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ILK Statement

on the Utilization of Nuclear Energy in Germany

Für deutsche Fassung bitte umdrehen!

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Foreword

The International Committee on Nuclear Technology (Internationale Länderkommission Kerntechnik, ILK) was established by the three German states of Baden-Württemberg, Bavaria and Hesse in October 1999. It is currently composed of 13 scientists and experts from Finland, France, Germany, Sweden, Switzerland and USA. In its capacity as an independent and objective advisory body to the German states on issues related to the safety of nuclear facilities, radioactive waste management and the risk assessment of the use of nuclear power, the ILK aims in particular to make an important contribution to the assessment of the future viability of nuclear power in Germany.

Against the background of an expected steady rise in the electricity demand and of economic and ecological challenges it is necessary to establish a course of action for the electricity supply up to the year 2020. In doing so, the issue of the utilization of nuclear energy has to be taken into account. Therefore, the ILK has dealt with the sustainability of electricity supply scenarios and the necessary safety-related framework conditions for the continued utilization of nuclear energy. The results are presented in the current statement on the utilization of nuclear energy in Germany, which was adopted at the 38th ILK meeting on November 14th/15th, 2005 in Landshut. The ILK concludes that the contribution of nuclear energy to a sustainable electricity mix is indispensable. The safety of nuclear energy is ensured and is continually tested. Progress in solving the disposal issues can be swiftly achieved.

This statement is addressed to the German state authorities in their function as the commissioning party of the ILK, and also targets the federal authorities, licensees, political actors and the general public.

The chairman

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Statement

Executive Summary

The contribution of nuclear energy to a sustainable electricity mix is indispensable

- Against the background of an expected steady rise in the electricity demand and of economic and ecological challenges as well as technological developments, which can be more realistically assessed today, it is necessary to establish a course of action for the electricity supply up to the year 2020 and beyond.
- The selection of future electricity supply technologies should, in addition to technological factors, strive to meet the objectives of sustainability, i.e., of economic, ecological, and societal objectives in a balanced manner and cover the whole life-cycle of each technology. The ILK has offered a model for this assessment.
- The sustainability assessment of available electricity supply technologies shows that no technology satisfies all objectives in an ideal way. Nuclear energy exhibits very good economic and ecological performance parameters. However, its assessment in terms of societal factors is not as good.
- To ensure competitiveness, guarantee supply security, and attain the Kyoto goals, the contribution of nuclear energy to a sustainable electricity mix is indispensable; a stable political basis should be established and a higher public tolerance should be encouraged.
- Regarding the often favored expanded use of wind energy, its stochastic nature, the costs of necessary reserve capacities ("shadow power plants" with CO_2 emissions) and the maintenance of grid stability need to be taken into account.

The safety and security of nuclear energy is ensured and is tested continually

- Numerous internationally accepted processes provide for a continual assessment and maintenance of nuclear safety at a high level. These processes include periodic safety reviews, the assessment of safety management and safety culture, aging management, and maintenance of staff competence.
- These processes and safety-related backfits have led to an excellent safety record of the German nuclear power plants, which is reflected in the substantial decrease of the residual risk of hypothetical accidents.
- Opportunities to improve plant safety, especially for reducing risks from hypothetical severe accidents, should continue to be pursued - preferably by reaching agreement between the regulatory authorities and the licensees, with due attention to the appropriateness of the proposed measures.

- German nuclear power plants are protected against terrorist actions by the existing design, additional security measures undertaken by the licensees, and national precautionary measures. All these measures decrease the attractiveness of nuclear power plants as targets.
- The threat of proliferation ensuing from the use of nuclear energy in Germany is very low due to the applied safeguards and international monitoring.
- Education at universities and corresponding research in the field of nuclear engineering and the active participation of German institutions in international research initiatives should be promoted. Thus the implementation of new findings in nuclear technology can be achieved and innovative plant concepts can be elaborated in Germany also in the future.

Progress in solving the disposal issue can be swiftly achieved

- The concept of two separate final repositories should also be maintained in Germany. It is firmly rooted in international practice.
- National and international peer reviews of a final repository for high-level radioactive, heat generating waste at Gorleben have so far not questioned its suitability. For this reason, the moratorium should be lifted, the underground site exploration of Gorleben should be resumed and a total systems performance assessment should be undertaken.
- The construction of the Konrad repository, which is a licensed final repository for non-heat-generating radioactive waste, should begin as soon as possible.

The Atomic Energy Act should be updated and the regulatory system should be reviewed

- Due to their excellent safety record, longer operating periods of nuclear power plants should be allowed. For operating periods exceeding 40 years, a special safety review and assessment should be carried out.
- The regulatory oversight system should be evaluated by a peer review panel with international expert participation. The comparison with current international practice, for example, regarding the independence of the regulatory body and the implementation of a risk-informed and performance-based oversight, should be used for improving the current system.

1 Introduction

The following evaluation takes a look at future electric power supply in Germany and in particular the potential role of nuclear energy within a sustainable electricity mix. Due to the global reach of the energy issues (e.g., availability of resources, climate change) and the interconnectedness of electricity markets (the EU is aiming for an internal competitive market), developments and assessments from outside Germany are also taken into account.

1.1 Setting the scene

Germany should strive for an appropriate growth, both from a national perspective and also in order to help implement the Lisbon-strategy of the EU ("most competitive and dynamic knowledge-based economic zone in the world"[1]). The "Green Paper" [1], [2] of the European Commission uncovers large structural flaws in the energy sector and addresses the necessity of strategic decisions in the coming years, addressing issues of

- competitiveness (removing the barriers to the proper functioning of the energy market);
- security of supply (reducing the dependence on energy imports, in particular from geopolitically sensitive regions, which is projected to be 70% in 2030) and
- "environmental protection / sustainable development" (primarily fulfilling the Kyoto protocol or even more stringent CO_2-reduction requirements).

The development of less polluting energy sources is one of the goals and nuclear energy is explicitly included as an option.

The European Economic and Social Committee [3], [20] stated that nuclear energy is indispensable in the medium-term and should be kept open as an option until new technologies are available, e.g., nuclear fusion, and thus should be maintained for at least the next 30 to 50 years. Key problems, such as protection against accidents, residual risk minimization, decommissioning and waste management / final disposal, should be approached in a "harmonized" way, ensuring a high level of safety and healthy competition via operating rules.

[1] Quotation from "Presidency Conclusions" at the special meeting of the European Council in Lisbon on March 23/24, 2000

In addition, from a technical perspective[2] and an organizational standpoint[3], international developments can be observed that are significant to the assessment of nuclear energy and its utilization in Germany.

The ILK takes the above aspects into account and focuses especially on the sustainability assessment of electricity supply options and an assessment of the safety of nuclear systems and the framework of its utilization. These topics lie within its scientific competence. The statements on the electricity demand and the reflections on supply scenarios are based on external expertise.

1.2 Electricity supply in Germany: Current status and future outlook

Over the past decades and up to now, Germany has been able to produce electricity to cover its own demand, unlike some other European countries [7]. However, while Germany also delivers electricity to other countries, the volume of these exports is very small and much lower, for example, than the electricity exports by France [7]. The general approach as a self-reliant electricity producer has proven successful in terms of the positive effects on the domestic job market and the security of the national electricity supply and is rarely called into question. It will be assumed for this study that Germany will not become a net importer of electricity in the near future.

