EUROPEAN COMMISSION
DIRECTORATE-GENERAL
JOINT RESEARCH CENTRE

Institute for Energy and Transport
SET-Plan Information System (SETIS)

Key Performance Indicators for the

European Sustainable Nuclear Industrial Initiative

Date: 19 March 2012

1 Introduction

In 2010 six European Industrial Initiatives (EII) of the SET-Plan were launched, of which one was the European Sustainable Nuclear Industrial Initiative (ESNII) [1]. ESNII comprises three nuclear reactor concepts with fast neutron spectrums, i.e. Sodium-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR), and Gas-cooled Fast Reactor (GFR). The fast neutron spectrum allows for example significantly more efficient use of the fuel and less waste production.

To measure the development of the EIIs and the effectiveness of their implementation, a set of quantifiable Key Performance Indicators (KPI) and reference values were established. This document presents the methodology in evaluating the KPIs and how they are measured.

Eventually the KPIs will be used for monitoring and reviewing the progress of ESNII. The KPIs will be used for planning R&D work that is funded under European framework programmes and other funding schemes. Project proposals should demonstrate a link between their objectives and the KPI(s) they will be contributing to. The collection and monitoring process, knowledge sharing, review and feedback procedures are still to be defined. These procedures will be developed during the course of 2012.

2 General principles

2.1 KPIs

This document describes the KPIs and reference values chosen for monitoring the development of the three reactor concepts of ESNII.

All three reactor concepts of ESNII use the same set of KPIs. Fourteen KPIs were defined, which are categorized in five groups:

1. Safety and Proliferation Resistance & Physical Protection
2. Economical Performance
3. Sustainability
4. Availability
5. Environment

The choices of KPIs for ESNII are mostly driven by regulatory requirements and GEN IV objectives. Regulatory requirements are a prerequisite to achieve (e.g. safety and proliferation resistance) and GEN IV objectives are often more challenging in terms of aiming to achieve substantial improvements compared to the state of the art of nuclear reactor systems of today (e.g. fuel usage). The chosen KPIs shall also match up with the goals of the SNETP Vision Report [2] for GEN IV systems. In addition, for some cases

KPIs were chosen in order to illustrate how nuclear power distinguishes itself from renewable energy systems (e.g. capacity factor) and in other cases to show how nuclear power can complement renewable energy (i.e. load following).

From the fourteen KPIs four were chosen as overarching KPIs. These are seen as representative for displaying the advantage of future fast reactor concepts vis-à-vis the third generation of thermal nuclear reactors (Gen III), but they are not necessarily more important than other KPIs. The remaining ten second-tier KPIs measure the performance in other important areas with regard to the reference system.

Nuclear reactors of ESNII would be commercially available only in 2040-2050. Due to the long time schedules from first developing demonstrators/prototypes and eventually building production systems, ESNII has chosen a target KPI for the production system only. Figure 1 exemplifies how different projects could feed input to the reactor concept of SFR.

