SUSTAINABILITY OF NUCLEAR ENERGY WITH REGARD TO DECOMMISSIONING AND WASTE MANAGEMENT

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ABSTRACT
Sustainability aspects of nuclear power are analysed with regard to such environmental liabilities that are associated with decommissioning of nuclear facilities and with nuclear waste management. Sustainability is defined and evaluated based on information searches that also include energy from combustion of coal. It is concluded that the claims on sustainability put forward by different parties are inconsistent and that coherent methodologies for evaluation are needed together with appropriately structured knowledge bases. Examples are presented from the perspective of the Swedish Radiation Safety Authority. It is found that nuclear power can qualify as sustainable only if the nuclear liability associated with protection of health and the environment - now and in the future – is appropriately managed. Sustainability awareness is analysed in a historic perspective, and it is found that it has been around for at least as long as agriculture, and that at least some of the shortcomings are actually modern inventions. Comprehensive perspectives are essential, since sustainability awareness may appear as trends. It is a historical fact that planning for decommissioning and estimation of associated costs are frequently treacherous exercises. However, costs must be relatively accurately estimated already at early stages so that adequate funds are available at the time when they are needed. Thus, the timing of the technical planning is often governed by the needs for financial planning. It is the duty of the present generation to assess what is adequate and to find responsible solutions. But the next generation should also be asked to carefully consider the perspective that they provide to us.
Keywords: cost calculation, liability, nuclear, segregated fund, sustainability, younger stakeholders.

1 BACKGROUND, PURPOSE AND SCOPE

1.1 Nuclear liability evaluation and financing in Sweden

Generally, legislations do not prohibit the license holders of industrial facilities to carry out activities that have a potential for causing detriment to health and environment. Instead, legislations – as well as the associated authority oversight and supervision – limit the risks for such detriment.

In Sweden, it is the duty of the Swedish Radiation Safety Authority (SSM), (Swedish name Strålsäkerhetsmyndigheten) to oversee the following:

- *radiation protection*, under The Radiation Protection Act [1],
- *nuclear activities*, under the Act on Nuclear Activities [2], and
- *financial oversight*, under the Nuclear Liability Act [3].

These Acts are comprehensive and cover all kinds of radiological and nuclear activities, including operation of nuclear power reactors. These Acts – as well as the associated SSM oversight – also cover the planning for the final storage of the nuclear waste, the planning for the decommissioning of nuclear facilities and the system for financing the associated future costs.

It is stipulated in the Nuclear Liability Act [3] that plans and cost calculations shall be submitted to SSM each year for nuclear power plants and every third year for other facilities.

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For nuclear power plants, there are two 'compartments' for securities and fees to segregated funds managed by the Government:

a. the anticipated costs for decommissioning and waste management etc., and
b. a risk fee intended to cover the risk that the Government takes in its management of the fund system.

Compartment (a) comprises a combination of assets in segregated funds and securities (unlimited in time). The securities are lifted at the same pace as that of the payments that flow into the segregated funds.

Securities must also be provided to cover 'unplanned events'.

It is the owners and operators of the nuclear facilities who have the full responsibility for protecting health and the environment. This responsibility includes that they must ensure that adequate funding is available at the time when it is needed to cover any associated liabilities. The role of SSM and other authorities is twofold:

- to instigate such work, and
- to ensure that any obligations are fulfilled

Most of the nuclear liabilities concern the decommissioning and waste management associated with our 12 light-water nuclear power plants (two of which have been permanently shut down). However, more than 10% of the estimated total liabilities are associated with old nuclear technology development facilities, including the Ågesta heavy-water nuclear power reactor which was in operation during 1963–1973. Actually, facilities covering laboratory and pilot scale work on most of the nuclear fuel cycle were built at the Studsvik site which used to be our nuclear national laboratory.

Experience has shown that there are considerable obstacles and pitfalls related to the planning for decommissioning and associated cost estimates, especially for old nuclear facilities. Consequently, it is a daunting and demanding task for owners and operators to comply with the requirements on financial planning. In concordance, the SSM must have a good knowledge base for its oversight. It is therefore the duty of the SSM to carry out and to commission relevant research work [4]. Recent publications include Refs. [5–15].

1.3 Objective

The purpose of the present paper is to analyse sustainability aspects of nuclear power with regard to such environmental liabilities that are associated with decommissioning of nuclear facilities and associated nuclear waste management. It is also the purpose to define and evaluate sustainability based on information searches and to make comparisons with generation of electric energy from combustion of coal.

It is anticipated that the results will be used as a part of the knowledge base needed for assessments of sustainability for nuclear power in general and for comparisons between different sources of energy. It is also the objective to illustrate how environmental liabilities can be managed for different energy systems and in different fields of technology.

Thus, section 2 of this paper provides some thoughts on system analysis and comparison together with the associated need for tools. The elements of nuclear energy sustainability are presented in section 3, and examples of recent work are summarized in sections 4 and 5.