Electricity demands in Europe will continue to grow: In the EU, the annual increase for the next years is expected to be in the range of about 1,6% and about 2,2% for the new member states, while for the EU-15 states increases in the range of 1% [8], [9] are projected. According to some sources [9], the resulting demand for replacement and new plants is judged to be around 300 GWe by 2020 with replacement plants representing 2/3 of this demand.

For Germany, projections on future electricity demand forecast only small increases [10] or even a stable demand. This is due to the current economic situation as well as increased electricity savings and efficiency in industry and private households. However, a drop in demand for electricity is not expected in the near future; the supply gap[4] caused by phasing out nuclear energy will therefore not be avoided by a drop in demand alone.

[2] E.g., European utility requirements [4], development and construction approval of EPR

[3] E.g., Convention on Nuclear Safety of the IAEA [5], WENRA requirements [6]

[4] Today's share of nuclear is 28% and of renewables 9%. DENA [19] projected wind energy production in 2015 to be 77,2 TWh compared with the nuclear energy production in 2004: 167 TWh. Even if the share of renewables were to increase to 20% in 2020 (as politically envisaged), this would not come close to compensating the loss resulting from the phase-out of nuclear energy

The electric power industry will continue to face challenges, e.g., increasing economic pressure due to the liberalized market, greater importance of the security of supply with energy resources (e.g., natural gas) and price increases, which are unevenly distributed among the different technologies and are difficult to predict. In addition, ecological challenges have emerged over the past decades and will continue to have a major, possibly increasing influence (e.g., even stricter measures against the rise of CO_2 emissions).

Against this background, it is necessary to establish a course of action for the medium-term electricity supply, in particular up to the year 2020. Such an evaluation is more realistic today due to the fact that some technological developments, particularly in new technologies (e.g., wind, solar and biomass) and the impact of political measures, can be much better assessed than some years ago. Currently, the potential of CO_2-capture and storage, e.g., in exploited gas or oil fields, is being discussed with regard to electricity supply from fossil energy carriers. However, the ILK views a grand-scale utilization of this technology as unlikely to happen within the timeframe under discussion and will therefore not give it further consideration in this statement.

In order to evaluate a course of action, the ILK assessed the impact of two potential electricity mix scenarios for Germany, which were presented in a recent study by the VDE [18] (see section 2.4).

There are certainly different approaches when it comes to the question of which technologies to choose from for supplying electricity. In the view of the ILK, in addition to economic considerations that have dominated the debate thus far, ecological constraints as well as societal perceptions have to be taken into account from the start for formulating a future-oriented energy policy. These considerations in turn influence the legal framework in which decisions on future power plants are taken. Therefore, the ILK proposes to evaluate future electricity supply technologies and mixes based on the three dimensions of sustainability (see below).

2 Sustainability

2.1 Sustainability assessment of electricity supply technologies

The concept of sustainable development is defined by the capability to "meet the needs of the present without compromising the ability of future generations to meet their own needs" [11]. As in most approaches to a sustainability assessment, the ILK applies the three dimensions of economy (e.g., guaranteeing the security of supply and „affordability“), environment (e.g., protecting natural resources and climate), and societal well-being (e.g., contributing to social peace), since in this way all relevant aspects can be covered in a balanced and non-discriminating manner. These dimensions should be operationalized using generally acknowledged criteria and quantifiable indicators. Although several organizations, e.g., UN[5], IAEA or OECD, have been working on this subject, a generally acknowledged set of specific indicators for the field of electricity supply technologies currently does not exist. The ILK has thus established a methodical approach [12] based on a study by the Paul Scherrer Institute [13] for comparing electricity supply technologies for Germany.

The intention of this instrument is to enable a broad sociopolitical discussion of the various electricity supply technologies with reference to the aspect of sustainability. It covers the whole life-cycle of a technology, not just power generation as such, but also the preceding extraction, processing and manufacturing steps of (raw) materials and equipment, as well as the final waste management.

For aggregation of the various, very different indicators, a multi-criteria decision analysis (MCDA) approach has been proposed, thereby allowing for stakeholder preferences and securing a high degree of transparency. This method has the side effect that unfavorable properties of an energy carrier in one dimension can be compensated by favorable ones in other dimensions. For example, some aggregations show relatively good results for solar energy in spite of exorbitant high production costs of 60 cent/kWh. Other models for aggregation are often restricted to total costs assessment and do not adequately take societal aspects into account.

The comparative and comprehensive approach of the ILK follows the view that - in all probability - no single technology can meet all the principles and indicators in the best possible way and thus can provide an "optimal" electricity supply. Therefore the pros and cons of available technologies have to be considered and should be broadly discussed prior to a decision. The model proposed by the ILK is one pos-

[5] Commission on Sustainable Development (CSD)

sible framework for such a discussion that may provide quantitative insights into the impact of various assumptions and conflicting viewpoints on the overall desirability of a particular technology.

The ILK model was applied to electricity supply technologies currently in use in Germany, assuming average performance characteristics of these technologies. The evaluation extends to the full energy chains of fossil (lignite, hard coal, oil and natural gas), renewable (hydro, wind and solar (photovoltaic)) and nuclear energy carriers. Due to the unavailability of specific data, it was not possible to include biomass as an electricity supply technology.

The ILK provided weightings in the aggregation process that it regarded as suitable from its "stakeholder-perspective". Discussions with experts [14] showed considerable support for this approach and a great potential for consensus.

It would in principle be possible to apply the ILK sustainability model to future electricity supply technologies in Germany. However, such an assessment requires a sound scientific and prognostic determination of the large amounts of data for the corresponding technological development - these data were not available. Nevertheless, influences on conclusions can at least be shown in a qualitative way (cf. section 2.4).

2.2 Characteristics of nuclear energy

The results obtained for the complete set of indicators for the various energy technologies[6] are listed in Appendix 1. It should be noted that some of the indicator results are associated with substantial uncertainties; however, these results may be sufficiently accurate for comparative purposes, e.g., establishing a preliminary ranking order. They also provide a basis for addressing the strengths and weaknesses of specific energy technologies/technology chains ("pros and cons"), all from a purely sustainability point of view. Favorable and less favorable aspects of nuclear energy are as follows:

➡ Nuclear energy is characterized by very high scores on economic indicators:

- Production costs that are the lowest for all technology options, partly due to potentially long plant operating periods (40 and more years of operation), very high availability (exceeding 85%) and low fuel price sensitivity[7].

[6] major assumptions: NPPs amortized; wind and solar installed without costs for reserve (backup) capacities

[7] The production costs would only increase by 9% if the fuel price were to double[48].

Note: The already internalized costs for dismantling nuclear plants and final disposal of radioactive material but are unlikely to challenge the top ranking of nuclear energy for production costs. Investments into new plants may result in higher production costs, however, nuclear will even then remain one of the most favorable options.

