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D6.2 Poly-generation options for MSR





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Executive Summary

The objective of this deliverable is to identify the most promising end-use applications, other than electricity production, for exploiting the flexible use of Molten Salt Reactors (MSRs), with a focus on applications requiring thermal energy. To this end, a trade study was conducted with the contributors to Task 6.2 in order to compare several candidate end uses and identify the main limitations and opportunities related to their operating conditions, technical requirements and potential integration with MSR systems.

The trade study methodology was based on the definition of mandatory requirements (“Musts”) and weighted selection criteria (“Wants”). The Musts were used to verify the compatibility of each candidate application with the assumed technical capabilities and safety constraints of the nuclear power plant. The Wants were then used to compare the retained solutions according to criteria such as economic viability, initial investment, technology readiness level, flexibility, market demand, decarbonization potential, integration constraints and compatibility between power demand and supply. Several candidate applications were considered, including hydrogen production technologies, industrial heat applications, district heating, water desalination, oil refining, fertilizer production and paper production. Steel production was excluded from the retained options because its temperature requirements exceed the assumed thermal capability of the considered MSR configuration. End uses relying only on electricity, such as alkaline electrolysis, proton exchange membrane electrolysis and data center electricity supply, were also excluded from the trade study scope, as they do not require a specific thermal coupling with MSRs.

The ranking of the Wants showed that the most influential criteria were the existence of market demand, the decarbonization potential of the solution and its economic viability. The final comparison of the weighted scores did not lead to a unique ranking shared by all participants. However, district heating emerged as the most robust option overall, as it was consistently ranked within the top three by all participating entities. Chemical industry applications also appeared promising, with consistently high rankings across the participant matrices. Other options showed more dispersed rankings. Water desalination and oil refining were ranked very differently depending on the participant, reflecting differences in assumptions regarding market context, decarbonization impact, long-term industrial demand and integration constraints. Hydrogen production routes also showed contrasted results: thermochemical routes such as Sulfur-Iodine and Copper-Chlorine generally ranked lower due to lower maturity and limited available information, while Solid Oxide Electrolysis Cell hydrogen production appeared more promising for some participants but remains affected by technology readiness and integration uncertainties.

The study did not lead to a complete consensus on the ranking of all candidate solutions, but it identified the most relevant factors to be further investigated in future work. These include economic viability, CO₂ reduction potential, process efficiency, technology readiness level, and compatibility between industrial heat demand and MSR operating conditions. Overall, the results provide a first structured basis for identifying promising non-electric applications of MSRs and for defining future analyses required to assess technical feasibility, market relevance and integration constraints.



Keywords: European Molten Salt Reactor Designs, MSR, flexibility, cogeneration.



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1 Introduction

The objective of this deliverable is to identify the best end-usages, other than electricity production, for exploiting flexible use of the MSRs. To this end, a trade study was conducted among all contributors to this task, identifying limitations and opportunities related to the operating conditions and needs of said end-usages. Nine different end-uses have been considered for this study, each of them representative of a substantial use of thermal energy that could be decarbonized by nuclear energy.

Section 2 describes the main uses of heat consumption in industry and civil society. These uses need different power levels and, depending on the heat source used, they also release a greater or lesser amount of CO₂. They present various new markets for nuclear energy production companies.

Section 3 describes the trade study method, which was used in the frame of this task. A trade study must follow a definite set of steps to identify the most relevant criteria leading to a successful comparison between candidate solutions.

Section 4 describes the application of this method, to compare different end-usages for MSRs in terms of expected performance regarding various requirements.



2 Main context: Need for industrial, low carbon heat

Energy decarbonation, as well as energy supply security and sovereignty, are strategic goals for the European Union (EU). The energy transition strategy relies heavily on substantial electrification of many sectors, replacing fossil fuels, supported by the accelerated deployment of renewable electricity generation capacity. Nuclear and renewable energies are considered as the backbone of a carbon-free European power system. However, decarbonizing only the electricity sector is not enough, representing only about one-third of the way to net-zero emissions [1]; achieving net-zero emissions will require a radical transformation in the supply, conversion, and usage of energy. That is why it is crucial to address the use of nuclear energy beyond electricity production. In this case, nuclear reactors can be dedicated to a non-electric application or operate in co/poly-generation. Depending on the considered nuclear technologies (Generation 2, Generation 3 and Generation 4), the temperature level of the produced heat can range between 100°C and 1200°C.