2 SUSTAINABILITY AND ASSOCIATED METHODOLOGIES FOR ANALYSIS AND COMPARISON

2.1 Sustainability definitions

According to the Brundtland report [16] from 1987, sustainable development can be defined as follows:

'*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:*

- *the concept of "needs", in particular the essential needs of the world's poor, to which overriding priority should be given; and*
- *the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.*'

This principle of sustainable development is closely associated with the polluter pays principle (PPP). It is also dealt with in the Brundtland report [16] which in this case refers to an OECD decision from 1972 [17] according to which environmental costs should be included in the prices of various commodities. A corollary to the PPP is the principle of equity between generations.

The balancing of future risks, costs and benefits fairly across generations was dealt with by a panel of the United States National Academy of Public Administration [18], and some of the conclusions are as follows:

***'Trustee Principle** — Every generation has obligations as trustee to protect the interests of future generations.*

***Sustainability Principle** — No generation should deprive future generations of the opportunity for a quality of life comparable to its own.*

***Chain of Obligation Principle** — Each generation's primary obligation is to provide for the needs of the living and succeeding generations. Near-term concrete hazards have priority over long-term hypothetical hazards.*

***Precautionary Principle** — Actions that pose a realistic threat of irreversible harm or catastrophic consequences should not be pursued unless there is some compelling countervailing need to benefit either current or future generations.'*

These conclusions are reiterated and elaborated in an OECD Nuclear Energy Agency (NEA) report [19] on decommissioning funding and associated ethics.

2.2 The need for tools and knowledge bases for assessments

It might be tempting to assume that the above quoted basic principles might be readily applied to various industrial activities including energy production. However, the conclusions reached are not entirely coherent.

For instance, the World Nuclear Association concludes the following [20]:

'*Our confidence that nuclear power is a "sustainable development" technology because its fuel will be available for multiple centuries, its safety record is superior among major energy* *sources, its consumption causes virtually no pollution, its use preserves valuable fossil resources for future generations, its costs are competitive and still declining, and its waste can be securely managed over the long-term'*.

Similar conclusions, although expressed more moderately, can be found in a report [21] from the OECD/NEA.

The conclusion above '*that the waste can be securely managed*' should not be interpreted to imply that systems are in place for final disposal of all nuclear waste in all countries. In fact, comprehensive research – including demonstrations on pilot scales – has been carried out, but no country has yet commissioned a repository for civilian spent nuclear fuel or high level waste from reprocessing of such fuel.

Actually, OECD/NEA, the International Atomic Energy Agency (IAEA) and others are very active in promoting adequate decommissioning of nuclear facilities after the end of their useful life and appropriate management of the nuclear waste. Details on the selection of strategies for decommissioning can be found in an OECD/NEA report [22].

What about comparison with other sources of energy? The present authors have not carried out any extensive searches on this issue, and there may not be very many publications anyway. However, residues from thermonuclear and 'thermochemical' energy generation are being compared in a recent OECD/NEA report [23]. Nothing embarrassing is presented in Ref. [23] on the residues from coal combustion (the topic of the report), but without proper reference, the report states that emissions from coal combustion cause almost one million fatalities a year (no comparison was found with emissions from nuclear facilities under normal and accident conditions). Since the quote is out of context, the reader is lead to believe that this is what happens whenever coal is being combusted. However, it is well known in the coal combustion community that cooking on a coal stove without ventilation – as is commonly done in many poor countries – is not good for your health, while modern coal fired plants, for example, in Europe and the United States are not allowed to operate unless health and environment are properly protected, see for example, Ref. [24].

The coal combustion community is able to speak for itself, however. Thus, it considers [25] three pillars of sustainable development: '*economic prosperity, social well-being and environmental sustainability*', (cf. the Brundtland report above) and makes the following observations:

- '*The Coal Industry Advisory Board recognises the paramount important sustainable development. The CIAB emphasises that policies must put equal weight on all three pillars of sustainable development in order to be effective.*
- *Coal will play an important role in energy systems that support sustainable development for the foreseeable future. This is because of coal's unique combination of advantages: it is affordable, is safe to transport and store, and is available from a wide range of sources. Coal therefore remains essential in achieving a diverse balanced and secure energy mix in developed countries; it can also meet the growing energy needs of many developing countries.*
- *Further improvement in coal's environmental performance will be required. While improved coal technologies have provided very substantial efficiency and emission improvements to date, accelerated technological effort is required to reduce greenhouse gas emissions.*'

Of course, carbon capture (carbon dioxide sequestration) is still at the development stage.

Assessments of merits and relative merits of various sources of energy are clearly outside the scope of the present paper. The important conclusion is instead that the application of the fundamental principles of sustainability is not straightforward. Tools for assessment and comparison are needed as well a knowledge bases structured in such a manner that it can be readily utilized.

2.3 Tools for assessment and need for appropriately structured knowledge

Tools for assessment of the functioning of industrial facilities originate from safety-related work on steam engines with coal combustion. In the case of Sweden, this work started in an organized way in the 1890s, and the history is documented in the 100th year anniversary book *The Good Power* published by what is now ÅF AB [26].

Modern tools have largely been developed in conjunction with the planning and safe operation of advanced industrial facilities, especially in the chemical and nuclear industries, and examples include Refs. [27–30]. The importance of utilization of feedback from experience and lessons learnt can hardly be exaggerated.

