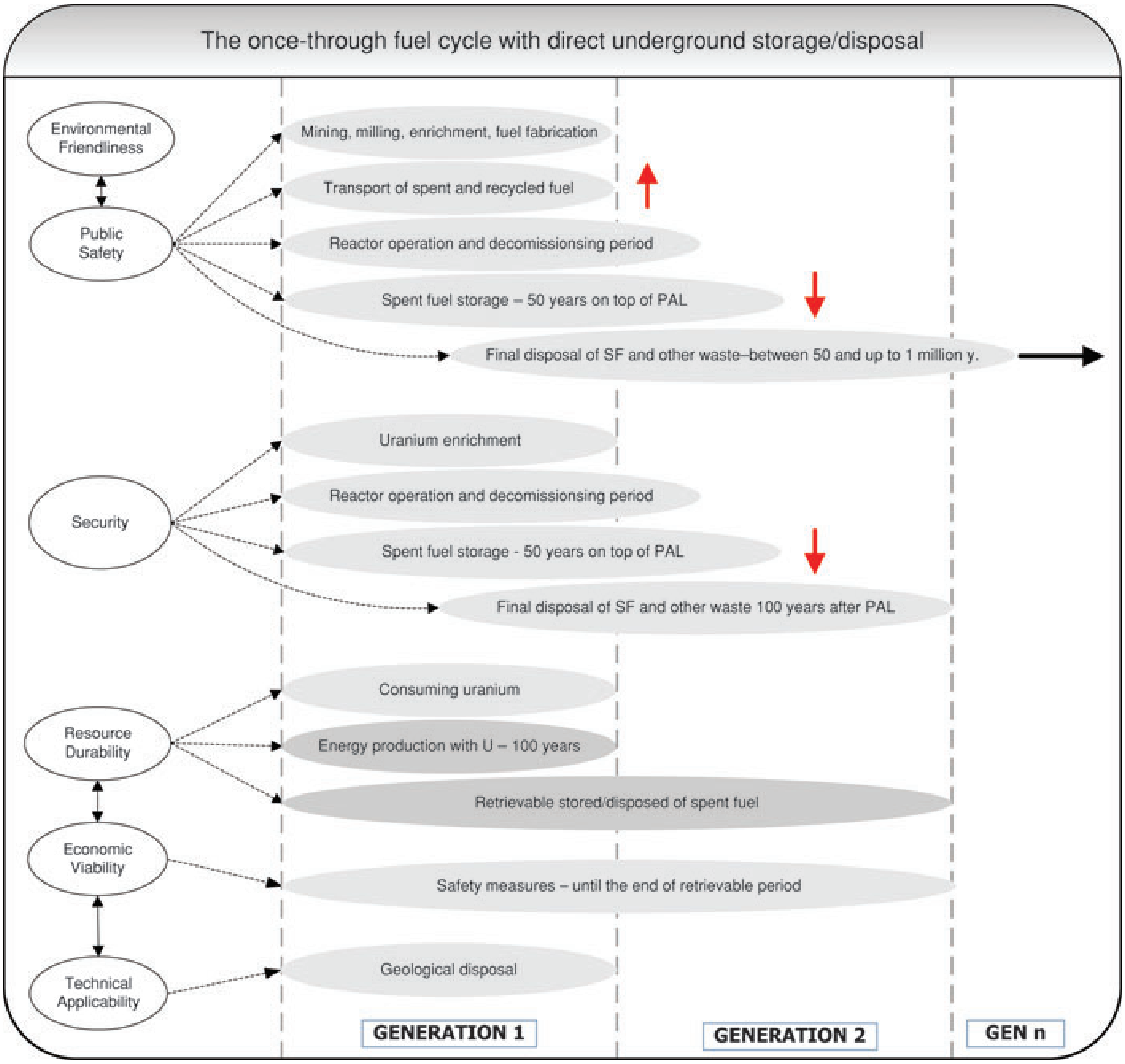

Fig. 4. Relating moral values to concrete consequences on the basis of a once-through fuel cycle with direct disposal in storage/disposal facilities. The elements indicated in red (see online version for colors) represent the divergences from current practice in the United States as illustrated in Fig. 3. The horizontal black arrow depicts a projection of certain considerations extending into the future and far beyond the time frame of the charts. The alterations with respect to the *conventional* once-through fuel cycle (as illustrated in Fig. 3) are indicated by means of arrows pointing up and down to denote the respective increase and decrease in the burdens and benefits.

licensing process with the added data collected during the storage period would provide confidence in the models used to design the repository for disposal purposes. Should the site prove unsuitable for disposal, the spent fuel will be retrieved and disposed of elsewhere. However, during this time, the spent fuel will have been securely stored. This option does, however, increase the transport risks because radioactive (and hot) spent fuel thus has to be transported to the storage/disposal facility. If Gen. 2 decides to leave spent fuel (because it has no economic value) the very long-term safety concerns will remain unchanged. The alterations with respect to the *conventional* once-through fuel cycle are indicated by means of the arrows in Fig. 4 pointing up and down to denote the increasing and decreasing of the burdens and benefits.

