Comparison of Innovative Nuclear Energy Systems Based on Selected Key Indicators and Their Weighing Factors

A.Egorov[1], V. Korobeynikov [1],

[1] Institute for Physics and Power Engineering, Obninsk, Russia

E-mail contact of main author: afegorov@ippe.ru

Abstract. The paper presents a methodological study on comparison of nuclear energy systems whose commissioning and commercial-scale operations are in the planning stage. These studies are carried out within the framework of the joint project INPRO.

Systems with numerous technical and economic uncertainties are poorly amenable to technology assessment using the INPRO methodology (for all areas, basic principles and criteria). Furthermore, it seems unreasonable to assess reactor systems in isolation from the system they were designed for. Some indicators from among those that should be referred to the key ones are system-related indicators. They directly affect not only the assessment of reactor facility, but also the characteristics of nuclear energy system as a whole. At the same time, there are indicators, which are slightly related to the system or are generally unrelated to it. Therefore, the study compares particularly the systems with their inherent key indicators, rather than the technologies taken separately.

For the comparison of innovations, a set of key indicators was selected and aggregated into a single function by assigning weights to each indicator. At this stage, there is also an uncertainty both in key indicator assessments, and in determining the importance of each indicator among those selected (weighing factors of indicators).

The paper discusses several key indicators of sustainability for innovative nuclear energy systems from different areas of assessment (economics, technology readiness, waste management). As an example, consideration is given to several types of countries with different nuclear capacities. Key indicator weights were selected based on the intrinsic features of the countries; the comparison of innovations is presented. The paper presents the sensitivity of the weights of selected key indicators to the result of innovations comparison.

In addition, the paper identifies the ways of key indicators development. The study of assessment uncertainties using the key indicators could be one of the methodological improvements. Together with the sensitivity analysis of key indicators’ weighing factors, it can significantly promote the study of the comparison of innovations in the context of the methodology described in the paper.

Key Words: Fast reactor, Two-component nuclear energy system, Key Indicator.

1. Introduction

At the moment, the major part of Russian Nuclear Energy fleet consists of commercial thermal reactor units (VVER-type). In case of high growth of capacities and worldwide distribution of VVER technologies, a reliable thermal reactor fuel supply should be ensured, as well as an adequate solution of the SNF (spent nuclear fuel) problem. The solution of the above problems is associated with fast breeder reactors’ technology (FR’s) development. The progress achieved in this area in Russia (stable operation, high safety standards) and good opportunities for further technology improvement of BN-350, BN-600 and BN-800 reactors have allowed advancing in the direction of fast reactor technology commercialization.

Power units with fast reactors have great advantages for large-scale nuclear energy development. Among other things, according to the experts, it is expedient to operate fast reactors in conjunction with thermal reactors.

2. Objectives & Problem Statements

Present case belongs to a methodological study. It does not show any possible direction of Russian nuclear energy development however it reflects the country experience in the field of FR technology extension.

The study is assumed to show the experience in fast reactor technology development, to try out the methodology of the KIND project (key indicators for innovative nuclear energy systems) and a KIND-ET tool (program based on the multi attribute value theory). KIND methodology and the KIND-ET tool for comparative assessment of NES (Nuclear Energy System) aimed to help the leaders of the industry/ decision makers and experts conducting research to support decision-making in the choice of the direction of technological NES development.

KIND-ET is a MAVT Excel sheets tool developed for the NES multi-criteria comparative evaluation in accordance with the methodology and recommendations being elaborated in the KIND project based on the MAVT method.

To achieve the objective the following tasks were set:

1. Develop a bunch of key indicators for the fast and thermal reactors include peculiarities of correspond nuclear energy systems;
2. Conduct calculations and make assessments of relevant key indicators according to the KIND methodology.
3. Using the KIND-ET excel sheets tool and a limited number of key indicators, prepare a preliminary comparative evaluation of NES.