General considerations in such analyses include the following:

- definition of the system, including what are the prerequisites (outside the system) and what is inside;
- identification and description of features, events and processes;
- identification and studies of scenarios;
- comparison (e.g. for best available technology) based on comparing one type of characteristic at the time, and to make overall assessment thereafter.

The Swedish research on nuclear waste disposal and associated planning, including financial planning, was inaugurated in the 1970s, and have since then been rather intensive in industry (the major effort) as well as at the SSM and its predecessors. An overview of objectives and direction of the authority work can be found in Ref. [4].

Examples of SSM and SSM-sponsored work include the safety assessment SITE 94 [31, 32] and associated identification of features, events and processes [33, 34] as well as scenario development [33–35]. The scientific knowledge base was utilized for the recurrent reviews of the waste management programme of the industry [36] and of the financial planning [5–15]. The SSM research has also formed the basis for various regulations, including Refs. [37, 38].

The SSM work has preceded as well as has been carried out in parallel with work in other countries, and also provided input to OECD/NEA and the IAEA in their 'consolidating' reports; see, for example, Refs. [39–41]. and [15], respectively.

The issues of decommissioning and nuclear waste are not any property of the technical community. They belong to everyone including the political sphere. Consequently, the research has included the social sciences also, and the developments have been similar to those in the natural sciences. What is now the Swedish National Council for Nuclear Waste has thus had a significant influence of the ethics involved, including the principle that a final repository should be designed to render controls and corrective measures unnecessary, but not impossible. Another example is risk perception and communication; see Ref. [42].

Lessons learned from the SSM work include that assessments and comparisons is a topic in itself, and requires substantial efforts. Pitfalls are numerous, and structured approaches are essential. Critical areas include integration between disciplines and awareness of the sociological, financial and legal dimensions. Perspective on time is also important, including difficulties in making prognoses for chemical developments, awareness of all different relevant issues – which may change considerably with time – and the general level of scientific and technical knowledge which is being elevated all the time.

3 NUCLEAR ENERGY SUSTAINABILITY

3.1 Availability of uranium and the efficiency in its utilization

All contemporary nuclear power reactors use uranium-based nuclear fuel. Uranium ore typically contains levels of uranium at a fraction of a percentage or lower. This implies that most of the ore becomes tailings that may emit radioactive radon to the surrounding air, and various elements in the periodic table to the groundwater. Thus, remediation and reclamation are needed.

Reference [43] states that the total identified sources of uranium are sufficient to last for more than 100 years at the present level of consumption. The report also states that the deployment of advanced reactor and fuel cycle technologies could conceivably extend the long-term availability of uranium to thousands of years.

The present nuclear power reactors use uranium that has been enriched from the natural content of uranium-135 which is 0.7% to a few or several percentage. Such enrichment is expensive.

The efficiency of the utilization of the fuel depends on the degree of breeding, that is, to what extent uranium-238 is converted to plutonium-239 and other fissible nuclides. In the Swedish light-water moderated reactors, almost half of the total thermal energy generated originates from fission of transuranic elements together with fission of uranium-238 by high energy neutrons (45% for a boiling water reactor according to Ref. [44]). Most of the energy originates from fission of uranium-235 by thermal (low energy) neutrons.

There is a debate as to the sustainability of utilizing only such a moderate fraction of the uranium-238 in the fuel in the nuclear energy reactors of today. The price of the natural uranium constitutes only a small fraction of the total cost for nuclear energy generation, and thus even ores with low contents of uranium might be mined. This increases the potentials for environmental impacts, however.

Other types of nuclear reactors than those currently in use in Sweden – and commonly used elsewhere – may utilize uranium-238 to a much larger extent or use thorium. The formation of fission products is of course directly proportional to the burn-up. Since the fission products absorb neutrons much more than other matter in the reactor, reactivity decreases gradually after a refuelling. Thus, a high utilization of uranium-238 generally presupposes reprocessing, in which process the fuel taken out of a reactor is dissolved and the constituents separated. Typically, the categories obtained are as follows.

- Fission products that are converted to a form suitable for final disposal (usually glass). The fission products are highly radioactive.
- Depleted uranium, that is, uranium having a content of uranium-235 that is lower than 0.7% (which is the level for natural uranium).
- Transuranic elements, notably plutonium. Many of these isotopes are fissible by thermal neutrons, but some require high energy neutrons.

Advantages with reprocessing, in addition to the more efficient use of the uranium, include the burning of long-lived transuranium elements that would otherwise – in the case of direct disposal of spent nuclear fuel – constitute part of the waste.

The Swedish work on breeder reactors in a historical perspective has recently been summarized by Fjaestad [45].

3.2 Protection of health and the environment

Most of the potential for detriment to health and the environment from nuclear power generation originates from radiation. The radionuclides emitting the radiation may be natural or artificial. (A nuclide is a specific combination of elementary particles in the nucleus of an atom.)

A radionuclide emits radiation on conversion to either a form having a lower energy or to another nuclide (sometimes also a radionuclide). The natural radionuclides are either long-lived or daughters of very long-lived ones. Man-made radionuclides show very large variations in longevity. Moderately long-lived ones give rise to most of the doses during operation of a nuclear facility, and very long-lived ones may have to be isolated from man and the biosphere for tens and hundreds of thousand years.