4.3. Transmutation of Actinides: LWR-FR

In some countries (such as France and Great Britain), spent fuel is currently recycled in order to extract uranium and plutonium for reuse in LWRs and to reduce the waste life-time.(57) It is, however, a method that has received widespread criticism because of the proliferation risks attached to separating plutonium. A future possibility, to retain the advantages of recycling but to avoid security burdens, would be to develop an integrated fuel cycle that extracts uranium as fuel and *consumes* plutonium, together with minor actinides, in fast reactors.[25] This kind of fuel cycle *partitions and transmutes* (P&T)(59, p. 23) fission products and actinides. Before this type of fuel cycle can be deployed at the industrial level, it needs to be technologically refined and it must be economically viable.(60,61) By using multiple reprocessing and recycling, this approach would be capable of substantially reducing the long-term concerns for Gen. 2–n, as the long-lived actinides will be fissioned (or transmuted) in fast reactors.[26] However, the additional economic, safety, and security burdens attached to developing the required technology and building the necessary extra facilities (i.e., reprocessing facilities and fast reactors) will mainly be borne by Gen. 1.

In our further analysis, we refer to this fuel cycle as the LWR-FR (transmuter). In Fig. 5, the P&T approach is assessed and the differences when compared to the once-through cycle are highlighted in red (visible in online version).

4.4. LWR-FR, the Breeder Configuration

The last fuel cycle to be considered is one in which fast reactors are used in the breeder configuration to breed (or make) more fuel than they consume. As breeders are capable of using uranium much more efficiently than LWRs, the period of resource durability and the potential benefits of resources[27] rise to thousands of years.(2) On the other hand, these future benefits bring about more current burdens in terms of the technological challenges attached to developing such fuel cycles, the economic burdens arising from the additional investments that need to be made in R&D, and the building of additional facilities, as well as all the further safety and security concerns. To conclude, Gen. 1 will ultimately bear significant safety, security, and economic burdens while facilitating adequate energy supplies and minimizing the long-term waste problems for future generations. In Fig. 6, this breeder fuel cycle is assessed and compared with the once-through fuel cycle. The dark-gray ellipse outlined in red (visible in online version) indicates the long-term benefits of resource durability.

The type of concerns behind the transmutation approach and this type of fuel cycle (the breeders) are similar, but all these concerns increase when fast reactors enter into the breeder configuration formula. There are two reasons for this: (1) the breeder fuel cycle system is based on the notion that eventually all the LWRs will be phased out and the whole energy production process will be based on breeders (and on the multiple recycling of waste), which will involve building more fast reactors and, thus, creating more economic burdens for this generation and (2) this fuel cycle is primarily based on plutonium, which gives rise to further security concerns.

In this section, we assessed the current practice of nuclear power deployment and the three future alternatives in accordance with the criteria of intergenerational equity. The following section merges these comparisons and presents them in an integrated analysis.

5. COMPARING FUEL CYCLES

So far, we have introduced a set of central values and we have formulated value criteria for an intergenerational assessment of fuel cycles in terms of their impacts on different generations. The serious challenge now lies in how to compare these alternatives in accordance with the proposed value criteria. We can distinguish here between two approaches to this analysis: the aggregate and the disaggregate methods.

The aggregate method is based on synthesizing the scores of each alternative and on drawing together the numerous and diverse criteria in order to aggregate—or add together—all the individual scores to make up one overall score. The best known aggregate method is cost-benefit analysis, which expresses (as much as possible) the values in terms of monetary values. Such approaches have attracted criticism for a couple of reasons. Firstly, they ignore the fact that the values involved are *incommensurable* or not directly comparable (e.g.,

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[25] An alternative to fast reactors for the purposes of P&T is an accelerator-driven system that is also capable of fissioning actinides.(58)

[26] A Canadian study on nuclear waste management explicitly considers partitioning and transmutation (P&T) because of the possibility to reduce waste radiotoxicity and volume, but rejects it as a Canadian option for technical and economic reasons.(62, Ch. 5) More will be said about this study in Subsection 5.4. Another Swedish report reaches more or less the same conclusion where Sweden is concerned and states that P&T as a future possibility definitely encourages retrievable disposal so that future generations will have the chance to eliminate or further treat the waste.(63,Sec.III)

[27] If this benefit is to be enjoyed by future generations, we need to abandon the assumption that nuclear fission deployment will continue for 100 years. It seems fair, however, to make allowances for this as a *potential* future benefit.