- Very satisfactory security of fuel supply.
  Note: Large uranium resources are distributed throughout the world[8] and are therefore less vulnerable to negative geo-political developments; the fuel is easily storable and, in addition, future advanced fuel cycle technologies might also improve this aspect.

➡ Nuclear energy is characterized by very high scores on environmental indicators:

- Very low CO_2 emissions and air pollution, thus having a significant effect on avoiding global warming.
  Note: When employing a life-cycle analysis, the specific emissions are even comparable to those of wind energy and much lower than for solar energy.

- Low risks associated with normal operation and accidents.
  Note: This is due to the barely existent detrimental effects of operating releases on general public health and the very low frequency of severe accidents.

➡ Nuclear energy is characterized by unfavorable scores on societal indicators[9]:

- Extraordinarily long necessary confinement times for radioactive waste.
  Note: The construction and use of final waste repositories may cut down the importance of this aspect in the public perception. Future advanced fuel cycle technologies (partitioning and transmutation of actinides) could lead to a substantial reduction in the necessary confinement times.

- Proliferation as a specific negative aspect.
  Note: The threat of proliferation ensuing from the use of nuclear energy in Germany is very low due to the applied fuel cycle safeguards and international monitoring by the IAEA and EURATOM. The importance nevertheless associated with this topic in public opinion could diminish with future advanced fuel cycle technologies.

[8] About 30% of all uranium reserves are located in Australia; other countries with high uranium resources are Canada and Kazakhstan (ca. 15%) and South Africa (ca. 10%).

[9] The societal indicators and their weights reflect to a large extent perceptions of the population, e.g., risk aversion, which may change independent of technical developments.

- Risk aversion against electricity supply technologies most pronounced for nuclear energy.
  Note: Singular events such as Three Mile Island and Chernobyl have greatly worsened public perception. The perceived risk and acceptance seem not to be affected by further reductions in the risk figures. Instead, they may depend on factors like the non-availability of better alternatives, the increase in energy prices and the changing attitude towards other technologies.

- Perceived vulnerability of nuclear power plants to terrorist attacks[10].
  Note: Not only are German nuclear power plants protected against terrorist attacks by the specific plant design, but also by additional measures of the utilities, air lines and the State. However, many of these measures are not publicized and therefore do not have an influence on public perception.

- Anticipated high mobilization potential of nuclear opponents[10].
  Note: The use of nuclear energy is not accepted by a certain part of the population. Special events (e.g., nuclear transports to Ahaus and Gorleben) have frequently triggered large and sometimes violent public demonstrations accompanied by a resulting coverage in the media.

In addition to this sustainability assessment, it is worth mentioning that nuclear energy has shown to be well suited for reliable and secure electricity supply on a large scale (in Germany almost 30% share of electricity supply, unplanned non-availability < 5% [15], [16]). Due to its cost structure (low variable costs), it is especially advantageous for base load supply; in addition, the siting of nuclear power plants can be well adjusted to the requirements of a stable grid (production close to consumers). Nuclear energy uses up raw materials that are presently either in sufficient supply or cannot be used for other purposes.

2.3 Aggregation of results

The indicators need to be aggregated to single specific values to provide a more user-friendly input for overall assessments and related decision-making processes. Such aggregated single values have been calculated by the ILK [12] using total cost consideration and, alternatively, the multi-criteria decision analysis (MCDA). The total costs covers the internal (production costs) and external costs (even including the impacts of severe accidents or global warming). However, they neglect impor-

[10] These two aspects belong to the societal dimension, however, they were not sufficiently or not yet incorporated in the sustainability assessment of the ILK [15]

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tant societal criteria. Applying the second approach, the MCDA, a linear normalization of all indicators is undertaken, followed by a subsequent weighting of the indicators among each other and of the three dimensions (economic, environmental, societal) of sustainability. The resulting ranking remains quite stable given a "moderate" variation of the weights. The benefits of applying MCDA reside in considering all criteria and, at least partly, different preferences of stakeholders involved.

Based on the MCDA [12] it becomes obvious when looking at the specific results for each of the three dimensions that no single electricity supply technology satisfies all sustainability criteria in an "ideal" way. However, regarding overall performance[11], hydro and wind energy achieve the best results, while nuclear energy takes the third best position, along with natural gas (the highest ranked fossil-based electricity supply technology).

Looking at the overall result, nuclear energy exhibits excellent economic as well as environmental properties under German conditions (see section 2.2). However, it is also confirmed that its ranking within the societal dimension is not high.

The above assessment does not take into account the extent to which each technology can ensure a reliable electricity supply. For instance, the potential of water energy is already used to a large extent in Germany.

2.4 Preferable electricity mix for 2020

As there is no single electricity supply technology available that is able to optimally fulfill all sustainability criteria and that is capable of covering most of the base and peak load on its own, a reasonable mix of technologies must be aimed at ensuring future electricity supply. This may sound trivial, in particular as this aim also follows the widely accepted rule of diversification [3]. However, this also means that the "best" future electricity supply mix is heavily influenced by the emphasis that is placed on certain aspects. A mix based on predominantly economic objectives will be different from one which highlights the environmental dimension.

From the multitude of potential electricity mix scenarios, the ILK takes two scenarios described by the VDE [18] for demonstration purposes. The aim of this VDE study focused on the impact of an increased utilization of renewable energies. According to this study, the share of renewables will increase from currently 5% to ca. 25% in the year 2020 for both scenarios. Scenario 1 of this study assumes a continued phase-out of nuclear energy, while scenario 3 is based on the aim of dramatically

[11] Equal weight has been given to all three dimensions; weighting factors for indicators are based on best judgment; all are subject to changes within certain constraints.

reducing CO_2 emissions; this will lead to a continued utilization of nuclear energy at the current level and a reduction of electricity supply from fossil energy carriers[12]. The assessment criteria were primarily the necessary costs for investments and the CO_2 emissions of each scenario.

Since the VDE study [18] does not cover all elements of sustainability and in particular does not look at all parts of production costs and the societal dimension, the ILK has undertaken a more comprehensive sustainability assessment of these scenarios from its perspective. As was mentioned before, the work by the ILK [12] was restricted to individual current technologies and did not include an evaluation of a possible mix. However, a qualitative appraisal of the sustainability of the indicated scenarios is possible. In so doing, an evolutionary progression is assumed for all technologies. Revolutionary technological changes are not evident particularly when taking into account the long design and construction periods especially for large-scale deployment of a technology. However, the societal assessment of electricity supply technologies may change independently of technological developments; these are not foreseeable and therefore a change of the collected data will not be assumed.

A combination of the sustainability indicators for individual (current) technologies based on their share in the electricity supply in the year 2020 according to [18] leads to the following comparative statements on the two "extreme" scenarios 1 and 3 if the ILK model is applied:

- Scenario 1 (Phase-out of nuclear energy)
  The assumed "replacement" of the current share in electricity supply by nuclear energy in roughly equal parts by renewables and natural gas, i.e., 25% and 22% respectively, when compared to the current state leads to poorer economic results while the environmental scores stay constant. The negative aspects of nuclear energy, including proliferation, long confinement times of high level radioactive heat-generating waste and risk aversion, would be avoided in this scenario, which would improve the societal dimension of sustainability and therefore societal acceptance. The benefits of nuclear energy in terms of production costs and CO_2 emissions can not be realized in this scenario. This tends to be supported by the result of the VDE-study [18]: According to scenario 1, the phase-out of nuclear energy will lead to 300 million tons of CO_2 emissions in the year 2020 and will cause total investment costs of € 123 billion; both values are higher than those for scenario 3 (see below).