Radiation from different radionuclides may have very different absorption properties. Some types might be effectively arrested by a sheet of ordinary writing paper, while other types might require as much as a few centimetres of steel to be attenuated by 50%.

The International Commission on Radiological Protection (ICRP) was already formed in 1928. It has published numerous reports, including its recommendations [46] which form the basis for radiation protection worldwide. The basic principles are as follows:

'The Principle of Justification: *Any decision that alters the radiation exposure situation should do more good than harm.*

The Principle of Optimisation of Protection: *The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.*

The Principle of Application of Dose Limits: *The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the Commission.'*

These principles of protection also apply to doses to future generations that might come about as a result of activities of the present generation; see, for example, Refs. [37, 38].

So far, doses in Sweden from nuclear activities have been kept well within limits for the most part. In particular, doses to the public have been very far below the limits. We have also been fortunate in that radiological consequences of deviations from normal operating conditions have been insignificant.

Accidents do occur, however, as is illustrated by the Chernobyl disaster which affected Sweden by fallout [47]. This particular type of accident is not technically possible with our designs of reactors. Nonetheless, it is an appropriate attitude from a safety point of view not to discard the possibilities of accidents. The accidents at the Fukushima nuclear power plants in Japan in the year 2011 illustrate this point.

Decommissioning of a nuclear facility typically costs at least a couple of orders of magnitude more than the demolition of a corresponding non-nuclear facility. The reason for this is the presence and properties of the remaining radionuclides (cf. the description above). Moreover, the waste from decommissioning will have to be deposited, typically – and in the case of Sweden – together with other waste that has been kept in interim storage. According to present domestic plans, the spent nuclear fuel will be deposited in a separate facility, however.

This constitutes an environmental liability that has to be appropriately managed in terms of technical and financial planning (cf. section 1.1 above). Such appropriate management is an essential prerequisite for nuclear energy to qualify as sustainable.

4 RESULTS FROM INFORMATION SEARCHES

4.1 Historical perspective

It has been said that one should deal with the past to shape the future better. So what can we learn from history?

Sustainability awareness is often thought of as a modern phenomenon, but is actually likely to be at least as old as agriculture. Our forefathers freed their farmlands from stones and put them in walls to protect the crops from grazing animals. This example illustrates a strong solidarity with descendants.

Legislation on preservation and protection of forest extends beyond written records, and statements to this end exist even in our oldest written law, the older Westgothia law from around the year 1220. Early environmental legislation includes the statement by our Queen Kristina on 18 March 1639 when she banned burn-beating by the penalty of banishment. Lack of perspective is actually partly a modern phenomenon, as is illustrated by the example of institutional investors that sometimes focus on short-term profits and neglect long-term responsibilities and benefits.

The greenhouse effect has been known for more than 100 years not only as some curiosity in exotic scientific literature but also, in popular and well-circulated literature in which it was put forward in 1919 by the Swedish scientist Svante Arrhenius [48] as more or less a matter of course. It was pointed out as just about the only mechanism by means of which mankind might achieve an increase in world temperature. He also calculated that the carbon dioxide reserves in the atmosphere would last for only about 37 years should it not be replenished by microbial activity and coal combustion.

It is appropriate to wonder why the issue of global warming was laying dormant for about a century, and then relatively recently and suddenly became a major issue. This raises the question of what other important issues might escape contemporary attention only to become major issues tomorrow.

The book by Arrhenius [48] deals rather extensively with the issues of sustainability of mineral and energy resources, and it ends with emphasizing the need for recycling and the exhort: '*thou shalt not waste*'.

Another example of what might be referred to as incubation or initiation effects concerns the awareness of the significance of manmade radionuclides.

Konrad Röntgen published his discovery of the X-rays and his X-ray tube in 1896. This was a great blessing in medicine since for the first time in history, doctors could look inside a human body without having to use a knife. X-ray equipment was installed in many places soon after the discovery and in the case of Stockholm already in 1897. It then took a couple of decades before it was discovered that the radiation could give rise to cancers many years after exposure. (This was the rationale for the establishment of ICRP mentioned above.)

The first controlled chain reaction took place in 1942. The hazard associated with radiation was well known at this time, but there was no experience with induced radioactivity. It took until the mid-1970s until nuclear waste research caught on speed. According to the national implementer of this R&D programme, the Swedish Nuclear Fuel and Waste Management Company, SKB, the accumulated R&D cost until present at the price level of today is about G€1,90 (see www.skb.se).

A similar but less transient development of awareness is taking place since about 20 years on the issue of decommissioning of nuclear facilities. Examples of recent work are presented in the subsequent sections 4.2 and 5.

4.2 Environmental liabilities and the PPP

Background to this section in the form of previous publications by the present authors can be found in Refs. [5–15].

The PPP has been implemented in the Swedish Environmental code [49] as follows: '*Persons who pursue or have pursued an activity or taken a measure that causes damage or detriment to the environment shall be responsible, until such time as the damage or detriment ceases, for remedying it to the extent deemed reasonable …*'. Since there is no limit in time, a liability will exist as long as remediation has not been completed.