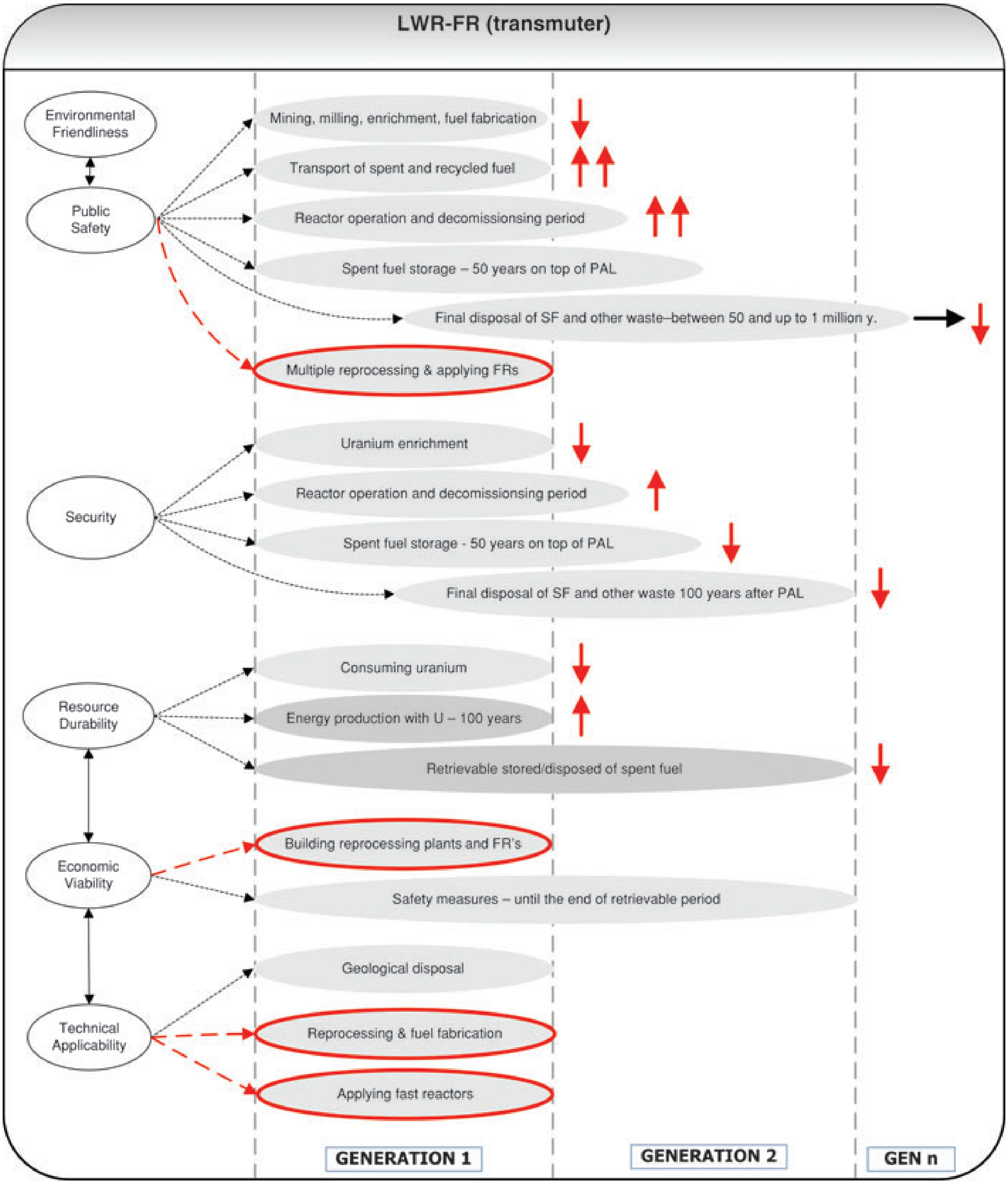

Fig. 5. Relating moral values to concrete consequences in line with the transmutation approach. The elements indicated in red (color visible in online version) represent the divergence from current practice in the United States as illustrated in Fig. 3. The horizontal black arrow depicts a projection of certain considerations extending into the future and far beyond the time frame of the charts. The alterations with respect to the *conventional* once-through fuel cycle are indicated by means of arrows pointing up and down to denote the respective increase and decrease in the burdens and benefits.

environmental values vs. economic values). Second, different stakeholders may prioritize and trade off the relevant values in different ways, even if they uphold the same basic values.

The disaggregate approach separately presents the impacts for each alternative. It uses a method introduced by policy analysts to compare policy alternatives, which is known as the *scorecard*