[12] The scenario 2 of this study [18] looks at a cost-optimized interim solution, which results in a slowing down of the phase-out of nuclear energy; however, this scenario will not be covered by the ILK.

- Scenario 3 (Nuclear energy as part of the electricity mix)
  Keeping nuclear energy at the current level and reducing the share of traditional fossil fuels in favor of a higher share of renewables (and natural gas), when compared to the current state leads to better results in the areas of environment and society, but (also) to poorer economic results. Compared to scenario 1, slightly higher economic and considerably higher ecological scores are achieved, however, the score for the societal dimension is not as good. The beneficial and negative aspects of nuclear energy and renewables compensate each other in some areas (e.g., production costs, risk aversion), while in other cases, e.g., sensitivity to fuel price increases and CO_2 emissions, their benefits are doubled. This corresponds with the results of [18], whereby the continued utilization of nuclear energy will lead to a reduction of CO_2 emissions down to an amount of 200 million tons and the total investments will be € 100 billion.

On the basis of this assessment and in particular due to the distinct reduction in CO_2 emissions, scenario 3 and therefore the continued utilization of nuclear energy, coupled with an increased utilization of renewables, turns out to be the preferable option.

Since all covered scenarios include an enhanced role of renewables, referring mostly to wind energy, a closer look at the effects of an increasing share in the electricity mix is provided[13]:

- Due to the stochastic nature of wind - and also of solar - energy, they do not possess the capability to provide the base load of electricity on their own. The guaranteed capacity of wind energy corresponds to an average share of about 6% of the installed capacity[14], i.e., 10 GW installed capacity correspond to only 600 MW statistically guaranteed capacity.

- The necessary stability of the electricity grid will require an extension of the transmission network. The resulting costs are estimated at € 1.1 billion up to the year 2015.

- Since most future wind energy parks are planned to be placed offshore in the north of Germany, an additional extension of the electric grid is necessary to connect these sites with the national electricity grid. The costs for this amount to € 5 billion by the year 2015.

[13] The arguments are mainly based on [19], a study financed by associations and private companies in the energy sector (including wind-power) as well as by the Federal Ministry of Economy and Labor, thus supported by as many stakeholders as possible. This study assumes an increase of the installed onshore wind capacity from currently 14,5 to 26,2 GW in 2015 and of offshore wind capacity from currently 0 to 8,4 GW.

[14] The guaranteed capacity refers to a level of reliability of energy supply of 99%.

The last two aspects pose the greater challenges the more the use of wind energy is expanded and furthermore additional costs (e.g., subsidies).

In summary, the application of the ILK model, proposed for assessing sustainability of all electricity supply technologies, has shown that no technology satisfies all objectives in an ideal way. Nuclear energy is a valuable electricity supply option which should not be abandoned when taking the dictum of sustainability into account. Its low production costs, its security of electricity supply, and its overall independence of increasing fuel prices promote a stable economic development. Furthermore, it helps to realistically achieve the Kyoto-targets and to meet even more restrictive CO_2 emission standards.

Special efforts should be undertaken to inform the public and stakeholders about the importance of the continued use of nuclear energy in a transparent and non-discriminating manner and to let them participate in the decision-making. This may lead to an increased acceptance of, or, at least, tolerance regarding the use of nuclear energy.

These results and recommendations are in agreement with the "Green Paper" of the EU-Commission [1].

3 Safety-related framework for the continued utilization of nuclear energy

Despite the attractiveness from the point of view of a sustainable electricity mix, a continued use of nuclear energy can only be justified if a sufficiently high level of plant safety and security can be ensured. Besides technical issues, e.g., aging of components, and a potential loss of technical competence, changing contextual factors have to be taken into account, such as the constraints of a liberalized market. The latter create an additional pressure on costs for operation and maintenance and lead to changes in the corporate and organizational structure. In addition, progress needs to be made with regard to waste management issues. In the following, ILK will focus on these topics as they lie within its scientific competence; purely political, legal and socio-economic issues will not be addressed.

3.1 Safety of nuclear power plant operation

3.1.1 Verification and preservation of safety

The licensees bear the responsibility for the safety of their plants. The regulatory authority, in turn, ascertains whether the licensees fully meet their high responsibilities. Some of the tools and methods being applied to regularly assess the safety of each NPP are addressed as follows.

Periodic safety review

Besides continuous oversight by the authorities, an important tool for ensuring a high level of safety is given by the periodic safety review (PSR) [21], [22]. This is carried out for each plant at intervals of 10 years[15] and represents an investigation of its current safety and security status.

The existing safety precautions are assessed using both deterministic (with regard to the protection goals to be achieved) and probabilistic means (probabilistic safety analyses (PSA) for determining the frequency of hazardous conditions). This combined approach enables the required assessment of the existing safety status and, furthermore, can point out in which areas improvements are reasonable.

For all German NPPs, a first PSR - mainly performed on a voluntary basis - has been carried out and further safety reviews are under way or are scheduled for the coming years [23]. At the same time, the corresponding PSR guides [21] are currently undergoing review and are expected to include the evaluation of shutdown operating modes, accident management measures, external events and possibly the addition of level 2 PSAs.

Safety management and safety culture

Next to technical equipment, organizational measures targeting safe operating management and safety culture are highly significant for maintaining a high level of safety. They have undergone a constant evolution and gained more importance over the past decades.

[15] Note: these intervals do not correspond to 10, 20 or 30 years of plant operating time. The specific dates for each individual plant are stipulated in the German Atomic Energy Act [23].

According to current IAEA and INSAG standards and guidelines ([24], [25], [26] and [27]), the safety management system, in general terms, aims:

- to improve the safety performance of the organization through the planning, control and supervision of safety related activities in normal, transient and emergency situations;
- to foster and support a strong safety culture through the development and reinforcement of good safety attitudes and behavior in individuals and teams so as to allow them to carry out their tasks safely.

A good safety management and safety culture may become evident in, e.g., a clear safety policy which demonstrates the organization's commitment to strive for a high safety performance. Requirements on the sufficiency and competency of staff, effective control and planning of work, as well as a rigorous root cause analysis of events should be included as well. The root cause analysis includes organizational aspects and human performance, resulting in appropriate corrective actions. Additional elements of a good safety management are a self assessment system that addresses organizational and personnel aspects and audit and review systems which provide feedback on safety performance.

German licensees have already implemented safety management systems and safety culture self-assessment systems, both of which are or have been recently reviewed by the regulatory authorities (see also [28]).

Aging management

The question of how long NPPs can safely be operated while maintaining a high safety standard has been intensively discussed by experts in recent years ([29], [30]). Together with the experience gained in terms of operation and research, no phenomena relating to plant safety features were found that would make a general limitation of the operating period necessary.