The most useful MCDA(multiple-criteria decision analysis) method for the Russian case study is MAVT (Multiattribute Value Theory). The transition from the actual specifications for key indicators (KI) to their values/estimates (transition from table II to table III) requires defining an objective for each KI. For instance, the first key indicator "Nat. U" is responsible for the efficiency use of natural uranium. Therefore, a nuclear energy system that generates more electricity per tonne of uranium produced, among other considered NES-alternatives, would have a rating 1. Therefore, the target for the indicator "Nat. U" — to maximize the production of electricity per tonne of natural uranium. On the same principle, the objectives for the remaining key indicators were set.

The form of the single-attribute value functions for table II is linear and objective for #1 KI is maximum and #2–5 KI’s is minimum. Table III shows KI from the table II in unified form.

3. Formulation of NES options

Current multi-criteria study considers 4 alternatives for 20 GW and 3 for 100 GW electrical capacities.

Country with a 20 GWe capacity has 4 alternatives and represents a country with low electricity capacity:

— once through nuclear fuel cycle based on thermal reactors TR1 (OFC1 (TR1)),

— once through nuclear fuel cycle based on thermal reactors TR2 (OFC2 (TR2)),

— a joint close nuclear fuel cycle based on fifty percent of thermal reactors TR1 and fifty percent of fast reactors FR1 (joint CNFC1 (FR1, TR1)),

— a joint close nuclear fuel cycle based on fifty percent of thermal reactors TR3 and fifty percent of fast reactors FR2 (joint CNFC2 (FR2, TR3)).

Country with a 100 GWe capacity has 3 alternatives and represents a country with high electric capacity:

— once through nuclear fuel cycle based on thermal reactors TR3(OFC3 (TR3)),

— a joint close nuclear fuel cycle based on fifty percent of thermal reactors TR3 and fifty percent of fast reactors FR2 (joint CNFC2 (FR2,TR3)),

— a closed nuclear fuel cycle based on fast reactors FR2 (CNFC3 (FR2)).

The last alternative for the 100 GWe country capacity has an additional feature. The system works on the fast reactor technologies without any thermal reactors. The system does not have plutonium at the moment of deployment that is why CNFC3 (FR2) system requires natural uranium for startup, so part of FR2 works on enriched uranium.

The key indicator features of above mentioned alternatives are presented in table II.

4. Indicators determination

For a starting point under the KIND project was taken by a set of KI developed by the GAINS project (Global Architecture of Innovative Nuclear Systems based on Thermal and Fast Reactors including Closed Fuel Cycles) [1]. The main idea of KIND is that KI must reflects the most essential features of an issue and pointed to technical and/or infrastructural nuclear energy system characteristics. Also, a KI's should be as independent as possible from each other due to avoid assign wrong weighting factors. Minimization of KI's set facilitates the assessment process, but it should not be overlooked KI that are essential to evaluate the systems.

The current structure of KI came from INPRO methodology [2], GAINS project and discussions during the KIND meetings in regard to specific key indicators for the comparative evaluation of NES in the early stages of developing their innovative elements. The current set of KI's includes economics, waste management, environment and maturity of technology areas. The safety area is not considered. It is assumed that the facilities at the time of technology introduction met the existing safety requirements in the country. Proliferation resistance has not been considered yet.

Also, the study investigates a single-level objective tree and five key indicators. Further, there is a short description of the key indicators from above mentioned areas:

1) The amount of useful energy produced by the system from a unit of mined natural uranium/thorium. The key indicator came from GAINS, as KI-2. Hereinafter this KI is referred to as "Nat. U", unit is GWe*h /t;
2) LUEC (Levelized Unit Electricity Cost) — is a cumulative key economic indicator. In accordance with the classic economic theory, it shows the specific value of the final useful product cost (Secondary Electricity), taking into account the return of interest on capital investments, O&M (operation and maintenance) and fuel costs.
   Levelized cost of energy product and services came from GAINS, as KI-9. Hereinafter this KI is referred to as "LUEC", unit is \$/MWh.
   According to the results of the BN-800 fast reactor deployment, one of the main requirements imposed on the FOAK (First-of-a-kind) BN-1200 fast reactor project is the reduction of the cost of electricity generated. The main difference between BN-800, and the BN-1200 project is a significant progress in safety and economics areas.