It was mentioned in section 1.1 that for nuclear liabilities, financial resources are generally accumulated in segregated funds so that funding will be available at the time when it is needed. The funding should be sufficient but not superfluous. A prerequisite for the functioning of such a system is that future costs can be estimated with sufficient precision. There are numerous examples of deviations in this regard, and consequently a structured approach is warranted.

First, it should be recognized that end of license is different from end of liability. End of license may come about under the Radiation Protection Act [1] and the Act on Nuclear Activities [2]. Liabilities may, however, still remain even after end of license. End of liabilities may come about as a result of an authority decision under the Nuclear Liability Act [3]. Planning for decommissioning is to be carried out under all of these acts. It is not unusual that radiological and operational planning is carried out in one organizational unit and financial planning in another. As a consequence, different plans may be prepared. If this is the case, then it is imperative that they are well harmonized.

Switching from an operational mode into one of decommissioning is a very large step in a facility. It happens easily, that data from radiologic surveying that is perfectly adequate for operation purposes is used for decommissioning planning where it may be totally inadequate. Decommissioning planning must be carried out based on its own needs. The main issues in this planning are radiological surveying (for the needs of decommissioning), methodology selection and identification and evaluation of potential cost raisers.

At least for private enterprises, the nuclear [3] as well as the financial [50–53] legislations require that liabilities be calculated with a high or even very high precision. The harshest punishment – up to six years in prison – might come about as a consequence of the penal law [54] in cases where the financial reporting is grossly misleading.

Such deviation might actually not be very far-fledged since it has proven recurrently difficult to make precise cost estimations for decommissioning, especially for old research facilities. A good advice is therefore to follow – or at least carefully consider – existing standards [55, 56], and to conscientiously declare any remaining uncertainties together with the reasons why they still exist. It should be noted that errors in estimates of environmental liabilities may easily escape identification and attention by the company auditors. The reason for this is that they usually lack the detailed scientific and technical knowledge that is required to find such insufficiencies. Consequently, deviations may escalate with time, and thereby become increasingly difficult to deal with once they are discovered.

What is just said implies that the timing of the planning for decommissioning is governed by the needs of the financial planning. This is 'unnatural' for many technically oriented people, since much of the planning needed for financial reasons could preferably be deferred if the relevant considerations were solely technical.

Although the responsibility for health and environment – including liabilities – rests solely with the owners and operators, it is essential that there also exists a public oversight, an authority that instigates and controls, and thereby executes the role of ombudsman for the public. Only then can full credibility be earned regarding sustainability of nuclear energy with regard to decommissioning and waste management [6, 57].

5 SOME RESULTS FROM FIELD STUDIES

5.1 Introduction

When dealing with intra-generational tasks and liabilities, it is crucial that information is disseminated and communicated openly and that result of research work is published in scientific as well as in public media. Such issues may concern investments in infrastructure, such as, for example, the Öresund Bridge that connects the Swedish town Malmö with the Danish capital Copenhagen, and which was inaugurated in the year 2000. Decisions on long-term investments that largely benefit future generations, but have limited benefits for the present one, are normally passed only after lengthy and cumbersome processes. The decision to build the bridge was made in the late 1980s and the construction was carried out during the 1990s, but detailed plans and cost estimated existed already in the 1920s. Part of the financing of the bridge comes from road tolls which are based on a time span of one generation, but actually, the toll should be based on the entire life-span of the bridge which is probably considerably longer. Such a longer perspective would thus probably lead to a lower toll today, since also future generations will contribute to the payment. The present system is fair, however, if the life-time were actually only one generation.

The basic principle that is governing investment decisions is that the cost shall be allocated according to usage. This principle is fairly well accepted in normal investment situations and also works reasonably well when the perspective is at most one generation.

In the case of nuclear waste, the cost for decommissioning nuclear facilities and for managing nuclear waste may arise after longer times than one generation, possibly even several generations. In this respect, nuclear energy is different as compared to renewable and long-term sustainable energy sources like hydropower, windmills, sun panels, etc. The same comparison can be made between nuclear energy and fossil fuels such as coal, oil and natural gas. Nuclear energy, in comparison with fossil fuels, gives rise to almost as good a carbon dioxide reduction as does energy from renewable sources. Consequently, nuclear energy might be labelled as semi-sustainable, that is, sustainable under certain conditions. The 'technical' aspects of this – management of the long-term liabilities – have been dealt with earlier in this paper. But the issue of sustainability also relates to the values held by stakeholders in our society. Since we discuss trans-generational issues, it is of particular importance to compile the views held by the next generation. Such data and their evaluations are therefore presented in the subsequent sections.

However, it should be noted in this respect that the intergenerational liabilities, and when prudently managed also corresponding cash-flows, may be highly different depending on the selection of energy source. Investments in energy sources like windmills or sun-reflectors are normally written off within one generation and the cost for dismantling is normally just a fraction of the original investment. Other major sources of energy may be used by two and up to three generations as is the case for hydropower plants, but they too have a relationship between investment and dismantling (disinvestment) where the latter is just a fraction of the former. This relationship is in principle valid for the renewable fuels and renewable energy production.

5.2 The field study

Sustainability is about the future, and about whether people in the future will experience an improved or a depleted basis for their existence. Of course, we cannot ask them, and consequently we have to rely on the adequacy of our own preferences.