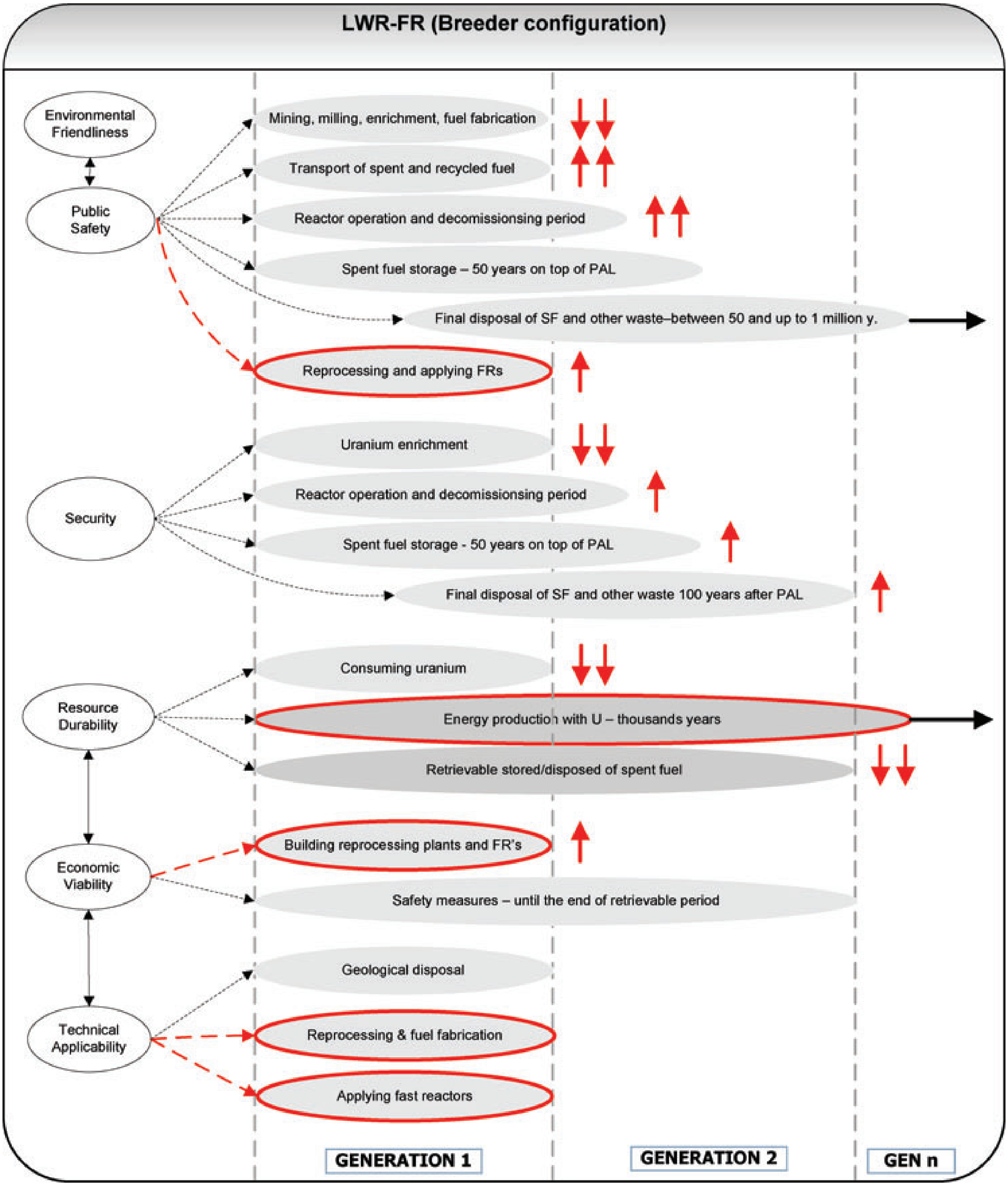

Fig. 6. Relating moral values to concrete consequences and to the light water reactors-fast reactors in the breeder configuration. The elements indicated in red (color visible in online version) represent the divergences from current practice in the United States as illustrated in Fig. 3. The horizontal black arrows depict a projection of certain considerations extending into the future and far beyond the time frame of the charts. The alterations with respect to the *conventional* once-through fuel cycle are indicated by means of arrows pointing up and down to denote the respective increase and decrease in the burdens and benefits.

method.[28] A scorecard enables one to rank different alternatives according to a single criterion (and its impact on the relevant alternatives). In that way, considerations concerning ways of ranking and prioritizing the criteria become central to the decision process itself.(67) For this overall ranking, which will eventually culminate in the final choice of a certain alternative, the scorecard is not, however, an appropriate instrument as it only facilitates ranking for a single criterion.(68) The scorecard could, however, assist us to clarify tradeoffs when choosing an alternative; more will be said about this in Subsection 5.3.

The creation of a scorecard begins with the entering of the alternatives and their impacts on an *impact table*. Each column in such a table represents one alternative and each row a certain criterion's impacts on all the alternatives.[29] An entire column is thus a single alternative's score for different criteria and an entire row denotes the impacts that one single criterion has on all the alternatives. Impact tables often contain quantitative and qualitative information regarding the scores of different criteria for different alternatives. Since it might be difficult for the decisionmaker to decipher the patterns and tradeoffs in such a detailed kind of table, a schematic representation of the impact table is proposed in the form of colored cells in order to further clarify the tradeoffs. That is what is known as the scorecard.

5.1. The Scorecard and the Four Fuel Cycles

If we merge the alternatives into an impact table, we can evaluate the four cycles according to the proposed value criteria (expressed in terms of impacts); the alternatives are compared solely on the basis of a qualitative assessment of the single value criteria. High, Medium, and Low are chosen as the ranking designations. The scorecard is completed by adding the three traffic light colors to denote the ranking of the alternatives according to one single value criterion. Red stands for the most unfavorable option, green for the most favorable, and amber indicates that either there is barely a difference between the alternatives, or that the consequences are intermediate;[30] see, in this connection, the scorecard given in the Appendix. When assessing burdens, high impacts are unfavorable and are thus colored red while amber and green are used consecutively. When benefits are rated (such as the benefits of energy production) high impacts are colored green.

To emphasize the intergenerational considerations (as shown in the burden/benefit charters of the last section), the demonstrated scorecard distinguishes between Gen.1 and the subsequent generations. The two columns given under each alternative in the scorecard indicate Gen. 1 and Gen. 2–n. In order to make this schematic presentation convenient to use, shading is added to highlight the time dimension. When choosing one alternative, two types of comparisons can be drawn: (1) the impacts for the first generations indicated by the *brightly* colored cells and (2) the impacts on future generations, indicated by the *shaded* cells. When two different alternatives score *the best* for different generations, the conflict arising from choosing the alternative should be regarded as a matter of intergenerational equity. While this graphical characterization may seem complex, studying the scorecard gives the decisionmaker a general appreciation of all the tradeoffs between and within generations that need to be made.

5.2. Choosing an Alternative

Different alternatives score differently for different value criteria and that gives rise to conflict; tradeoffs between the criteria seem inevitable. Hammond *et al.* propose two ways of facilitating the making of tradeoffs between the various alternatives: the even swap method and the method of eliminating the dominated alternatives.(66, Ch. 6) The even swap method is based on ignoring a criterion when the alternatives are equally rated. Forcing us to think about one criterion in relation to other criteria renders alternatives equivalent to a given criterion while reducing the number of decisive criteria. The second method is to eliminate the dominated alternatives: that is, when alternative A scores better than B on some objectives and no worse on all the other objectives, B is said to be dominated.(66, p. 85)

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[28] Scorecards first appeared in 1973 in a study that the Rand Corporation conducted for the U.S. Department of Transportation(64) and shortly after in a later RAND study for the Dutch Ministry of Transport, Public Works, and Water Management.(65) Some, such as Hammond *et al.* in his book *Smart Choices: A Practical Guide to Making Better Decisions*, refer to the same methodology as that given in the consequence table.(66)

[29] The scorecard proposed by many scholars gives the impacts vertically and the alternatives horizontally, but the basic idea remains the same.