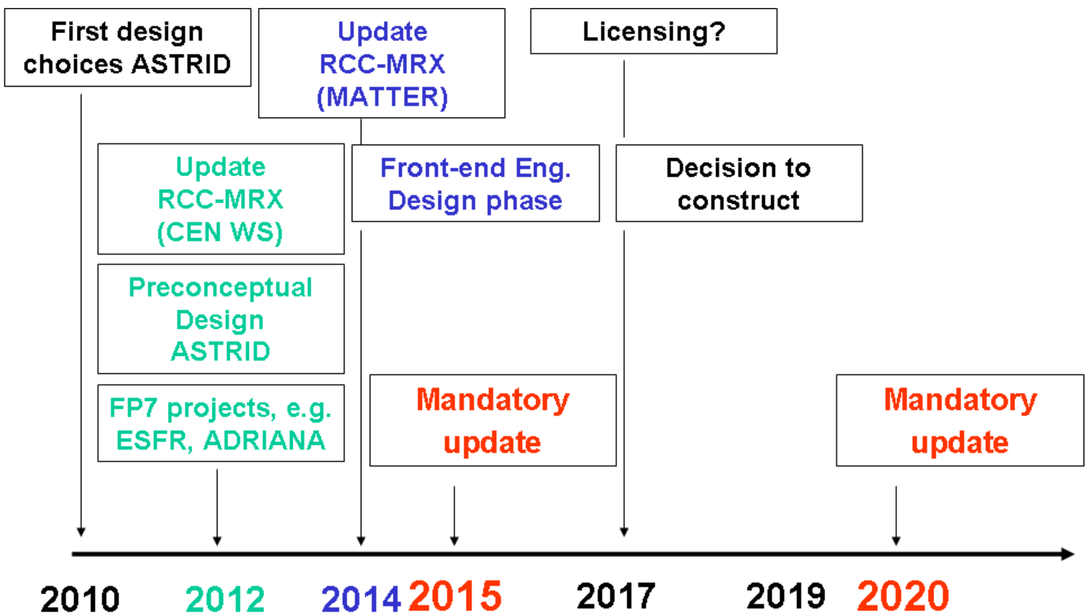

Figure 1. Example of projects feeding into ESNII-1 (SFR).

Based on information about supporting project time schedules, each of the KPIs is planned to be reviewed and updated in 2015 and 2020. At these revisions the index KPI and the uncertainty range are updated. The uncertainty range is expected to narrow over time as projects complete their testing and evaluation. Table 1 illustrates how the KPIs for Capacity factor could narrow the uncertainty range over time.

Table 1. Example of KPI for Capacity factor.

KPI	Units	GEN.III LWR Open FC	Scenario	2011	2015	2020	PRODUCTION SYSTEM
Capacity Factor	%	91	*pessimistic*	75	80	82	95
			realistic	90	92	93	
			optimistic	95	95	95	

For the initial set of KPI values, some do not contain an uncertainty range, but instead give a best estimate.

2.2 Reference values

The reference system is a generic Generation III reactor with open fuel cycle based on data for the EPR, AP1000, ESBWR, and the ABWR reactor concepts. The ARIS database of IAEA [3] and reports from IEA [4], the NEEDS project [5], WENRA [6, 7] and NEI [8] were used to collect data.

3 Explanation of the KPIs proposed for ESNII

As mentioned above, that KPIs are defined according to the ultimate goals of ESNII, i.e. the future production systems. The KPIs, take into account the ESNII long term goals and provide measures of progress for the three reactor concepts during the period of 2011-2020. An illustration of the overarching KPIs can be found in Figure 2. Figure 3 displays the second-tier KPIs.