3) Radioactive waste inventories per unit energy generated — cumulative annual amount came from GAINS, as KI-5. Hereinafter this KI is referred to as “Wastes”, unit is t/TWe*h. “Wastes” key indicator shows an annual generation of wastes produced by the system. It might be one of the main drivers in the transition from an open nuclear fuel cycle system to a two-component nuclear energy system based on fast and thermal reactor technology in a closed fuel cycle.
4) Time needed to mature the technology key indicator shows a time during which the technology will be matured. Hereinafter the KI is referred to as “TtMature”, unit is years. Technology maturity requires a series of units and a proven technological scheme. For instance, at the moment, thermal reactor and open nuclear fuel cycle system are mature.
5) R&D cost came from GAINS, as KI-10. Hereinafter the KI is referred to as “R&D refund”, unit is bln $. The development of fast reactors became a long term goal for many countries. Billions of dollars were spent on R&D in nuclear energy around the world. The Governments of the OECD countries spent about $50 billion (2007 prices) on R&D in the area of fast reactor technologies. Russia (inc. the USSR), which is not the OECD member, spent an estimated $12 billion on the R&D in the area of fast reactors [3]. At the moment, they are even higher.

5. Indicators evaluation

There is no focus on specific reactor technologies under the current trial consideration while general features of thermal and fast reactor units are studied. The characteristics correspond to steady state reactor operation, see table I below.

The following types of reactors were considered in the case study:

— Thermal reactor (TR) from TR1 to TR3 have the same technical characteristics from the point of natural resources (uranium) consumption and spent fuel/wastes generation. The main disparity between two types of thermal reactors TR1 and TR2 contains in the back end part of Levelized Unit Fuel Cost (LUFC). The table I shows, TR1 and TR2 has the same costs exclude disposal cost. For TR1 disposal cost is 850 $/kg HM (average value for the disposal), and for TR2 disposal cost is 1580 $/kg HM (top value for the disposal range). Among others, LUEC of TR3 reactor consist of disposal cost 850 $/kg HM and escalation of uranium base price — 100$/kg 2%/year. So, TR1 and TR3 has the same costs exclude front-end part. All the thermal reactors consume UOX-fuel see table I below.

— There are two types of fast reactor (FR) technologies in the current study. The first fast reactor FR1 is on the way for near time future. As a new technology, LUEC is higher than for thermal reactors, see table I. The fast reactor FR2 is a concept project with improved safety design and more attractive LUEC. FR1 consumes MOX-fuel, FR2 depending on the alternative system consumes MOX or enriched uranium fuel.

Content of U-235 in natural uranium is 0.007114.The plutonium extracted from the thermal and fast reactor fuel is assumed to be re-cycled. The input data on thermal and fast reactors and associated fuel cycles, technical characteristics necessary for the cases simulation was taken from the following source [4].

Discount rate for the case study is 5%. LUEC was calculated using NEST (NESA Economic Support Tool) [5]

In case of two component system (CNFC) LUEC calculated as the sum of LUEC of fast and thermal reactor multiplied by corresponding weight which is proportional to particular reactor type installed capacity in the system.

“TtMature” and “R&D refund” key indicator was evaluated based on international and domestic publications and expert opinions.

TABLE I: TECHNICAL, ECONOMICAL REACTOR AND NFC DATA.

Parameter	**Nuclear capacity**	**Nat. U cons**	**LUEC**	**Wastes**
Unit	MW(e)	t/y	$/MWh	t HM/y
TR1	1000	178	39[1]	23
TR2	1000	178	42[2]	23
TR3	1000	178	41[3]	23
FR1	800	0	50	1
FR2	1200	0	42[4]	1

TABLE II: PERFORMANCE TABLE.