[30] Using the color green could be misleading as we are talking about a form of energy production. In choosing these colors, we follow the relevant literature in policy analysis and comparable studies. The colors as applied in this analysis merely facilitate a comparison in a row without making any inference to other forms of energy.

The even swap method presupposes certain commensurability between the criteria, implying that they could be translated into each other, which is what renders this method unfit for our purposes. However, the basic idea behind this method—if we ignore the irrelevant criteria—could help us to eliminate value criteria that do not discriminate between alternatives. For instance, under the central value of "economic viability," the value criterion "safety measures costs until the end of the retrievable period" is not different in the four alternatives and could therefore be ignored in the decision-making process. It is, however, important not to remove this criterion from the list because a future alternative fuel cycle could give rise to changing impacts for this value criterion. In our comparison, no alternative scores worse than the others on all the value criteria and so no alternative could be dominated; see also the scorecard given in the Appendix. Even though it is quite clear that the fourth alternative (breeder) scores worse on almost all the criteria, it remains the best option when we consider the central value of "resource durability." This alternative fuel cycle is based on applying breeder reactors that are capable of using the more abundant isotope of uranium (^{238}U) and of using uranium much more efficiently.

5.3. Clarifying Tradeoffs when Choosing an Alternative

As numerous incommensurable value criteria are still involved, the scorecard is not helpful for choosing the final fuel cycle alternative based on numerical ranking. However, it can help the decisionmaker to understand a certain choice by providing information about the implicit tradeoffs that this choice involves. In other words, the scorecard clarifies *the societal expense* of any choices made and the burdens that will be incurred upon different generations.

Let us illustrate this by giving an example. Suppose that the decisionmaker decides to continue the current practice (Alt. 1). Based on the central values of "public safety"[31] and "security," this alternative scores relatively high; the short-term safety burdens of spent fuel storage and the long-term safety burdens of final disposal for Gen. 2–n are then implicitly accepted as a consequence of this choice. As this alternative basically involves applying existing technology (with many fewer technological challenges) it scores well for "technological applicability" when compared with other alternatives. For this and other reasons, the alternative gives rise to less economic concern. Alt. 1 furthermore scores badly in terms of "resource durability," as the less abundant isotope of uranium (^{235}U) is used once only in a reactor as fuel; reasonably priced uranium is available for this fuel cycle for no longer than 100 years.

What is lacking in this scorecard is a priority ranking of the values collected on this table. The priority ranking will largely depend on the value system of the decisionmaker and the society of the time. Will the decisionmaker value resource preservation more than cost or security? This is why such a scorecard can only highlight issues.

Let us also briefly consider a choice for Alt. 3 (the transmuter option) that is designed to eliminate as much as possible (long-lived) radioactive material in spent fuel. This alternative is based on utilizing fast reactors in transmuter configurations and reprocessing. The latter brings about greater safety and security concerns as reprocessing involves the separating of plutonium. The fast reactors (and their fuels) also need to be further developed, which imposes technological challenges as well as economic burdens on the present generation. An extensive discussion on the scorecard and the ranking of the alternatives based on single value criteria is presented in the Appendix.

While the ratings for each of the categories of the table given in the Appendix may be subject to some disagreement, the process for establishing the color coding should be the subject of expert solicitation and consensus in a deliberative process. Such a process can be used to clarify positions on key questions, which should assist the decisionmaker and enhance the transparency of the decision. By studying the table, one can develop an appreciation of the generational benefits and burdens when it comes to finally assessing the best course of action based on intergenerational equity principles.

5.4. The Canadian Example

Before moving on to the concluding remarks of this article, let us pause for a moment to discuss a case in which values have been incorporated in decision making on nuclear-energy-related issues. The Canadian Nuclear Waste Management Organization (NWMO) launched a mission to engage Canadians in debates and decision making on the future of Canada's spent fuel. In dialogues with thousands of people, the NWMO first sought to understand the values of Canadians, from which they drew their

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[31] It should not be forgotten that for ease of analysis "public safety" is merged with "environmental friendliness."

objectives, for example, public health and safety, environmental integrity, security, and economic viability.(62) Even though the NWMO acknowledges that some objectives are competing and that tradeoffs are inevitable, common ground was found in two major areas, that is, "the approach must be safe and secure—for people, communities and the environment; and it must be fair—both to current and future generations."(69, p. 3) Geological disposal is believed to perform well against value-driven objectives in the very long term, due to the combination of engineered and natural barriers, despite the uncertainties involved in this time period.

We discuss this example for two reasons. First, because this analysis and the method presented here share some similarities in that we both take values as the foundation of our comparison, the values presented and the objectives determined in NWMO's study coincide to a high degree with our values that are mainly drawn from the literature. The second reason for mentioning this example is because in its underlying analysis it emphasizes the fact that there are very many complicated considerations in actual decision making that have not even been addressed in our analysis. The solution proposed by NWMO is to have Adaptive Phase Management, which is not only a technical method but also a management system capable of moving toward retrievable geological disposal.[32]

Like in the NWMO study, we take sustainable development to be the main underlying notion and acknowledge the relevance of intergenerational equity in discussions related to nuclear power. Our analyses are, however, divergent from the point of view of how the latter is addressed. Intergenerational equity is referred to as one of the important objectives that needs to be taken into consideration by the NWMO while to our understanding of this notion it is the framework that enables us to address the intergenerational conflicts that arise when choosing a certain alternative.[33]

6. CONCLUSION

In this article, we have presented a method that provides insight into future fuel cycle alternatives by clarifying the complexity of choosing an appropriate fuel cycle. A set of central values is derived from the notion of sustainable development. By operationalizing these values and mapping out the impacts, value criteria are introduced for the intergenerational assessment of fuel cycles according to the distribution of burdens and benefits between generations. The current nuclear power deployment practices, together with three future fuel cycle scenarios cycles, were subsequently assessed according to these value criteria.