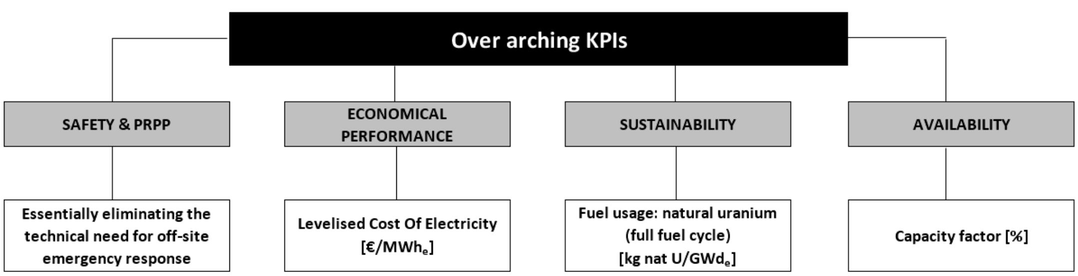

Fig.2 – Overarching KPIs for ESNII

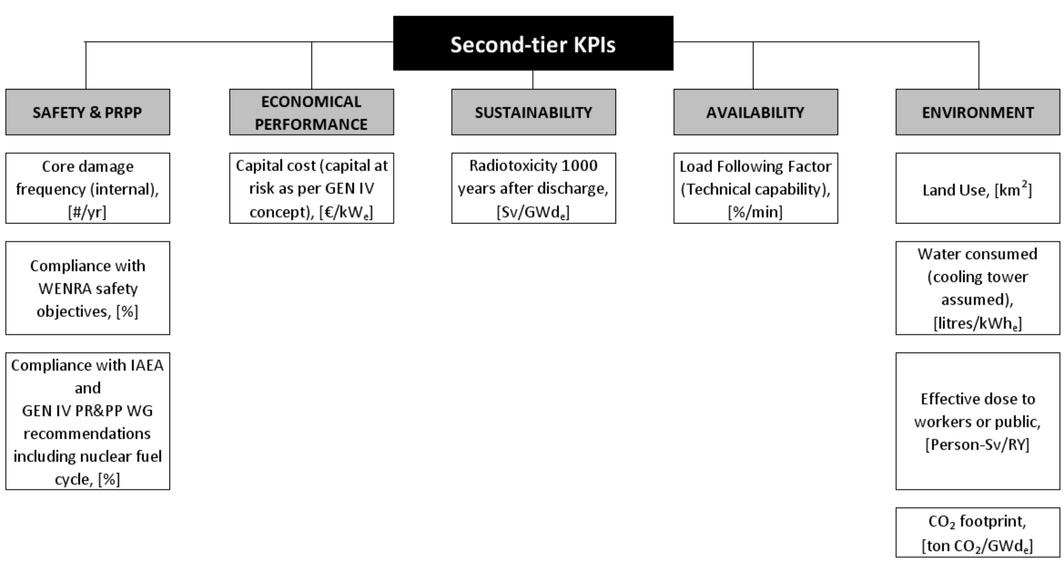

Fig.3 – Second-tier KPIs for ESNII

Below is an explanation for the choice of each subset of KPIs. Furthermore, a description of each individual KPI and the associated measurement unit is provided.

3.1 Safety and Proliferation Resistance & Physical Protection (PRPP)

Achieving the highest safety performance of nuclear power reactor systems and supporting infrastructures is paramount. Safety requirements must be met to ensure the protection of people and the environment.

Existing nuclear power plants in Europe already achieve high performance. ESNII aims to further improve this record by reducing:

- the number of possible accident initiators
- the probability of severe core damages
- potential off-site radioactive releases

Proliferation resistance is another critical element for the new generation of fast reactor systems and their fuel cycles. The new reactor systems and their fuel cycles must be assured to impede the diversion or undeclared production of nuclear material or misuse of technology. The degree of proliferation resistance depends on technical design features, operational modalities, institutional arrangements and safeguard measures.

Physical protection is also paramount in order to impede the theft of materials suitable for nuclear explosives and protection against terrorist acts towards facilities and transportation.

3.1.1 Essentially eliminating the technical need for off-site emergency response

Along the goals of Generation IV reactors, the accidents which have the potential of intolerable releases of radionuclides shall be eliminated by design or "practically eliminated". It will be demonstrated through the implementation of sufficient provisions to practically eliminate postulated events. The evaluation will be made through a combination of Objective Provision Tree analyses as a deterministic method and the Probability Safety Assessment (PSA) as a probabilistic method. The analysis will follow the guidelines of the Risk and Safety Working Group of the Generation VI International Forum. [9]

Unit: Yes/No.

3.1.2 Core damage frequency

The likelihood of core damage is another typical indicator used in PSA. Here, the core damage frequency for internal hazards is monitored. It is a quantifiable measure of the robustness and safety of the plant.

Unit: Number/yr

3.1.3 Compliance with WENRA safety objectives

In 2009 the Western European Nuclear Regulatory Association published a document with a set of proposals for Safety Objectives for New Power Reactors [6,7]. The objective was to achieve a harmonized approach to safety and radiation protection in Europe and their regulation for new reactors.

<u>Unit: percentage of compliance with WENRA safety objectives</u>

3.1.4 Compliance with IAEA and GEN IV PR&PP WG recommendations

Proliferation Resistance: measures in place that impede the diversion or undeclared production of nuclear material or misuse of technology. The assessment methodologies prepared by GIF [10] and IAEA [11] will be used.

Physical Protection: the demonstration that adequate measures are in place to protect the nuclear installations from malicious attacks (internal and/or external) or theft of nuclear material. The assessment methodologies prepared by GIF [10] and IAEA [12] will be used.