Effective control of aging degradation is achieved by means of a systematic aging management process consisting of the following tasks that are based on an understanding of the aging of structures, systems and components [22]:

- Operation within operating guidelines with the aim of minimizing the rate of degradation;
- Inspection and monitoring consistent with the applicable requirements with the aim of the timely detection and characterization of any degradation;

- Assessment of the observed degradation in accordance with appropriate guidelines to assess integrity and functional capability;
- Maintenance (repair or replacement of parts) to prevent or remedy unacceptable degradation.

Aging phenomena are registered and dealt with in the German plants in various ways. All of these activities, which include, e.g., the documentation and the use of experience from maintenance and recurrent inspections, are de facto part of an aging management system. They are not always performed according to a standardized and comprehensive approach, but are often event-based, which led to a recommendation to install a systematic and comprehensive aging management at the German plants [30].

Backfit measures

The design provisions for safety and safe operation of a plant follow the basic concept of defense-in-depth. The overall goal is to prevent accidents wherever possible through the design and operation of NPPs, and, in the unlikely event of an accident, to control the reactor through engineered safety systems and operational systems reliably in order to maintain fuel integrity also in such conditions.

These measures and procedures were necessary conditions for licensing. Although the original design and operation of the plants have been considered to be safe enough, their safety has been continuously improved over the course of time. This is a result of using the operating experience, probabilistic safety assessments, and the evolution of the general state of the art in science and technology. In addition, significant advances in reactor safety technology have led to an increase of licensing requirements - and utility requirements [4][16] as well - for new plants coupled with a corresponding improvement of their safety provisions.

Plants already in operation have been able to keep up with this development to a large degree, since the utilities have provided additional measures beyond the original design base of safety systems in the last decades for further risk reduction [31]. A prominent example is the requirement that the consequences of a core melt accident must be largely limited to the interior of the plant. Even though this requirement cannot be met completely with the buildings of the current plants, the risk posed by such a postulated accident was, however, decisively reduced by internal accident management measures. This was achieved by taking precautions to avoid

[16] The European utilities requirement (EUR) document was being developed by a group of major European electricity generating companies, including VGB Powertech, an association of German power generating utilities.

a core melt even in the event of a failure of the safety system and by taking measures to prevent containment failure types with large early releases. These include primary and secondary side pressure relief and feeding (bleed-and-feed), elimination of hydrogen gas that arises during a core melt until a safe concentration has been reached and the filtered depressurization of the containment vessel. Such measures were suggested in the past by the Reactor Safety Commission (Reaktorsicherheitskommission, RSK) and implemented by the utilities even in the absence of a requirement issued by the authority.

Recent examples of backfit measures include measures to prevent clogging of sump suction strainers and improved quality assurance of fuel elements.

In sum, experience to date shows that, beyond the preservation of status quo, the existing plants were able to achieve substantial improvements in safety. The core damage frequency as well as the frequency of a large release of German NPPs have been demonstrably decreased significantly over the past decades.

International cooperation

The ILK has already dealt with the international cooperation of the regulatory authorities and research organizations in separate documents ([32], [33], [34]).

German operators participate in international exchange of operating experience, especially through the programs offered by the international operator association WANO. These programs provide participants with an opportunity to learn from each other's collective experiences in order to help further improve plant safety and reliability. For example, in recent years, German NPPs participated in an exchange of experience on topics such as safety culture, human performance, PSA application and maintenance staff training.

International comparison of safety performance indicators and operating experience

The nuclear industry's pursuit of improving the safety of its installations is confirmed by the operational safety reviews (OSART) of the IAEA, which in 2004 also included Philippsburg Unit 2. An overall improvement was certified for the areas of safety management, industrial safety and plant material conditions. Internationally, the number of significant (notifiable) events remains low and additional emphasis has been given to a detailed analysis of operating events in order to gain insights for human performance enhancements.

In addition, international peer reviews were carried out in German NPPs by WANO,

for example in Neckarwestheim in 2001 and ISAR 1 in 2003; Biblis follows tentatively at the end of 2005.

These reviews provide an independent assessment of the effectiveness of the safety management system and its implementation against external best practices. Appropriate corrective actions are identified and implemented in response to audit and review findings and objectives for improvements are identified as part of a continuous process.

The performance of the World nuclear power plants as measured by WANO Performance Indicators has steadily improved over the past decade.

Training and maintaining competence

According to the IAEA [35], the issue of maintaining competence has been identified as one of the problems facing the manufacturers, the utilities, the regulatory bodies and their technical support organizations. This is not limited to countries where nuclear power is stagnant or declining but, instead, is a challenge for the entire nuclear community. In addition, research and education have to attract future professionals to this field. An aggravating factor is that in the meantime many universities have reduced or eliminated their support for the study of nuclear science and engineering.

With an aging workforce, the need for the renewal of skills will become more pressing for all the organizations active in the nuclear field, both the utility itself as well as subcontractors. Systematic programs to compensate for loss of knowledge, especially through retirement, have to be developed and applied. This requires:

- a considerable forward planning to allow the establishment of a medium- and long-term outlook concerning the necessary resources for each profession;
- creative methods and techniques in education, training and applications of quality management processes to ensure that the knowledge, skills and abilities from the current generation are transferred to the work force of the future.

Regarding research and education, there has been a continuous decrease for some years in Germany. While companies have been active in the design of new reactor types (e.g., EPR), the last German NPP was ordered over 20 years ago. The phase-out of nuclear energy according to the German Atomic Energy Act has further accelerated the trend towards reduction in research funds and educational programs at the universities.

The ILK [32] deems it is necessary to adapt the supply to current and emerging requirements in a targeted manner, e.g., using the following measures and initiatives:

- Build-up of regional and supraregional competence centers under the auspices of the national Alliance for Competence[17] in nuclear technology;
- Research support programs for universities with an increased cooperation between universities and research centers, including external financing of university chairs and sponsoring of students;
- Promotion of university infrastructure for an education in nuclear engineering, including the creation of university networks and the content diversification of nuclear engineering degrees.

Recently, there have been some positive developments as well. The Technical University of Munich has set up a new chair in nuclear technology and is offering a new Master's degree in nuclear technology in cooperation with the Institut National des Sciences et Techniques Nucléaires (INSTN) and the École Centrale in Paris. The University in Stuttgart intends to reappoint the chair for nuclear technology in cooperation with the Research Centre in Karlsruhe and the Technical University of Dresden has put a new nuclear reactor for training purposes into operation.

In summary, numerous internationally accepted processes provide for a continual assessment and guarantee of safety. Education and research in the field of nuclear engineering and the participation of German institutions in international research initiatives should be promoted, so that the implementation of new findings in nuclear technology can be achieved and innovative plant concepts can be elaborated in Germany also in the future.

3.1.2 Current status of safety

In more than 35 years of nuclear energy use, corresponding to an operational experience of about 650 reactor years in Germany at the end of 2004, no impacts on public health and the environment through ionizing radiation have been identified. No radiological releases occurred that exceeded the permissible annual values for the normal operation of a NPP. The German safety philosophy has worked well - based on conservative safety principles that make core damage extremely improbable. This positive overall safety record of German NPPs is similar to the safety record of most countries using NPPs of Western design and operating practice. For these commercial NPPs, so far, only one accident with core damage (Three Mile Island) occurred over 25 years ago, and, even in this case, no serious amount of radioactive materials was released into the environment.