The key questions that ultimately need to be answered prior to finally opting for a particular alternative are these. Should Gen. 1 accept significant safety, security, and economic burdens for the benefit of future generations, thus in that way facilitating extended energy supplies (as proposed in Alt. 4) or minimizing the long-term waste problems (as outlined in Alt. 3)?

If the current analysis of the long-term risk of a nuclear waste repository is correct to conclude that the risks and burdens of geological repositories to future generations are very low,[34] how can one justify placing a burden on the present generation to minimize future risk further by adopting reprocessing and transmutation? On the other hand, the questions of to what extent the transferring of risk to the very distant future is acceptable and how and under what conditions this generation could consent to risks being imposed on future (still to be born) people need to be addressed.[35] These are not easy questions to answer and we do not claim that our method provides all the answers but it does illuminate the choices that need to be made and raise these questions and dilemmas in an informed manner. What this article challenges is the notion that intergenerational

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[32] We are not reflecting on whether this is the right conclusion to reach. We discuss this case merely because of the fact that this study—which appears to be quite influential in Canada—takes values as the basis of its analysis. The problem of ranking values—as discussed in this section—is one that has also been acknowledged and addressed here. Also the progress in technology and its influence on policy is something that the NWMO takes into considerations (see footnote 21); we referred to this matter in discussing the notion of "technological applicability."

[33] Another perhaps more obvious difference is that we are comparing future fuel cycles while the Canadian study focuses on future waste management options. It should further be noted that the NWMO report is focused on how to find common ground among the public for "Choosing a Way Forward," as its name suggests, while this article merely focuses on presenting a method for understanding the intergenerational dilemmas and tradeoffs in choosing a fuel cycle.

[34] The Environmental Protection Agency has set radiation standards that require radiation protection from disposed of nuclear waste for 1 million years (see also footnote 19).(51) In 2008, the U.S. Department of Energy (DOE) filed a license application for the Yucca Mountain Repository with the U.S. Nuclear Regulatory Commission.(70) It maintained that it could comply with the EPA's radiation protection standards for the desired period. See, for a historical background, Samuel Walker's *The Road to Yucca Mountain.*(71, Ch. 8)

[35] Shrader-Frechette refers to this problem as the problem of "proxy consent."(25)

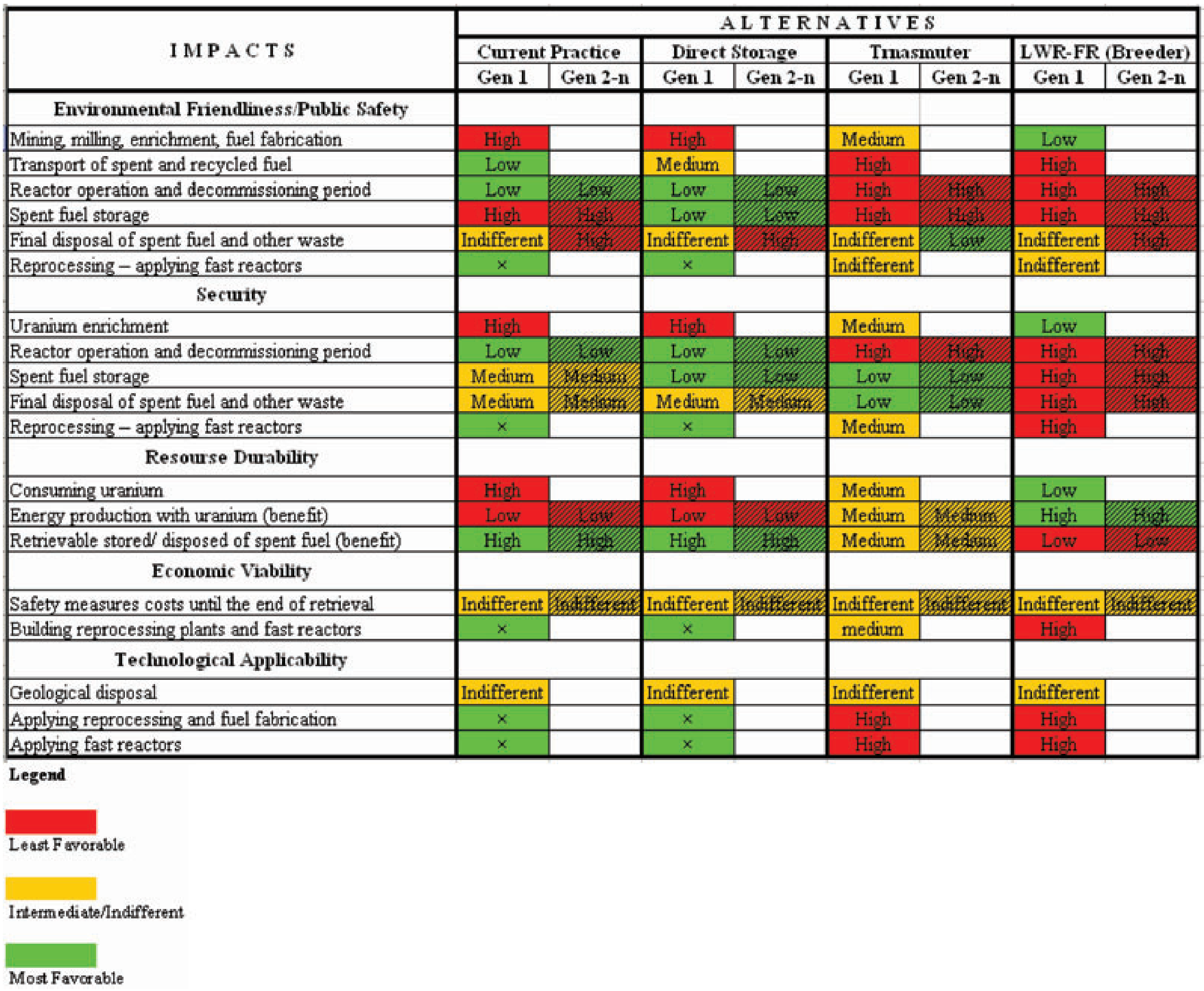
equity simply means disposing of nuclear wastes in this generation since the burdens and benefits need to be carefully balanced before such a decision is made.