KI **System**		**1) Nat U GWe ·h/t**	**2) LUEC, $/MWh**	**3) Wastes t/TWe ·h**	**4) TtMature, years**	**R&D refund, bln $**
20 GWe	**OFC1**	43	39	3.0	0	0
	OFC2	43	42	3.0	0	0
	joint CNFC1	86	44.5	0.1	8	12
	joint CNFC2	88	41.5	0.1	18	17
100 GWe	**OFC3 (TR3)**	43	41	3.0	0	0
	joint CNFC2	88	41.5	0.1	18	17
	CNFC3	210	42	0.1	18	17

TABLE III: SINGLE-ATTRIBUTIVE VALUE FUNCTION PARAMETERS.

KI **System**		**1) Nat U GWe ·h/t**	**2) LUEC, $/MWh**	**3) Wastes t/TWe ·h**	**4) TtMature, years**	**R&D refund, bln $**
20 GWe	**OFC1**	0	1	0	1	1
	OFC2	0	0.455	0	1	1
	joint CNFC1	0.96	0	1	0.33	0.2
	joint CNFC2	1	0.545	1	0	0
100 GWe	**OFC3 (TR3)**	0	1	0	1	1
	joint CNFC2	0.263	0.5	1	0	0
	CNFC3	1	0	1	0	0

6. Weights

The weights quantitatively represent the experts opinion regarding the importance of a particular KI. Changing weights means changing the strategy and each vector of numerical weights shows a particular option of the development of NES. Determination of weight values as a way of formalizing preferences of experts is the most important part in the formal application of multi-criteria methods, it requires authenticity in their assignment.

In the study weight grade is the following: 0 is the lowest priority and 1 is the highest priority. Table IV has two options of weights identification for 20 GWe and 100 GWe systems:

- For 20 GWe, option I: — “LUEC” KI weight is 0.25, “Wastes” KI weight is 0.3. The relatively low "LUEC" KI weight and high "Waste" weight means that there are some issues of spent fuel and wastes at the back end part of the fuel cycle and is very acute and requires considerable effort and funds in a relatively short time. This means that the "TtMature" KI also needs a valuable weight of 0.25.

For 20 GWe and option II: — “LUEC” KI weight is 0.5, “Wastes” KI weight is 0.2. This option represents the situation where the spent fuel and radioactive waste issue is less acute than in option I, and allows to postpone a decision.

In addition, in option I and II it is assumed that the reactor technology is sufficiently matured and investment in their creation are mostly returned ("R&D refund" KI is equal 0,05).

TABLE IV: PRIMARY WEIGHTING FACTORS

Final weight	20 GWe		100 GWe	
KI	I	II	I	II
1) Nat. U	0.15	0.15	0.2	0.2
2) LUEC	**0.25**	**0.5**	**0.35**	**0.4**
3) Wastes	**0.3**	**0.2**	**0.35**	**0.4**
4) TtMature	**0.25**	**0.1**	**0.05**	**0**
5) R&D refund	0.05	0.05	**0.05**	**0**

- For 100 GWe, option I has following weights: “LUEC” and “Wastes” KI weight is 0.35, “Nat. U” KI is 0.2 and “TtMature” and “R&D refund” KI weight is 0.05. This shows respectable difficulties with resources supply because of large electricity system and natural uranium resources limitation. The large 100 GW system creates conditions for the R&D refund and to complete the development of the technology. Therefore, the "TtMature" and "R&D refund" key indicators can be assigned small weight - 0,05.

Option II — the weight of indicators "LUEC" and "Waste" is 0.4. It increased in comparison with option I. The weight of the "Nat. U" KI is 0.2. The weights for "TtMature", "R&D refund" KI are 0. The increase in the economic importance of the region and the final stage of the nuclear fuel cycle is driven by the "TtMature", "R&D refund" KI.