[17] Research centres in Jülich (FZJ), Karlsruhe (FZK) and Rossendorf (FZR), Federal Institute for Geosciences and Natural Resources (BGR) and Materials Testing Institute University of Stuttgart (MPA) with its respective partner universities as well as Gesellschaft für Anlagen- und Reaktorsicherheit (GRS).

During the past decade, the frequency of reportable events and incidents for German plants has been almost constant. The same observation applies to the number of unscheduled reactor scrams, another important indicator for the quality of plant operation. If surrogate risk metrics such as the frequency of core melts or large early releases of radioactive material are used as the basis for assessing the evolution of the risk to the public from German NPPs, a decrease in risk over time can be demonstrated.

It has recently been stated by the Federal Government [16] that, as a result of the safety assessments performed and the resulting backfit measures and safety-related improvements, the licensed safety status of the plants has not only been maintained but, also, that newer safety findings were given appropriate consideration during the time of operation. Thus, the safety of nuclear power plants has largely been adapted to the state of the art in science and technology and as far as the plant design allowed.

In summary, the existing processes and backfit measures to increase safety, applied as appropriate, have led to an overall excellent safety record of the German nuclear power plants, which is also reflected in the substantial decrease of the residual risk of accidents with severe releases. Due to their high degree of safety the currently established limitation of electricity production quotas should be lifted. However, for operating periods exceeding 40 operating years at the latest, the ILK considers it advisable to ensure sufficient safety in the future by undergoing a preceding special safety review (cf. [17]).

3.1.3 Future improvements of plant safety

In the course of the measures presented in section 3.1.1, the original safety concept has been enlarged and already includes to a large extent elements of the safety level 4 of the defense-in-depth concept, i.e., measures for controlling hypothetical beyond-design events and for mitigating their consequences. Over the past years, research on the probabilities and consequences of various beyond design accident scenarios, also in the framework of the EPR design, provided new insights for the mentioned safety level 4 and also on the safety level 5 which was subsequently introduced and provides for measures to mitigate the impact of beyond-design events with significant releases of radioactive materials (see also [17]).

This approach should also be continued in the framework of the continued utilization of existing NPPs in Germany, even if the plants can be regarded as sufficiently safe and fulfill provisions stipulated by the German Atomic Energy Act without these measures. Since beyond-design-basis accidents are the focus here, measures should only be suggested if the safety-related benefit is in due proportion to the required expenditures.

In summary, opportunities to further improve plant safety, especially for minimizing risks from hypothetical severe accidents, should continue to be pursued - preferably by reaching agreement between authority and licensee and giving due attention to the appropriateness of measures.

3.2 Measures against terrorist attacks

German nuclear power plants are protected against terrorist attacks and airplane crashes. The level of protection varies according to the design of the specific plant.

Elements of the protection encompass detailed access control and preventive measures to reduce the possibility of unauthorized entry, also using vehicles, to the NPP site for persons and equipment. Sophisticated surveillance measures of the site enclosure make undetected intrusion very unlikely. In addition, civil structures act as barriers against attacks. The physical separation and special protection of redundant vital systems to maintain fuel integrity, e.g., heat removal systems, reduces the possibility of a destruction of the reactor core by terrorist attacks.

Different parties have taken measures to protect the reactor from intentional airplane crashes:

- Actions taken by the government, the aircraft industry and airlines are aimed at preventing the hijacking of airplanes;
- Reactor buildings are protected to a different degree to withstand the crash of a military aircraft. An analysis performed for a plant of the Konvoi-type indicates that at least these structures would also withstand the impact of a large commercial aircraft;
- Licensees plan to install systems capable of inducing fog at the NPP site to reduce the possibility of an airplane hitting the reactor building.

As a conclusion of its discussions the ILK also recommended the development of an overall concept against terrorist attack which besides NPPs also takes into

account the possible threat to other technical plants and infrastructure elements. Only a comprehensive package of measures applying to all potential terrorist targets can provide an effective protection of the general public.

In summary, German nuclear power plants are protected against terrorist actions by the existing design and additional precautionary measures which decrease the attractiveness of nuclear power plants as a target for terrorist attacks. Additional measures should be undertaken at the federal level based on a comprehensive vulnerability and risk study for all plants and activities that may be a potential target for terrorist attacks.

3.3 Safeguards against proliferation

Germany is subjected to a full scope and rigorous inspection by the IAEA of all nuclear facilities including pools for fresh and irradiated fuel as well as installations for intermediate storage of irradiated fuel. A full inspection of all nuclear facilities is also performed (separately) by EURATOM.

Independently of the remote possibilities for misuse of fissile material, the supervision by both international organizations IAEA and EURATOM and the elaborate control implemented by the licensees make a non-authorized handling of fissile material extremely unlikely.

Thus, the undetected theft of fissile material from German NPPs and fuel fabrication plants with the potential to construct a nuclear weapon is virtually impossible. In addition, the construction of an atomic bomb with low enriched uranium used for the operation of commercial reactors is physically not possible.

However, the accumulation of some Pu-isotopes which are generated during operation through irradiation of U-238 has in principle the potential to be transformed into weapons-grade material. The separation of Pu from irradiated fuel requires reprocessing - a technology which is no longer used in Germany. Plutonium that is extracted from reprocessing of irradiated fuel from German NPPs in La Hague, France, or Sellafield, UK, is either stored at those sites and supervised by IAEA and EURATOM or is reprocessed together with uranium to MOX-fuel elements used in German NPPs[18].

[18] The (former) Karlsruhe reprocessing plant (WAK) is the only place In Germany which still has a relevant amount of Pu as part of the high active waste concentrate (HAWC). The HAWC is to be solidified in a vitrification plant which will soon begin operation; about 130 glass blocks in stainless steel containers suitable for repository storage will be generated.

In conclusion, the threat of proliferation ensuing from the use of nuclear energy in Germany is very low due to the applied safeguards, the type of fuel cycle and international monitoring.

3.4 Waste management issues

International developments in the past years with regard to the disposal of high-level radioactive waste (HLW) and/or spent fuel (SF) achieved significant progress. Only a few examples should be mentioned here:

- In Finland, both government and parliament took a policy decision in 2000 for two possible sites for a repository. At Olkiluoto, the finally chosen site, the construction of an underground research laboratory (URL) is underway and the first waste is expected to be emplaced into the repository in 2020.
- After an extensive screening process and extensive feasibility studies in eight municipalities, two sites are presently being investigated in Sweden. The start of the emplacement into the repository is intended for 2017.
- The Yucca Mountain site, which was selected by the U.S. Congress, was extensively investigated. The U.S. Department of Energy (DOE) intends to submit the license application for the construction of the repository to the U.S. Nuclear Regulatory Commission (NRC) during this year. In addition, DOE operates the WIPP repository for non-heat generating radioactive waste of defense origin since 1999.
- In France, a special Act with three lines of research (partitioning and transmutation, reversible or irreversible disposal in deep geological formations, waste conditioning and long-term storage) was passed in 1991. At the Bure site, two shafts are presently being sunk and first underground experiments were installed. Based on the results the French government and parliament will decide on the definition of a HLW management strategy in 2006.
- Based on the very good results from well drilling in opalinus clay, the Swiss Nagra submitted a demonstration of disposal feasibility in 2002 which was evaluated in 2005 by the authority in charge (HSK). Subsequently, a committee staffed with cantonal politicians was instructed to resolve the siting issue. A decision of the Swiss Federal Government on this issue is expected to be made in 2006.