<u>Unit: percentage of compliance with IAEA and GEN IV WG PR&PP</u>

3.2 Economical performance

The attractiveness of investing in the technology must be demonstrated to the utilities, and the reactor technologies must be competitive with other technologies. The cost for generating electricity is keenly important, however not disconnected from other performance measures which can influence costs, e.g. safety and reliability can directly influence the capital and operating costs. Fortunately, performance along one measure is positively correlated with other measures, i.e. high reliability improves safety which in its turn reduces the costs, at least up to a certain point.

3.2.1 LCOE

Levelised Cost Of Electricity (LCOE) is the composite cost of the production of electricity including all costs elements. This includes decommissioning and associated waste disposal costs too. Transmission lines and distributions systems are excluded. The guidelines of GIF Economic Methodology Working Group (EMWG) will be used to evaluate the LCOE [13].

The following assumptions are made:

- Discount rate of 8% and the economical life time of 40 years for power plant.
- Inflation should be netted out to secure constant price estimates (constant 2011 Euros).
- All prices net of VAT.

- Subsidies should not be included.

Unit: €/MWh_e

3.2.2 Capital cost (capital at risk as per GEN IV concept)

The total capital investment cost is an all-inclusive plant capital cost which is the amount financed though equity and debt to become a liability to the utility for the economic life of the investment. This cost is the base construction cost plus contingency, escalation (if included), indirect costs, owner's costs (including start-up), and commissioning. The guidelines of GIF Economic Methodology Working Group (EMWG) will be used when evaluating the capital cost [13].

Unit: €/kW_e

3.3 Sustainability

Fast neutron reactors can make better use of natural resources and minimize production of long lived waste requiring geological isolation. The latter includes both reducing the volume of waste as well as its long-term stewardship burden.

3.3.1 Fuel usage: natural uranium

Fast neutron reactors using a break-even conversion ratio use about 60 times less natural uranium than light water reactors. This significantly extends the duration that nuclear fission energy may be used into the future by minimising the drain on natural uranium resources and the need of extended capacities for (proliferation-prone) enrichment.

Unit: kg nat U/GWd_e

3.3.2 Radiotoxicity at 1000 years after discharge

The radiotoxicity of nuclear waste from the LWR open fuel cycle 1000 year after discharge is mainly attributed to plutonium and most prominently a few of the minor actinides (curium, americium, and neptunium). Since the plutonium derived from LWR used fuel can be reused in the fast neutron reactor and minor actinides transmuted by the fast neutron spectrum, the mass of the highly radioactive waste requiring geologic disposal is significantly reduced.

Unit: Sv/GWd_e at 1000 years after discharge.

3.4 Availability

Availability covers the traditional use of nuclear reactor to supply consistent base load electricity and support new opportunities in helping to balance future electricity systems that contain large shares of variable energy sources.

3.4.1 Capacity factor

The availability metric is a measure of the actual output of a power plant over a period of time. Utilisation of the facility based on hours/year including all needed maintenance and refuelling operations.

Unit: %/ yr

3.4.2 Load following factor (technical capability)

In future energy systems the share of renewables are expected to increase substantially. This means more variable electricity production, which needs to be balanced within the transmission and distribution system. Fast neutron reactors have the technical capability to adjust their power output faster than present LWRs, which could make them ideal for load balancing (and demand following) in future energy systems.

Unit: %/min

3.5 Environment

This group of KPIs measure the impact of operating fast neutron reactors on the environment.

3.5.1 Land use

Size of required facility footprint for the plant and the emergency planning zone required as part of the siting requirements.

Unit: km^2/GW_e

3.5.2 Water consumed (cooling tower assumed)

Amount of water used for operation per unit of electricity produced. In the future water scarcity is expected to increase and optimised use of water will increase in importance.

Unit: $litres/kWh_e$

3.5.3 Effective dose to workers

The amounts of radiation that workers are exposed to should be very low to minimise risk exposure. Ways to improve performance can include improved layouts for accessibility, materials choices, procedures for maintenance and repairs etc. The general philosophy is keeping exposures of radiation As Low As Reasonably Achievable (ALARA).