Quite how these questions should be dealt with and how the proposed value criteria that will lead to the choosing of one fuel cycle will be ranked are matters that extend beyond the scope of this article. We have merely compared four fuel cycle alternatives on the basis of the single values that we derived from the overarching value of sustainability. We have also clarified the implicit tradeoffs that decisionmakers make when they opt for a certain alternative. When choosing a fuel cycle, what societal costs and burdens are accepted for each generation and how are these factors justified?

ACKNOWLEDGMENTS

This article has been partly written within the Department of Nuclear Science and Engineering at MIT and partly at the Department of Philosophy at Delft University of Technology. The authors wish to thank both departments and in particular Ibo van de Poel, Jan Leen Kloosterman, and Charles Forsberg as well the *Risk Analysis* Area Editor Warner North and two anonymous reviewers for their useful comments. This paper is a contribution to an interdisciplinary MIT study about the future fuel cycle options for nuclear power production in the United States. An earlier version of this paper was presented during the annual Workshop on Philosophy and Technology in November 2008, in London.

APPENDIX: SCORECARD AND EXPLANATION OF IMPACTS AND RANKINGS



IMPACTS	ALTERNATIVES							
	Current Practice		Direct Storage		Trnasmuter		LWR-FR (Breeder)	
	Gen 1	Gen 2-n	Gen 1	Gen 2-n	Gen 1	Gen 2-n	Gen 1	Gen 2-n
Environmental Friendliness/Public Safety								
Mining, milling, enrichment, fuel fabrication	High		High		Medium		Low	
Transport of spent and recycled fuel	Low		Medium		High		High	
Reactor operation and decommissioning period	Low	Low	Low	Low	High	High	High	High
Spent fuel storage	High	High	Low	Low	High	High	High	High
Final disposal of spent fuel and other waste	Indifferent	High	Indifferent	High	Indifferent	Low	Indifferent	High
Reprocessing – applying fast reactors	×		×		Indifferent		Indifferent	
Security								
Uranium enrichment	High		High		Medium		Low	
Reactor operation and decommissioning period	Low	Low	Low	Low	High	High	High	High
Spent fuel storage	Medium	Medium	Low	Low	Low	Low	High	High
Final disposal of spent fuel and other waste	Medium	Medium	Medium	Medium	Low	Low	High	High
Reprocessing – applying fast reactors	×		×		Medium		High	
Resourse Durability								
Consuming uranium	High		High		Medium		Low	
Energy production with uranium (benefit)	Low	Low	Low	Low	Medium	Medium	High	High
Retrievable stored/ disposed of spent fuel (benefit)	High	High	High	High	Medium	Medium	Low	Low
Economic Viability								
Safety measures costs until the end of retrieval	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent
Building reprocessing plants and fast reactors	×		×		medium		High	
Technological Applicability								
Geological disposal	Indifferent		Indifferent		Indifferent		Indifferent	
Applying reprocessing and fuel fabrication	×		×		High		High	
Applying fast reactors	×		×		High		High	

Legend

🟥 Least Favorable

🟨 Intermediate/Indifferent

🟩 Most Favorable

ENVIRONMENTAL FRIENDLINESS/PUBLIC SAFETY

Mining, milling, enrichment, fuel fabrication

The two first alternatives are based on enriching uranium and they involve the highest risk. Breeders require plutonium or enriched uranium for the startup but in lower quantities than a typical LWR that continuously uses enriched uranium as fuel; a breeder fuel cycle then involves fewer steps that carry risks, which is why we have assigned the lowest risk to Alt. 4. The transmuter alternative (3) is based on transmuting the actinides in SF that come out of a LWR; Alt. 3 then involves less risk than the first two and more than the breeder alternative.

Transport of spent and recycled fuel

In Alt. 1, there is no recycled fuel; spent fuel is transported to interim storage places (sometimes onsite storage facilities) and eventually to disposal facilities. In Alt. 2, there is no recycling either; however, the transport risk is higher, as hot and more radioactive spent fuel that has just come out of the reactor is immediately transported to the underground storage facilities. These concerns are the highest for the two last alternatives, since recycling involves more transportation in the form of recycled fuel fabricating and returning to the reactor for irradiation.

Reactor operation and decommissioning period

There is a difference between the first two alternatives that solely use LWR and the last two that are based on FRs. The latter are generally sodium-cooled reactors, and those are relatively more difficult to decommission as the sodium needs to be disposed of and that requires storage in a cover gas shielding.

Spent fuel storage

In the last two alternatives that use sodium-cooled FRs it is difficult to store spent fuel, as we need to manage sodium, which needs to be stored in a cover gas shielding. Alt. 1 stores SF above ground and that also involves high health risks. Once SF in Alt. 2 is put underground, the safety impacts will be much reduced.