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[1] 100 $/kg U nat, disposal 850 $/kg HM

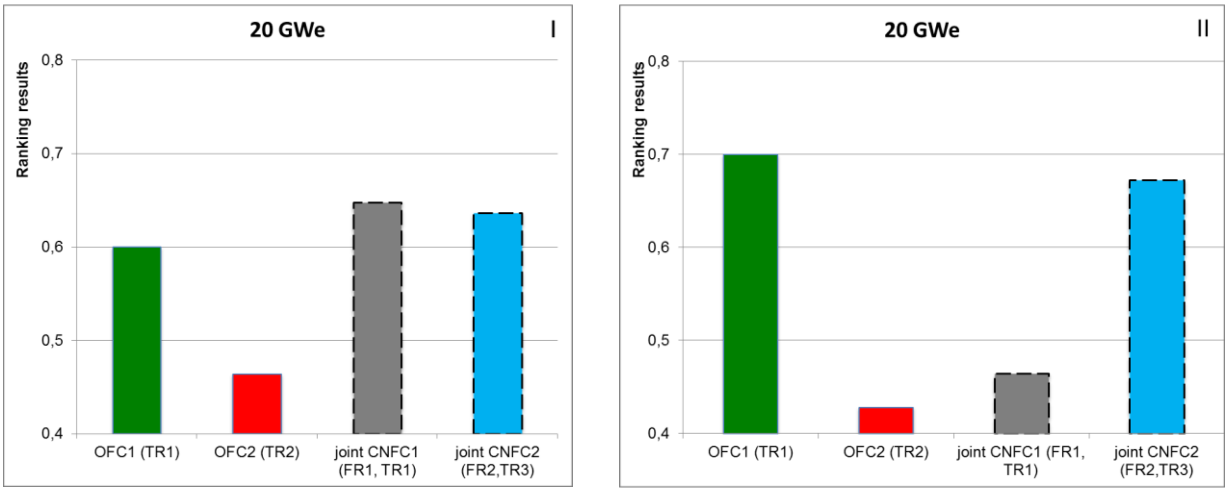
[2] 100 $/kg U nat, disposal 1580 $/kg HM

[3] disposal 850 $/kg HM, escalation of uranium base price - 100$/kg 2%/year.

[4] Serial units, construction time is 5 years

7. Ranking NES options (alternatives)

Based on above mentioned modelling conditions, *FIG. 1,2.* show the main results of comparative alternatives. *FIG. 1.* a) and b) show the result for 20 GWe country case. *FIG. 2.* a) and b) show the results for 100 GWe country case.