Unit: Person-Sv/Reactor Year

3.5.4 CO_2 footprint

Measure of the CO_2 impact over the facility lifecycle per unit of electricity produced. This includes plant construction, fuel production, facility operation and maintenance, decommissioning and dismantling, and waste disposition.

Unit: ton CO_2 /GWd_e

4 Key Performance Indicator values of ESNII

Sections 4.1 – 4.3 (Tables 2 – 4 respectively) display the Key Performance Indicators for the SFR, LFR and GFR.

4.1 Sodium-cooled Fast Reactor

Table 2. Key Performance Indicators of SFR.

	KPI	Unit	Gen III LWR Open FC	Scenario	2011	2015	2020	Production system
1. Safety & PRPP	1.1 Core damage frequency (internal)	*#/yr*	1.E-6	Pessimistic		Reassessed	Reassessed	1.E-6
				Realistic	1.E-6	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	1.2 Essentially eliminating the technical need for off-site emergency response	*Yes/No*	No	Pessimistic		Reassessed	Reassessed	Yes
				Realistic	TBD	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	1.3 Compliance with WENRA Safety Objectives for New Power Plants	*%*	100	Pessimistic		Reassessed	Reassessed	
				Realistic	100	Reassessed	Reassessed	100
				Optimistic		Reassessed	Reassessed	
	1.4 Compliance with IAEA and GEN IV PR&PP WG (incl. nuclear fuel cycle)	*%*	100	Pessimistic		Reassessed	Reassessed	100
				Realistic	100	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
2. Economical performance	2.1 LCOE	EUR/MWh_e	67	Pessimistic		Reassessed	Reassessed	TBD
				Realistic	TBD in 2015	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	2.2 Capital cost	EUR/kW_e	3500	Pessimistic		Reassessed	Reassessed	4000
				Realistic	4000	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	

				Pessimistic		Reassessed	Reassessed	
	3.1 Fuel usage: natural uranium (full fuel cycle)	*kg nat U/GWd$_e$*	480	Realistic	8	Reassessed	Reassessed	8
3. Sustainability				Optimistic		Reassessed	Reassessed	
				Pessimistic		Reassessed	Reassessed	
	3.2 Radiotoxicity 1000 years after discharge	*Sv/GWd$_e$*	2.E6	Realistic	<< LWR (no Pu in waste)	Reassessed	Reassessed	TBD
				Optimistic		Reassessed	Reassessed	
				Pessimistic		Reassessed	Reassessed	
	4.1 Capacity factor	*%*	91	Realistic	90	Reassessed	Reassessed	90
				Optimistic		Reassessed	Reassessed	
4. Availability				Pessimistic		Reassessed	Reassessed	
	4.2 Load following factor (technical capability)	*%/min*	±5	Realistic	TBD	Reassessed	Reassessed	TBD
				Optimistic		Reassessed	Reassessed	
				Pessimistic		Reassessed	Reassessed	
	5.1 Land use	*km^2/GW$_e$*	0.5	Realistic	0.5	Reassessed	Reassessed	0.5
				Optimistic		Reassessed	Reassessed	
				Pessimistic		Reassessed	Reassessed	
	5.2 Water consumed (cooling tower assumed)	*litres/kWh$_e$*	2.7	Realistic	TBD	Reassessed	Reassessed	TBD
				Optimistic		Reassessed	Reassessed	
5. Environment			0.7	Pessimistic		Reassessed	Reassessed	
	5.3 Occupational radiation exposure	*Person-Sv/RY*		Realistic	< LWR	Reassessed	Reassessed	TBD
				Optimistic		Reassessed	Reassessed	
				Pessimistic		Reassessed	Reassessed	
	5.4 CO_2 footprint	*ton CO_2 /GWd$_e$*	140	Realistic	<LWR (no mining, no enrichment)	Reassessed	Reassessed	TBD
				Optimistic		Reassessed	Reassessed	

4.2 Lead-cooled Fast Reactor

Table 3. Key Performance Indicators of LFR.