There is, however, a possibility to get some information on the issue by asking people who are young today since they constitute the next generation decision makers. This is not often done, notwithstanding that surveys are typically carried out via paper forms that are sent out by ordinary mail. Since young people today communicate mainly by other means, the response rates are typically insufficiently low.

Consequently, the approach chosen in the present work comprises personal interviews of 1,444 persons and the response rate achieved is close to 100%. The first stage of the present work has been reported in Refs. [7, 8]. It was carried out during 2007–2008 in the Polish towns Gdansk, Lublin and Elblag. The second stage was carried out during the first part of 2010 in the towns Trnava in Slovakia and Jaworzno (Katowice), Poland.

In the first part of this study, in-depth interviews were conducted with the purpose to clarify if the questionnaire needed to be altered before the collection of survey data started. In this process, the questionnaire was used to retrieve information from the abovementioned stratified samples. In the first part of study, a total number of 780 answers where collected. In the second part an additional number of 660 answers were collected.

5.3 Analysis of the results and compilation of the findings

Some of the major results are presented in Tables 1, 2, 3, 4, 5, 6 together with the questions asked. These results will be evaluated in the following.

No difference was found between the genders. Also, no difference was found between the towns in spite of the fact that Jaworzno is a coal mining town that is surrounded with coal condensation

Table 1: Which form of energy do you prefer?

	City	Gdansk-Elbąg-Lublin		Trnava		Katowice (Jaworzno)		Sub SUM		SUM	
Answer	Gender	M	W	M	W	M	W	M	W	M + W	%
Coal		9	22	0	8	11	29	29	59	88	4.4
Nuclear power		168	115	77	56	31	42	276	213	489	24.7
Hydro power		182	181	52	122	33	60	267	363	630	31.8
Windmills		184	213	52	117	34	57	270	387	657	33.2
Miscellaneous		25	24	24	24	9	9	58	57	115	5.8
Total		568	555	205	327	118	197	900	1079	1979	100

Table 2: Who shall take care of the Swedish nuclear waste?

	City	Gdansk-Elbąg-Lublin		Trnava		Katowice (Jaworzno)		Sub SUM		SUM	
Answer	Gender	M	W	M	W	M	W	M	W	M + W	%
Sweden		348	344	51	112	155	267	554	723	1277	88.1
Other countries		46	48	18	13	19	29	83	90	173	11.9
Total		394	392	69	125	174	296	637	813	1450	100

Table 3: Can you consider having a site for final disposal of nuclear waste near to your home?

	City	Gdansk-Elbąg-Lublin		Trnava		Katowice (Jaworzno)		Sub SUM		SUM	
Answer	Gender	M	W	M	W	M	W	M	W	M + W	%
Yes		90	62	17	22	19	16	126	100	226	15.6
No		303	326	157	275	48	109	508	710	1218	84.4
Total		393	388	174	297	67	125	634	810	1444	100

Table 4: What is your opinion towards a site for final disposal of nuclear waste?

	City	Gdansk-Elbąg-Lublin		Trnava		Katowice (Jaworzno)		Sub SUM		SUM	
Answer	Gender	M	W	M	W	M	W	M	W	M + W	%
In favour		112	83	37	64	22	31	171	178	349	24.3
Against		179	209	82	158	33	61	294	428	722	50.2
Indifferent		100	96	51	75	12	33	163	204	367	25.5
Total		391	388	170	297	67	125	628	810	1438	100

Table 5: Which aspects are in your opinion crucial for the acceptance of a final disposal?

	City	Gdansk-Elbąg-Lublin		Trnava		Katowice (Jaworzno)		Sub SUM		SUM	
Answer	Gender	M	W	M	W	M	W	M	W	M + W	%
Safety aspect		210	232	96	165	52	104	358	501	859	38.4
Environmental aspect		143	166	62	123	41	86	246	375	621	27.8
Location aspect, as far from home as possible		118	146	29	69	36	77	183	292	475	21.2
Method and techniques		53	56	21	26	17	20	91	102	193	8.6
Economic growth		19	10	8	11	12	11	39	32	71	3.2
Miscellaneous		7	4	5	0	0	0	12	4	16	0.8
Total		550	614	221	394	241	445	929	1303	2235	100

power plants, and the town of Trnava is close to the nuclear power reactors on the Bouniche site. Two of these reactors have been shut down permanently and are thus in the transition phase for decommissioning and the others are still in operation.

First question: Which form of energy do you prefer? The data in Table 1 shows that the younger generation prefers energy production by sustainable sources such as hydro power and windmills.

Table 6: Which of these values do you base your opinion on?

	City	Gdansk-Elbąg-Lublin		Trnava		Katowice (Jaworzno)		Sub SUM		SUM	
Answer	Gender	M	W	M	W	M	W	M	W	M + W	%
Trust for the involved stakeholders		78	59	15	13	9	15	102	87	189	11.5
Opportunities linked to a disposal for nuclear waste		64	44	15	14	11	18	90	76	166	10.1
Lack of knowledge		120	149	57	154	22	67	199	370	569	34.6
Uneasy of the risks		157	193	81	123	29	67	267	383	650	39.5
Miscellaneous		34	22	7	0	3	6	44	28	72	4.3
Total		453	467	175	304	74	173	702	944	1646	100

The other items are also sustainable alternatives such as, for example, sun collectors, local methane gas production and terminal heat. On this question, 1,443 students ticked in 1,979 answers on the various alternatives.