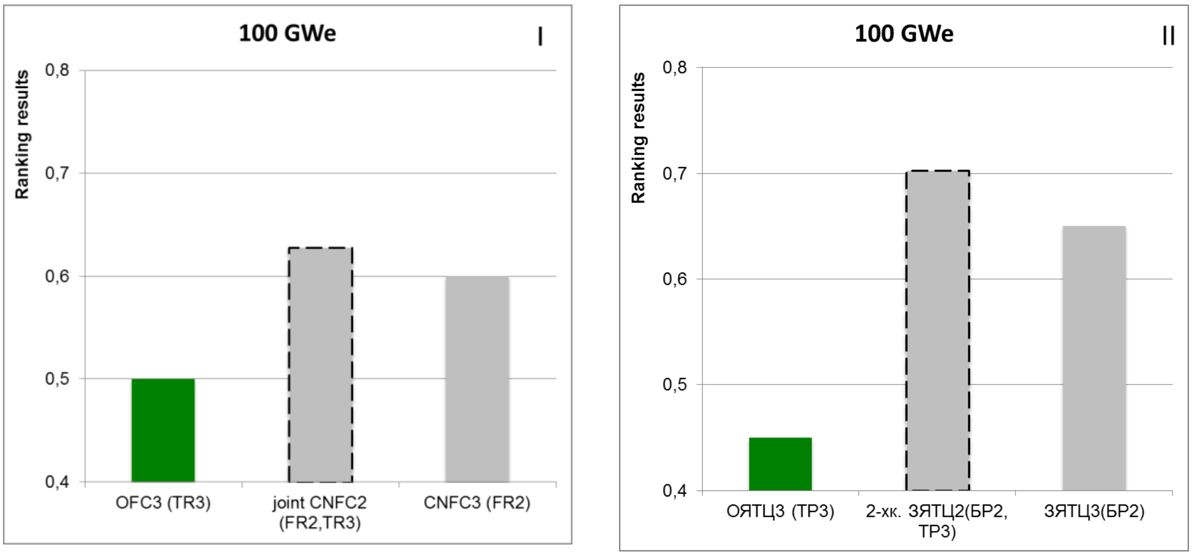


a) *b)*

FIG. 1. Nuclear energy systems comparative evaluation results for 20 GWe, option I — a), option II —b)

Option I shows that problems at the back end are not resolved; are perceived by society and the government as highly serious issue, the "Waste" KI has a grate weight. In this case, see *FIG. 1.* a), the potential of once through nuclear fuel cycle OFC1(TR1) will be lower then the joint close nuclear fuel cycle CNFC1 (FR1, TR1). This outcome shows that an acceptable solution to the problems of the back end of the NFC in a similar situation could be found on the directions of cooperation with the technology holder's country.

Option II allow to delay decisions regarding the back end part of the NFC, such as long-term interim spent fuel storage. The OFC1(TR1) system obtains the highest score/potential, see *FIG. 1.* b). It has 0.65 potential. This is an option where the best cost is the best alternative.



a) *b)*

FIG. 2. Nuclear energy systems comparative evaluation results for 100 GWe, option I — a), option II —b)

FIG. 2. shows, the large scale of NES gives preference to the systems with innovative technologies. The joint close nuclear fuel cycle CNFC2 is the best of the considered alternatives (among the option I and II). In option I joint close nuclear fuel cycle CNFC1 (FR1, TR1) has 0.58, in option II it has 0,65 (in the II compared with I, there is an increase in "LUEC" and "Waste" KI weights). In General, high scale of nuclear energy offers the possibility to develop innovative systems, create the conditions for a R&D refund.

Above mentioned examples demonstrate only a few capabilities of the developed model. Countries can choose their own track, setting the preferences using different weights. For some countries with expected high rates of nuclear energy development can be increased "Nat. U" key indicator weight, which will increase the potential of fast reactors and closed nuclear fuel cycle. In countries where the demand for electricity is low, and an environmental issues have a essential concern of public opinion the great influence on the choice of strategy can have a "Waste" KI weight increase, etc.

8. Conclusion

The comparative assessment of nuclear energy systems within the framework of KIND methodology was conducted for two scales of nuclear energy development: low power — 20 GWe and high power — 100 GWe. Five key indicators from different areas of the INPRO methodology were considered. A small number of key indicators in the study were selected to see the most significant trends and to ensure their maximum independence of one an other. The current mathematical model has shown:

- Priorities and preferences in the selection of key indicators, which are assumed at the stage of nuclear energy system strategy development and taken into account in the generated model via weighting factors, define the system architecture and its particular characteristics in comparison with other systems.
- Application of the mathematical model has demonstrated that for the most countries not planning to develop nuclear energy on the considerable scale, it is advisable to develop nuclear energy systems based on once through nuclear fuel cycle with thermal reactors. At the same time, if the issues at the back end of a fuel cycle are perceived by the society and the government as challenging, the potential of once through nuclear fuel cycle systems becomes lower than that of joint close nuclear fuel cycle based on thermal and fast reactors. This conclusion shows that an acceptable solution to the problems of the back end in the similar situation can be found on the way of cooperation with the country'holders of fast and thermal reactors, CNFC, as well as well-developed infrastructure of a two component system.
- The calculations performed with the use of the mathematical model generated for the countries planning a large scale nuclear energy development, have demonstrated that in this case the model gives preference to the systems based on fast reactors. For the countries seeking high rates of nuclear energy development and expecting nuclear fuel shortage, e.g. for India and China, the best of the above alternatives is a joint system with fast reactors with the fuel having short doubling time, and which are close to technological maturity. In the conditions of stabilisation of electricity consumption in the country in the long term, joint close nuclear fuel cycle based on thermal and fast reactors focused on the best economic indicators is becoming a priority.