	KPI	Unit	Gen III LWR Open FC	Scenario	2011	2015	2020	Production system
1. Safety & PRPP	1.1 Core damage frequency (internal)	*#/yr*	1.E-6	Pessimistic	1.E-5	Reassessed	Reassessed	1.E-7
				Realistic	1.E-6	Reassessed	Reassessed	
				Optimistic	1.E-7	Reassessed	Reassessed	
	1.2 Essentially eliminating the technical need for off-site emergency response	*Yes/No*	No	Pessimistic		Reassessed	Reassessed	Yes
				Realistic	TBD	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	1.3 Compliance with WENRA Safety Objectives for New Power Plants	*%*	100	Pessimistic		Reassessed	Reassessed	
				Realistic	100	Reassessed	Reassessed	100
				Optimistic		Reassessed	Reassessed	
	1.4 Compliance with IAEA and GEN IV PR&PP WG (incl. nuclear fuel cycle)	*%*	100	Pessimistic	95	Reassessed	Reassessed	100
				Realistic	100	Reassessed	Reassessed	
				Optimistic	100	Reassessed	Reassessed	
2. Economical performance	2.1 LCOE	*EUR/MWh_e*	67	Pessimistic	87	Reassessed	Reassessed	80
				Realistic	80	Reassessed	Reassessed	
				Optimistic	74	Reassessed	Reassessed	
	2.2 Capital cost	*EUR/kW_e*	3500	Pessimistic		Reassessed	Reassessed	3500
				Realistic	3500	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	

3. Sustainability	3.1 Fuel usage: natural uranium (full fuel cycle)	*kg nat U/GWd$_e$*	480	Pessimistic		Reassessed	Reassessed	8
				Realistic	8	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	3.2 Radiotoxicity 1000 years after discharge	*Sv/GWd$_e$*	2.E6	Pessimistic		Reassessed	Reassessed	TBD
				Realistic	<< LWR (no Pu in waste)	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
4. Availability	4.1 Capacity factor	*%*	91	Pessimistic	75	Reassessed	Reassessed	95
				Realistic	90	Reassessed	Reassessed	
				Optimistic	95	Reassessed	Reassessed	
	4.2 Load following factor (technical capability)	*%/min*	±5	Pessimistic	10	Reassessed	Reassessed	20
				Realistic	20	Reassessed	Reassessed	
				Optimistic	30	Reassessed	Reassessed	
5. Environment	5.1 Land use	*km^2/GW$_e$*	0.5	Pessimistic	0.45	Reassessed	Reassessed	0.4
				Realistic	0.4	Reassessed	Reassessed	
				Optimistic	0.38	Reassessed	Reassessed	
	5.2 Water consumed (cooling tower assumed)	*litres/kWh$_e$*	2.7	Pessimistic	2.7	Reassessed	Reassessed	2.2
				Realistic	2.2	Reassessed	Reassessed	
				Optimistic	1.9	Reassessed	Reassessed	
	5.3 Occupational radiation exposure	*Person-Sv/RY*	0.7	Pessimistic		Reassessed	Reassessed	TBD
				Realistic	< LWR	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	5.4 CO_2 footprint	*ton CO_2./GWd$_e$*	140	Pessimistic	140	Reassessed	Reassessed	95
				Realistic	110	Reassessed	Reassessed	
				Optimistic	70	Reassessed	Reassessed	

4.3 Gas-cooled Fast Reactor

Table 4. Key Performance Indicators of GFR.

	KPI	Unit	Gen III LWR Open FC	Scenario	2011	2015	2020	Production system
1. Safety & PRPP	1.1 Core damage frequency (internal)	*#/yr*	1.E-6	Pessimistic	1.E-5	Reassessed	Reassessed	1.E-6
				Realistic	1.E-6	Reassessed	Reassessed	
				Optimistic	1.E-7	Reassessed	Reassessed	
	1.2 Essentially eliminating the technical need for off-site emergency response	*Yes/No*	No	Pessimistic		Reassessed	Reassessed	TBD
				Realistic	TBD	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	1.3 Compliance with WENRA Safety Objectives for New Power Plants	*%*	100	Pessimistic		Reassessed	Reassessed	
				Realistic	100	Reassessed	Reassessed	100
				Optimistic		Reassessed	Reassessed	
	1.4 Compliance with IAEA and GEN IV PR&PP WG (incl. nuclear fuel cycle)	*%*	100	Pessimistic	95	Reassessed	Reassessed	100
				Realistic	100	Reassessed	Reassessed	
				Optimistic	Exceeding	Reassessed	Reassessed	
2. Economical performance	2.1 LCOE	*EUR/MWh_e*	67	Pessimistic	87	Reassessed	Reassessed	80
				Realistic	80	Reassessed	Reassessed	
				Optimistic	74	Reassessed	Reassessed	
	2.2 Capital cost	*EUR/kW_e*	3500	Pessimistic		Reassessed	Reassessed	TBD
				Realistic	TBD	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	