According to these answers, the most popular energy alternative is windmills, which was preferred by 33% of the students. Hydropower was preferred by 32%, followed by nuclear power with 25%. Energy produced by coal (coal condense power plants) was seen as an acceptable alternative for only 4.4% of the respondents.

This data supports the statement that the younger generation has a preference for sustainable sources, while traditional sources such as coal and other fossil fuels have a low priority. Nuclear power might best be described as a special case since it is non-sustainable in a strict sense but has lower carbon dioxide emissions compared to the traditional fossil fuels. As many as one-fourth of the students accept nuclear power as an energy source.

Second question: Who shall take care of the Swedish nuclear waste? See Table 2. This question was asked to investigate the propensity of younger citizens to adopt and follow the PPP. The question is particularly relevant to Poland since it has long borders to the Baltic Sea, and since – according to the joint-convention – all neighbouring countries are to inform each other about major nuclear activities. Hence, Poland has a treaty-based right to be informed about nuclear waste management in the area.

The data presented in Table 2 supports the statement that younger citizens accept the PPP. It is noticeable that as many as 88% are in favour of what may be described as a strict application of PPP according to which every country takes care of its own nuclear waste. Another 12% can accept a joint handling of nuclear waste within Europe. The result is in accordance with the Swedish law that states that it is the operator/owner of a nuclear facility that has the full responsibility for the decommissioning and the waste management, and the Swedish strategy to finally dispose all nuclear waste within the country.

Third question: Can you consider having a site for final disposal of nuclear waste near to your home? See Table 3. The response to this question shows that the younger generation clearly prefers not to have a facility for long-term storage of nuclear waste near to their homes and living quarters. This view was held by 84% of the respondents.

Fourth question: What is your opinion towards a site for final disposal of nuclear waste? See Table 4. This fourth question is related to the third question but it is somewhat rephrased. In this case, the question is more general and does not relate to the homes of the respondents. In this case, it is possible to see that still more than half of the respondents are against a repository, and the group that are in favour have increased from 16 to 24%. Another major difference is that the level of respondents that says that they do not have any strong opinion in the subject is a little more than one-fourth. If the responses 'indifferent' were to be relocated to the two other groups, there would be around one-third that is in favour and two-thirds that still are against a repository for nuclear waste.

Fifth question: Which aspects are in your opinion crucial for the acceptance of a final disposal? The responses showed that 859 answers out of a total of 2,235, that is, no less than 38%, gave the response that the safety aspect is the most important factor to consider in the process of dismantling and decommissioning of nuclear power plant and associated handling of nuclear waste. The second most important factor is the environmental aspect with a total response frequency of 28%. On third place is the geographic localization to the nature that the disposal of nuclear and radioactive waste should take place as far as possible from home. This factor was stressed as crucial in 475 answers out of a total of 2,235 answers; hence, this factor may account for 21% of the total number of answers given.

Hence, in the aggregated sample, these three reasons are together given as an explanatory power of nearly seven-eights, or more exactly 87%. The factors techniques used (8.6%), economic growth or financial wealth (3.2%) and other explanations (0.8%) are less significant.

Sixth question: What values do you base your opinion on? See Table 6. The data shows that unease with the risks is the most frequent answer, and it comes from 40% of the respondents. The second most frequent answer is the lack of knowledge with 35% support. Next is trust for the stakeholder involved with 12% and then opportunities linked to a disposal of nuclear waste with 10%. Finally, the smallest group which account for 4.3% of the total gave other reasons for their views.

5.4 Conclusions and lessons learnt from the field study

The results and findings above illustrate how interviews can provide insight into the views and opinions of the next generation. Further studies might include prerequisites for accepting or rejecting a final repository near to one's home. Such prerequisites might include compensation given to the individuals directly or indirectly via the municipalities in the region.

It should be noted that that if compensation is given to facilitate acceptance for a repository in a region, the same amount must in turn be included in the nuclear waste liability. Actually, since we do not know whether the coming generations will accept repositories of waste near their homes, the general principle of prudence demands that the degree of acceptance are estimated and that appropriate accruals are made for this in the accounts of the companies. If the general situation is that there is a regional or national fund, an equal injection must be done to the segregated waste fund.

If one were to have a system for calculating the total cost for future management of the nuclear waste that also includes the estimated need for compensation to the coming generations for the negative effect of having a repository in the region, then it might be reasoned that any such compensation should be balanced against the contribution of nuclear energy to the reduction of the carbon dioxide emissions and thus mitigating global warming.

It was mentioned above that it is not possible to find any difference in opinion between the previous cluster samples from Gdansk, Elblag and Lublin compared to the clusters from Jaworzno just outside Katowice and the Slovakian clusters from Trnava. Thus, we have not found any data that might support the hypothesis that younger citizens should tend to favour regional energy sources on behalf of sustainable energy sources. The data indicates that younger citizens base their values on the risks connected to the handling of nuclear waste together with lack of knowledge and low efficiency in the knowledge transfer. This may be interpreted as a cautious and conservative view regarding the total risks.