— The sensitivity analysis of the systems under consideration representing the alternatives to possible changes of key indicators has allowed the effect of KI on the nuclear energy system potential measurement to be determined. The dependences obtained provide the possibility in principle to control the construction of nuclear energy systems with pre-defined characteristics.

9. Appendix 1: Sensitivity analysis

FIG. 1. shows a sensitivity example for 20 GWe capacity, "LUEC" KI for basic weighting factors, option I. A sensitivity study by iteration modelling was conducted to determine the potential scope of the technologies under variation of weights. The reference weight vector is presented in the table IV above. It is the starting point for iteration modelling were the weights from expert evaluation. Then, the value of each indicator was consistently changed from 0 to 1 with a step of 0.05. The values of the remaining four indicators were varied proportionally, so the total value of all weights was equal to 1 under each step. Based on experts opinion, the study determines the frame for each key indicator weight. The frame for "LUEC" KI is 0.2—0.8. The most interesting aspect is that there is an intersection of the system potentials (lines and areas on the sensitivity *FIG. 1.*). Figure shows fluctuation areas for the KI separately. Yellow vertical line on the figure shows reference "LUEC" weight from the table IV.

The gray dashed line defines the potential of joint CNFC1(FR1, TR1) system. The blue line defines the potential of joint system CNFC2 (FR2, TR3). The green line shows the potential of nuclear fuel cycle system OFC1 (TR1) based on thermal reactors TR1, the red line shows the potential of once through nuclear fuel cycle system OFC2 (TR2) based on thermal reactors TR2. The shaded gray area on the figure shows the difference between the potential of a close nuclear fuel cycle based on different type of fast reactors.

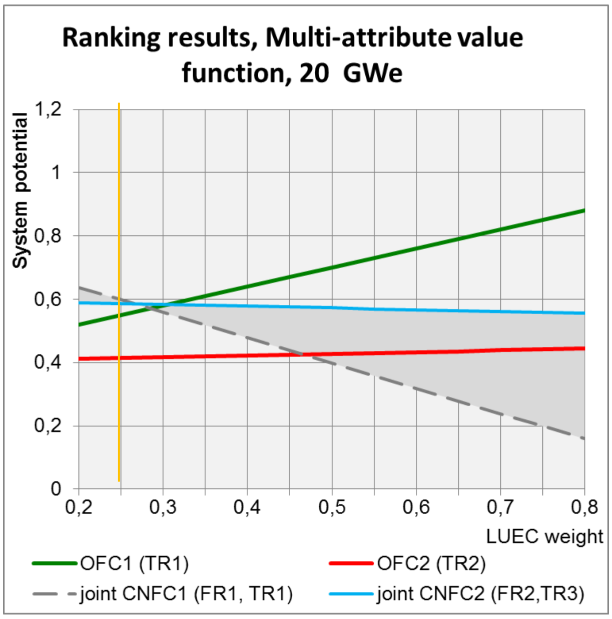


FIG. 1. 'Linear weight' to LUEC weights sensitivity, option I

FIG. 1. shows, at 20 GWe electrical system capacity: as the "LUEC" key indicator weight rises from 0.2 to 0.3, the potential of CNFC2 is bigger than the potential of OFC1 and OFC2;

as the “LUEC” key indicator weight exceeds 0.3, the OFC1 potential starts to surpass that of the CNFC2 and other systems.

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