3. Sustainability	3.1 Fuel usage: natural uranium (full fuel cycle)	*kg nat U/GWd$_e$*	480	Pessimistic		Reassessed	Reassessed	8
				Realistic	8	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	3.2 Radiotoxicity 1000 years after discharge	*Sv/GWd$_e$*	2.E6	Pessimistic		Reassessed	Reassessed	TBD
				Realistic	<< LWR (no Pu in waste)	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
4. Availability	4.1 Capacity factor	*%*	91	Pessimistic	80	Reassessed	Reassessed	90
				Realistic	90	Reassessed	Reassessed	
				Optimistic	95	Reassessed	Reassessed	
	4.2 Load following factor (technical capability)	*%/min*	±5	Pessimistic	5	Reassessed	Reassessed	10
				Realistic	10	Reassessed	Reassessed	
				Optimistic	20	Reassessed	Reassessed	
5. Environment	5.1 Land use	*km^2/GW$_e$*	0.5	Pessimistic	0.5	Reassessed	Reassessed	0.45
				Realistic	0.45	Reassessed	Reassessed	
				Optimistic	0.4	Reassessed	Reassessed	
	5.2 Water consumed (cooling tower assumed)	*litres/kWh*	2.7	Pessimistic	1.7	Reassessed	Reassessed	1.5
				Realistic	1.5	Reassessed	Reassessed	
				Optimistic	1.4	Reassessed	Reassessed	
	5.3 Occupational radiation exposure	*Person-Sv/RY*	0.7	Pessimistic		Reassessed	Reassessed	TBD
				Realistic	< LWR	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	
	5.4 CO_2 footprint	*ton CO_2 /GWd$_e$*	140	Pessimistic		Reassessed	Reassessed	TBD
				Realistic	< LWR	Reassessed	Reassessed	
				Optimistic		Reassessed	Reassessed	

5 Reporting

Data should flow from monitored ESNII projects, i.e. SFR, LFR, and GFR, on agreed dates for updates. Mandatory updates of KPI tables will occur in 2015 and 2020. Exact procedure for the data from remains to be decided.

6 References

1. SNETP, 2010, Brussels conference chosen for launch of European Industrial Initiative on Nuclear Energy (ESNII)

2. SNETP, 2007, A Vision Report, ISBN 978-92-79-05591-1

3. IAEA, Advanced Reactors Information Systems (ARIS), available at: http://aris.iaea.org/ARIS/aris.cgi

4. IEA, Projected cost of generating electricity, 2010, ISBN: 978-92-64-08430-8

5. NEEDS project, Final report on technical data, costs and life cycle inventories of nuclear power plants, 2007

6. WENRA, Safety Objectives for New Power Reactors, 2009

7. WENRA, WENRA Statement on Safety Objectives for New Nuclear Power Plants, November 2010

8. Nuclear Energy Institute, Water Use and Nuclear Power Plants, May 2011

9. Risk and Safety Working Group of Generation IV International Forum, Basis for the safety approach for design & assessment of Generation IV Nuclear Systems, Rev 1, GIF/RSWG/2007/002, 2008

10. GIF, Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, Rev. 5, 2006, GIF/PRPPWG/2006/005

11. IAEA, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, INPRO Manual – Proliferation Resistance, IAEA-TECDOC-1575 Rev. 1, 2008

12. IAEA, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems INPRO Manual — Physical Protection, IAEA-TECDOC-1575 Rev. 1, 2008

13. GIF-EMWG, Cost Estimating Guidelines for Generation IV Nuclear Energy Systems – Revision 4.2, 2007