Final disposal of spent fuel and other waste

With the first generation, there is no difference between the concerns related to final disposal. The designation “indifferent” for first generation waste should not, however, be read as “no concerns,” but the concerns remain fairly similar and cannot be ranked internally. The difference applies to Gen. 2–n in which Alt. 3 scores the lowest, as long-lived actinides are transmuted. Three other alternatives contain long-lived actinides that require isolation from the atmosphere for a very long time.

Reprocessing and applying fast reactors

The two first alternatives solely use LWR and do not involve reprocessing; therefore, there is no such risk involved. The two last alternatives involve some but more or less the same safety concerns.

SECURITY

Uranium enrichment

There is no difference between the two first alternatives, as the need for enriched U is the same. In Alt. 3, less enriched U is needed, as the transmuting of actinides also generates energy; Alt. 3 therefore involves medium security concerns. Alt. 4 requires the lowest amount of enriched uranium, as this fuel cycle is basically based on Pu.

The reactor operation and decommissioning period

Alts. 1 and 2 are the most favorable ones, as there is no separated Pu involved during operation; LWR work either on enriched U or MOX. FRs (Alts. 3 & 4) are the least favorable due to the presence of Pu.

Spent fuel storage

Alt. 4 is the least favorable option, as it involves Pu. The best option is Alt. 3 as it gets rid of all the actinides (including Pu). Alt. 2 involves less security risks as after irradiation the SF is immediately placed underground in physically difficult-to-reach places. Strictly speaking, there is a difference between the types of risk related to Alts. 2 and 3, but for the sake of clarity, we regard these two options as equal. In Alt. 1, we keep Pu in interim storage and therefore it scores worse than Alts. 2 and 3.

Final disposal of spent fuel and other waste

Alt. 3 is the best option as the actinides are removed and transmuted. The two first alternatives score lower as they use enriched uranium and make Pu in the cycle. The worst option is the last one because it is a pure Pu cycle; in the waste stream of a breeder reactor, there are still Pu isotopes that need to be disposed of.

Reprocessing and applying fast reactors

The two first alternatives solely use LWR and do not involve reprocessing; therefore, there is no such security risk involved. Alt. 4 is based on the reprocessing of Pu so that it can be reused a couple of times, all of which involves the highest security burdens. In Alt. 3, actinides (including Pu) are reprocessed several times and transmuted in FRs; however, the security concerns are lower than with Alt. 4.

RESOURCE DURABILITY

Consuming uranium (as a burden)

In the two first alternatives, we use the highest amount of U as there is no recycling (reusing) involved. Alt. 3 scores lower in terms of burdens; energy is produced when actinides are transmuted which therefore means that we use less U. Alt. 4 uses the lowest amount of U as it is a Pu cycle.

Energy production with uranium (as a benefit)

In terms of the benefits of energy production, applying breeders (Alt. 4) is the best option for this and the next generation, as that creates more fuel (Pu) than it consumes. Alt. 3 has fewer benefits as it still involves the use of U and the transmuting of actinides in SF. The first two alternatives have the lowest benefit as they consume most U. As we are indicating here benefits, "high" (benefit) becomes the most favorable option and it is colored green, etc.

Retrievable stored and disposed of spent fuel (as a benefit)

This row involves the potential benefits of retrieving spent fuel (or waste) and reusing fissile materials as *fresh* fuel. In the two first alternatives, there is still U and Pu present that could potentially be separated and reused. The transmuter cycle (Alt. 3) is based on the transmuting of actinides, but other actinides are produced during this process, which are fissile and could also be used as fuel. Breeders use up all the Pu. As we are indicating here benefits, "high" (benefit) is the most favorable option and it is colored green, etc.

ECONOMIC VIABILITY

Safety measures costs until the end of the retrieval period

There is no difference between the four alternatives, as costs need to be incurred in order to shield and keep SF safe before the final disposal phase. Even when we immediately put SF underground (Alt. 2), certain costs need to be incurred for monitoring and keeping it retrievable. We assume that these costs will be equal for the four alternatives.

Building reprocessing plants and fast reactors

The two first alternatives solely use LWR and do not involve reprocessing; therefore, there is no such risk involved. Alt. 3 involves building reprocessing plants and fast reactors, all of which is very costly. Alt. 4 is, economically speaking, the worst option as inevitably all LWRs will need to be replaced by FRs.

TECHNOLOGICAL APPLICABILITY

Geological disposal

It is the same for all four alternatives. Even though the design criteria for different disposal facilities differ, the technological challenges remain the same.

Applying reprocessing and fuel fabrication

The two first alternatives solely use LWR and do not involve reprocessing; therefore, there is no such risk involved. In the case of the last two, the technological challenges are great. Even though breeder fuel has already been generated (unlike actinide fuel for transmuters as in Alt. 3), there is still a technological challenge in Alt. 4 to fabricate fuel from recycled *breeder spent fuel*; most breeder fuel has not so far been recycled. The technological challenges for Alts. 3 and 4 are ranked equally, which means that they could have been denoted as "indifferent." By ranking them as "high," we aim to emphasize that these are serious challenges that need to be dealt with.

Applying fast reactors

The two first alternatives solely use LWR and do not involve reprocessing; therefore, there is no such challenge. The technological challenges attached to applying fast reactors in the last two alternatives remain the same. As with the last impact, the technological challenges for Alts. 3 and 4 are ranked equally, which means that we could have termed them "indifferent." By ranking them as "high," we aim to emphasize that these are serious challenges that need to be dealt with.

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