Based on the research results of several decades, the international scientific community is convinced that the safe disposal of HLW and SF is possible in deep geo-

logical formations and that satisfactory solutions can be implemented for the long-term aspects.

On the basis of an agreement between the Federal Government and the utilities [36], all German NPPs are constructing on-site interim storage facilities for their SF, with a licensed operational lifetime limited to forty years. The respective licensing processes were all successfully performed and construction is ongoing. In consequence, the two existing centralized storage facilities at Ahaus (Northrhine-Westphalia) and at Gorleben (Lower Saxony) are mainly used for the interim storage of THTR fuel elements or, respectively, of vitrified HLW which originates from reprocessing German LWR fuel. One political reason for the construction of local interim storage facilities was to avoid transportation of SF, which often triggers large and sometimes violent public demonstrations.

The above mentioned bilateral agreement [36] introduced a moratorium on the underground site investigations in the Gorleben salt dome, which became effective on October 1, 2000. It is planned to last for three years minimum and for ten years maximum. In several statements, the ILK already expressed its views on the general issue of a final repository at the Gorleben site [37], [38], [39].

Site investigations at Gorleben from the surface are complete. After sinking two shafts, the first possible disposal area was successfully explored. Until the moratorium became effective, no result was found which would have disqualified the salt dome as a repository. Until now, about € 1.3 billion were invested in the Gorleben repository project.

The former iron ore mine Konrad is foreseen to serve as a deep geological repository for non-heat generating radioactive waste. The license for construction and operation of the Konrad repository was granted by the responsible Lower Saxonian licensing authority in May, 2002. However, because of four pending law suits, construction can only begin after the respective court decisions. Investments into the Konrad repository project up to now amount to about € 800 million.

The intention of the previous Federal Government has been to start a completely new site selection process for one single repository in Germany. For this purpose, the AkEnd committee was installed. It elaborated a respective proposal between 1999 and 2002 [40], which has not yet been implemented (see [41] for a detailed statement by the ILK on this proposal). The ILK notes that no other country has opted for one single repository for all kinds of waste and recognizes good technical reasons to keep different waste types separated.

In the view of the ILK, progress in solving the disposal issue could be achieved fairly rapidly. In order to overcome the current deadlock in Germany, ILK recommends the following urgent actions [37]:

- Plan separate repositories for heat generating and non-heat generating radioactive waste (see also [38], [41]).
- Prepare all steps necessary to start construction of the repository Konrad for non-heat generating radioactive waste in case of a positive court decision (see also [38]).
- Lift the moratorium and resume the underground site exploration in the Gorleben salt dome as soon as possible in order to achieve a final judgment on its suitability as a repository (see also [38], [39])[19].
- Launch a total systems performance assessment of a repository site at Gorleben as soon as possible in order to obtain further insights and guidance on the continued work towards a safe repository (see also [39]).
- Evaluate the installation of an URL in the Gorleben salt dome[20].
- Launch a social program oriented towards the acceptability of disposal sites by the local population using some recommendations of the AkEnd committee such as the involvement of local stakeholders in the decision making processes.
- Assess and precisely define the roles and responsibilities of the implementer (planning, implementation and operation of the repository) and the authority (licensing and regulatory control) (see also [41]).

3.5 Licensing and regulatory control

The Nuclear Safety Convention [5] requires that each country establish a regulatory framework to govern the safety of nuclear installations. This framework should include safety requirements and regulations, a licensing system and regulatory inspections and assessments. This framework should be based on scientific-technical and politically neutral criteria. Therefore, the regulatory body should be independent from other organizations concerned with the promotion or phase-out of nuclear energy.

[19] National and international peer reviews of a final repository for HLW at the site Gorleben have so far not called its suitability into question.

[20] No such facility is available in Germany since the closure of the Asse research mine in 1995.

The ILK has recently dealt with the nuclear regulatory guidelines in Germany [42] and called for a revision that takes several recommendations into account. These recommendations include a flatter hierarchy of the guideline structure, a distinction between effectively binding requirements and non-binding recommendations, a reduced prescriptiveness, an international orientation, as well as a regular updating mechanism. The guidelines should be subjected to a peer review with international participation.

Contrary to most other countries, which are operating nuclear power plants, the regulatory situation in Germany is characterized by the existence of licensing and regulatory authorities at both the federal and individual Länder (state) level. Licensing and the regulatory inspections, assessments and decision-making are undertaken by each Länder ministry, acting on federal commission; however, the federal ministry can intervene and instruct the ministries. The federal ministry is particularly obliged to cultivate international cooperation and participate in international bodies (e.g., IAEA, OECD, NEA).

In the past, a number of problems occurred in the licensing and oversight of nuclear power facilities:

- Administrative processes, whose only objectives should be the protection of public health and safety, were used as tools in the political debate ("phase-out-oriented execution"). This was especially visible when the Federal Government and the individual federal states had different opinions on nuclear energy. ILK does not rule out that this could have a negative impact on safety.
- Germany devotes relatively large resources to the oversight of nuclear facilities. This results in a more detailed and exhaustive control of licensee activities than is the case for most other countries. ILK is concerned that this could lead to a regulatory oversight that is too prescriptive, which might de facto diminish the extent to which licensees take on full responsibility for their plants and impede the development of safety culture.
- The Länder participate in the international exchange of experience in a very indirect way. The authorities of the Länder are thus in technical-scientific isolation, which is not conducive to nuclear safety.

Therefore, ILK once again refers to its former recommendations on the promotion of international technical and scientific contacts [33] and on performing an IRRT review for the German licensing and regulatory authorities [34].

Generally, an active participation in international exchanges of experience and transnational projects may also be useful to learn lessons from incidents in comparable plants faster and more substantiated and to react in a flexible manner to new developments and challenges already at an early stage. Such developments include, e.g., the liberalization of electricity markets and its effects on the optimization of operative management, safety management and safety culture. In addition, on the international level, the regulatory principle is changing from a rule-based orientation to a risk-informed performance- and process-based orientation. Thus, the ability of authorities to adapt to new challenges is indispensable.

In summary, the oversight system should be subjected to a peer-review with participation of international experts. Such a comparison with up-to-date international experiences and approaches, such as with regard to the independence of the regulatory authority and an application of risk-informed and performance-based oversight, should be used for optimizing the present system.

4 Further development of nuclear systems

Although present reactors are considered safe and competitive, international initiatives were launched (GIF[21] [43], INPRO[22] [44]) to develop a new generation of reactors and associated fuel cycles; nuclear fission is regarded as indispensable for future energy supply. The GIF-objectives are to promote

- sustainability (focused on fuel cycle issues),
- economics,
- safety and reliability,
- proliferation resistance and physical protection.