Only 11.5% of the young citizens said that they based their opinion on trust for the stakeholders (cf. Question 6 and Table 6). At the same time, responses are high for unease with the risks together with lack of knowledge. This shows that concerns relating to protection of health and the environment, that is fundamental questions, have a higher priority than opportunistic issues like future benefits.

One of the most crucial criteria for acceptance of a repository for nuclear waste is that appropriate monetary resources have been accumulated in segregated funds. The basis of the associated calculations should include all costs today and in the future. The field study data that have been presented support the maxim that it is essential that this cost includes the assumed cost for compensation to the perceived drawback for future generations.

Another potential cost raiser for the future generations may be retrieval. If, for some reason, future generations find that they wish to manage already deposited waste in some other way, then there will be costs for retrieving it as well as costs for whatever new alternative that is to be implemented. It can be expected that the monetary resources in the segregated funds – in spite of the reserves for unexpected costs – will not be sufficient in such a scenario. It was proposed in the authority review of the programme for the management of the nuclear waste that the Swedish Nuclear Fuel and Waste Management Company published in 1989 that only 10% of the spent fuel in store should be deposited in a first stage, and that some years would be allowed to pass before the bulk of the waste was deposited. One of the reasons for this suggestion was that retrieval of 10% would be a manageable option also from a financial perspective.

Obviously, consensus will have to be found on the principles to be used for the evaluations of the nuclear liabilities, and implementers of waste disposal will have to come up with solutions and documentation that can not only be accepted in wide circles today but also stand the tests of time. If it can be concluded that the resources in the segregated funds actually correspond to the full nuclear liability, then nuclear energy may be accepted as a partially sustainable or semi-sustainable.

From a more practical point of view, it is possible to claim that the cost for compensating future generations can be a major cost driver, since it has been omitted in most calculations of future costs for decommissioning of nuclear facilities and management of associated nuclear waste.

6 CONCLUDING REMARKS

In spite of the fact that there are internationally well-accepted definitions on sustainability, the analyses and assessments carried out in different fields of technology are inconsistent and incoherent. This makes comparison difficult or perhaps even impossible. Therefore, generic methodologies are needed that enable comparisons to be carried out in a uniform and systematic manner. This requires that appropriately structured knowledge bases be established together with efficient modes for communication and knowledge transfer.

The sustainability of nuclear energy is not a matter of availability of uranium and efficiency in its utilization alone. It is also necessary that health and the environment are protected now as well as in the future. The protection in the future must be carried out in full compliance with the PPP. It is not necessarily required that the generation that benefits from the nuclear electricity also actually carries out the decommissioning of the nuclear facilities and permanently disposes all the waste. There may be good technical and economic reasons to operate nuclear facilities for longer than one generation. However, in such cases, the benefitting generations must leave behind the full technical solutions together with all the financial resources needed for adequate protection of health and the environment. So far, and in the case of Sweden, this has meant green field conditions.

The analysis in a historical perspective shows that sustainability awareness may well appear in the form of trends. This calls for comprehensive and systematic approaches based on appropriately structured knowledge bases as well as sufficient ingenuity to identify qualified candidates for future trends.

It is a natural element of human nature as well as human culture to care about the offspring and to leave behind a better basis for existence. Such action might, however, be impeded by short-term rewards, perhaps only to a few individuals, for example, exaggerated emphasis on quarterly reports by institutional investors or managers hungry for bonuses. The concern for descendants is not unconditional. Research suggests that an individual will sacrifice consumption to benefit future generations only if a guarantee exists that others will do the same [57]. This implies that bodies are required as ombudsmen for the public to ensure general compliance. Such solutions are proposed in Ref. [57].

Planning for decommissioning and waste management, together with the estimation of associated costs, has proven to be treacherous. Therefore, careful analyses are needed to obtain the precision required. This includes radiological surveying, selection of techniques to be used and identification and evaluation of potential cost raisers. It also includes sharing of lessons learned and comparison with already completed projects. The timing of such evaluations is governed by the needs for financial planning, and this may imply that the technical planning must be carried out many years, perhaps decades, before the plans may be needed for the actual decommissioning work.

It is thus the duty of our generation to act as ombudsmen for the future generations, and to ensure that levels of protection are established, that responsible solutions are found and that adequate funding is set aside. Since we cannot ask them, the best we can do is to protect future generation to at least the same level as that which applies for us who live today.

We do, however, have access to the next generation. It is therefore imperative that we learn about their values and carefully consider what they share with us. It is likely that the perspectives and requirements will be different in the future, and we should strive for solutions that have good prognoses for standing the ultimate tests of time. For instance, it is only 40 years since Sweden participated in a sea-dumping campaign that was carried out under the auspices of the United Nations. Such a practice is far from acceptable today.

Robust solutions require knowledge transfer to and dialogue with stakeholders, in general, and younger stakeholders, in particular. It is also important that information be passed on to future generations. The process should be in compliance with the requirements of the society, which, in turn, should support the process, for example, in terms of funding of financial resources and information about nuclear waste liabilities.

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*SKI = Swedish Nuclear Power Inspectorate, now Swedish Radiation Safety Authority (SSM). Reports are available at www.ssm.se.