The new nuclear systems should be developed through international projects, achieve the goals and needs of future modern society, and should be deployable by 2030.

The benefits of such innovative use of nuclear energy include reduced volumes and activity inventories of radioactive wastes and geological disposal, recycling of spent fuel as well as partitioning and transmutation of extremely long-lived actinides. Advanced applications of nuclear energy technology are intended such as hydrogen production and sea water desalination.

[21] The Generation IV International Forum (GIF) includes 10 member countries (Argentina, Brazil, Canada, France, Japan, South Africa, South Korea, Switzerland, United Kingdom and USA) and Euratom, while OECD-NEA and IAEA are permanent observers.

[22] International Project on Innovative Nuclear Reactors and Fuel Cycles by the IAEA

The new generation of nuclear systems under development in particular aims at further decreasing the costs through more efficient fuel cycles, design simplifications and better adaptations to the necessary plant sizes. Reduction or elimination of the need for prepared emergency responses are additional aims, apart from the protection of the investment, that one wants to achieve through simplification of systems, inherent safety features and design innovations.

For ensuring the intended design certification, the systems considered should all meet a safety approach that combines deterministic and probabilistic rules derived from risk analysis and the defense-in-depth philosophy. Innovative designs should also encompass the newest techniques ("best practice") as well as knowledge concerning internal and external events as well as human factors and safety culture. The safety approach should also be extended and be consistent for all activities and installations of the complete fuel cycle in view of satisfactorily demonstrating an effective risk reduction.

Another goal is to achieve a further improved protection against proliferation through extensive use of intrinsic physical barriers and extrinsic safeguards. Protection against terrorism should be achieved through increased robustness in the new systems.

International research and development projects are already under way. After selection of six innovative systems (gas-cooled fast reactor, lead-cooled fast reactor, molten salt reactor, sodium-cooled fast reactor, supercritical-water-cooled reactor and very-high-temperature reactor) [45], serious technology gaps ("show-stoppers") have been defined which might jeopardize concept development and are the focus of current work with significant participation of industry. The annual amount of research funding is in the range of US $ 250 mil.

The international project INPRO provides a methodology for assessing innovative nuclear energy systems developed and published under the auspices of the IAEA [46], [47].

In summary, it is extremely important for Germany to take an active part in such projects and to contribute its own experience and expertise to the international community of nuclear experts and get a benefit in return. This approach would offer the chance to attract younger generations to the technology and to associated research and development programs and thus serve to maintain technical competence.

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6 List of Abbreviations

AkEnd	Arbeitskreis Auswahlverfahren Endlagerstandorte (Committee on a Selection Procedure for Repository Sites)
DENA	Deutsche Energie-Agentur (German Energy Agency)
DOE	United States Department of Energy
EPR	European Pressure Water Reactor
EU	European Union
EURATOM	Treaty establishing the European Atomic Energy Community
GIF	Generation IV International Forum
GW	Gigawatt (10^9 watt)
GWe	Gigawatt electrical
HLW	High-level radioactive waste
HSK	Hauptabteilung für die Sicherheit der Kernanlagen (Swiss Federal Nuclear Safety Inspectorate)
IAEA	International Atomic Energy Agency
ILK	Internationale Länderkommission Kerntechnik (International Committee on Nuclear Technology)
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INSAG	International Nuclear Safety Advisory Group
LWR	Light water reactor
MCDA	Multi-criteria decision analysis
MOX	Mixed oxide
MW	Megawatt (10^6 watt)
NRC	United States Nuclear Regulatory Commission
NPP	Nuclear power plant
OECD	Organisation for Economic Co-operation and Development
OSART	Operational Safety Review Team (IAEA)
PSA	Probabilistic safety assessment/analysis
PSR	Periodic safety review
Pu	Plutonium
RSK	Reactor Safety Commission (Germany)
SF	Spent fuel
THTR	Thorium-High-Temperature-Reactor
TWh	Terawatt hours (10^{12} Watt hours)
UN	United Nations

URL	Underground Research Laboratory
VDE	Association for Electrical, Electronic & Information Technologies
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association
WIPP	Waste Isolation Pilot Plant (USA)

Appendix 1: Set of sustainability indicators for electricity-supply technologies [12]

Economic Indicators*

Impact Area	Indicator	*Unit*	Lignite	Hard Coal	Oil	Natural Gas	Nuclear	Hydro	Wind	Solar (PV)
Financial Requirements	Production cost	*€ cent/kWh*	3.3	3.0	3.1	3.6	2.1	7	9	60
	Fuel price increase sensitivity	*Factor*	1.6	1.5	1.8	1.8	1.3	1.0	1.03	1.1
Resources	Availability (load factor)	*%*	80	80	80	80	80	40	20	9
	Geo-political factors	*Relative scale*	100	80	20	40	80	100	100	100
	Long-term sustainability: Energetic	*Years*	400	2 000	100	100	500	∞	∞	∞
	Long-term sustainability: Non-energetic	*kg (Cu) /GWh*	13	11	12	4	5	1	510	230
	Load following	*Relative scale*	20	50	100	100	10	30	0	0

Environmental Indicators*

Impact Area	Indicator	*Unit*	Lignite	Hard Coal	Oil	Natural Gas	Nuclear	Hydro	Wind	Solar (PV)
Global Warming	CO_2-equivalents	*tons/GWh*	1 220	1 080	884	531	10	4	14	86
Regional Environmental Impact	Change in un-protected eco-system area	*km^2/GWh*	0.032	0.039	0.061	0.016	0.0017	0.0009	0.0029	0.011
Non-Pollutant Effects	Land use	*m^2/GWh*	52	198	335	47	7	92	29	65
Severe Accidents	Collective risk	*fatalities/ GWh*	5.7E-7	2.1E-5	4.5E-5	1.0E-5	2.3E-6	3.4E-7	1.1E-8	1.1E-7
Total Waste	Weight	*tons/GWh*	84	180	11	2	15	24	93	66

Societal Indicators*

Impact Area	Indicator	*Unit*	Lignite	Hard Coal	Oil	Natural Gas	Nuclear	Hydro	Wind	Solar (PV)
Employment	Technology-specific job opportunities	*Person-years/GWh*	0.21	0.86	0.47	0.65	0.16	1.2	0.36	6.6
Proliferation	Potential	*Relative scale*	0	0	0	0	100	0	0	0
Human Health Impacts (normal operation)	Mortality (reduced life-expectancy)	*Years of Life Lost/GWh*	0.061	0.068	0.12	0.023	0.005	0.011	0.007	0.020
Local Disturbances	Noise, visual amenity	*Relative scale*	10	8	6	2	4	5	7	0
Critical Waste Confinement	"Necessary" confinement time	*Thousand years*	50	50	0.1	0.01	1 000	0.01	1	50
Risk Aversion	Maximum damage of potential accident	*fatalities/ credible accident*	10	500	4 500	100	50 000	2 000	5	100

* The quantitative values for all technologies and all indicators had to be restricted to point scores; although desirable the state-of-the-art does not allow general quantification of ranges of uncertainties, which would be subject to substantial research.

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