Several European projects already studied specific co-generation solutions, such as NPhyCo (**N**uclear **P**owered **H**ydrogen **C**ogeneration), GEMINI 4.0 and TANDEM (Small Modular ReacTor for European **S**afe **a**nd **D**ecarbonised **E**nergy **M**ix). These projects consider the production of low-carbon hydrogen with nuclear implementing different processes:

- Low Temperature Electrolysis (LTE) for NPhyCo: the Alkaline ELectrolysis (AEL) is the most mature process of electrolysis. Most large-scale hydrogen production by electrolysis is today based on alkaline electrolyzers. The share of Proton Exchange Membrane electrolysis (PEM) is growing because of the specific advantages of this technology. Both processes use electricity and water only. To some extent, the possibility of high temperature steam electrolysis was investigated as well.
- High Temperature Steam Electrolysis (HTSE) for TANDEM: in this case, the SOEC (Solid Oxide Electrolysis Cell) technology is considered. It uses heat (produced by the nuclear reactor and recovered from the electrolysis process) and electricity to electrolyze water molecules; its efficiency is higher than LTE. However, its maturity remains one step behind LTE because the hydrogen production with SOEC still requires to be scaled up in the industrial scale (the GW scale). Development work is ongoing to meet this objective in the coming years.
- LTE, HTSE, thermo-chemical electrolysis or thermo-chemical water splitting such as the Sulphur-Iodine (S-I) process and Copper-Chlorine process (Cu-Cl) for GEMINI 4.0: the process to be coupled with the HTR is still open. It can use only electricity, only heat or both electricity and heat.

Another initiative, the NC2I (European **N**uclear **C**ogeneration **I**ndustrial **I**ntiative), aims at demonstrating innovative and competitive energy solutions for the low-carbon cogeneration of heat and electricity, and hydrogen production based on nuclear energy [2]. The initiative is based on the observation that there is an important potential market for industrial heat in most industrialized countries, with for instance a very large steam market [3].



This market is driven by the research of supply security and predictability (given the volatility of oil and gas) but also by the will to reduce carbon footprint and improve air quality in industrialized countries.



3 The Trade Study method

3.1 General presentation

A Trade Study is a System Engineering (SE) tool used by multidisciplinary teams in order to identify the most balanced technical solutions among a set of proposed viable solutions. Its objectives are the following:

- To be able to choose among alternative designs with uncertain or only partial information available.
- To make use of a multidisciplinary team, in order to benefit from a diversity of points of view on a given technical question.
- To identify key differentiating features between alternatives (among which the existence of a *killer* criterion, excluding a solution).
- To identify priority studies to be launched to be able to eventually differentiate candidate solutions if choice is not possible between alternatives (or too narrow).

The name comes from the fact that early design studies will often result in a tradeoff between performance, cost and risk when trying to find a satisfactory solution. Trade studies are a valuable tool in many fields of engineering (from aerospace to software development) to find the configuration (or design option) that best meets sometimes conflicting performance requirements.

Though they may be performed at any step of a given system's lifecycle, trade studies are often conducted at early stages of design, when quantified information can be scarce. In this context, experts' points of view are extremely valuable, and a well-defined method can be necessary to channel them into a decision-making process.

Trade Studies provide a metric for comparing chosen criteria first, and ultimately a quantified way to compare candidate solutions relatively to one another. Though not always conclusive, this method also points towards fields of interest for future studies on the same subject.

3.2 Detailed process

Ways for conducting trade studies can vary (e.g. see [4]), but the core principle remains very similar. It consists in a cross-evaluation of candidate solutions to a design problem with a set of weighted selection criteria under the form of a matrix. In the frame of the ISAC project, Trade Studies have been conducted to select among preliminary design possibilities. The Trade Study performed in the frame of ENDURANCE follows the same process, illustrated by Figure 1:

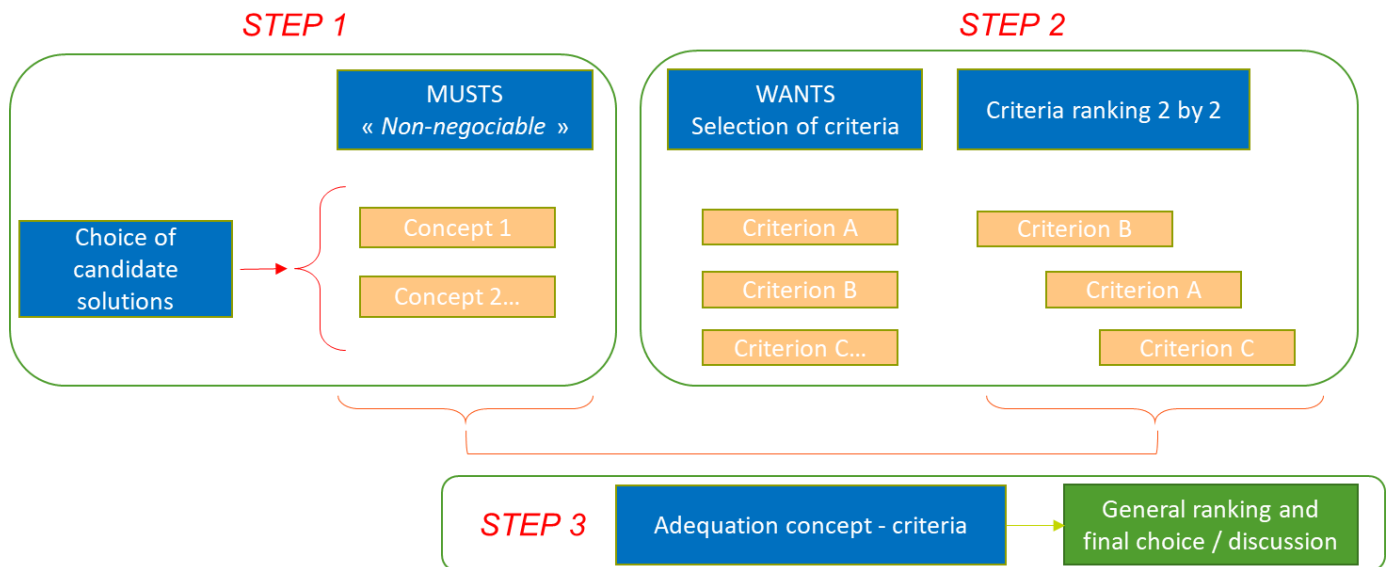


Figure 1: Step-by-step process of a trade study

The corresponding steps are described in detail in subsections hereafter.

3.2.1 Step 1: choice of candidate solutions and identification of the *Musts*

The definition of the *Musts* criteria has the objective of identifying and thus rejecting any solution which does not comply with mandatory technical or safety requirements. This preliminary phase is used as a basis for the study: it bounds the space in which alternatives can be selected for examination. It also sets up the baseline and therefore confirms the choice of the candidate solutions, as adequate possibilities for the final choice at the end of the process.

The identification of the candidate solutions also constitutes a fundamental step to the process and should be carefully conducted. The alternatives can be composed of different versions or design of the same concept: they need to be similar enough for their comparison to be relevant, and for the chosen criteria to apply to every alternative. However, their choice must also reflect a form of diversity for the trade study to be of effective value in the design process.

3.2.2 Step 2: selection of criteria (*Wants*) and weight assessment

Once the candidate solutions have been selected, and their compliance with the *Musts* requirements verified, the set selection criteria (*Wants*) can be formulated by the team. In contrast to the requirements (*Musts*), the *Wants* can be partially met by alternatives, the degree at which they are met being the measure for future evaluation. Their choice is therefore also fundamental for the trade study. Though difficult to achieve, independence between criteria should be searched. The cumulative number of candidate solutions and selection criteria (*Wants*) should remain limited, as every criterion added mechanically increases the size of the future decision matrix. Since every criterion is ranked against its neighbors, the number of comparisons to perform rapidly increases and can significantly lengthen the whole process past a certain number.

Once the set of *Wants* has been decided and confirmed, the weight selection phase can be conducted. It consists in a ranking of criteria by pairs each of them being confronted with every other. The ranking process consists in attributing a grade (on a scale from 1 to 5 in our case) showing the relative importance of a criterion with regards to every other. For instance, in the



case of a comparison between criteria A and B, a score of A1 would mean that criterion A is slightly more important than criterion B, whereas a score of B5 would mean that criterion B is extremely more important than criterion A. It thus results in a set of weights attributed to each criterion: the weight reflects the overall importance of the criterion and its future impact on the final decision.

The ranking phase is a collective process, conducted during a dedicated meeting. The grade of every pairwise tournament is chosen after discussion, consensually. Grading can include experts' judgement but also quantified elements when available. The result of this phase is a triangular matrix (due to obvious symmetry in the process), along with the weight corresponding to each criterion.

3.2.3 Step 3: Cross-comparison, final ranking and choice / discussion

The final process of the trade study consists in the cross-comparison between the candidate solutions from step 1 with the weighted criterion from step 2. The objective of this phase is to quantify the suitability of each candidate solution to each weighted criterion. The resulting score, once summed along the different criteria, will result in a final grade for each solution.

This final grading allows a ranking between the candidate solutions, but this ranking itself does not constitute the end goal of the trade study. The score obtained by each candidate solution relatively to the others is also a matter of comment, two solutions very close in terms of score meaning the process did not completely succeed in providing sufficient differentiation.

Furthermore, the values of the weights obtained at the end of step 2 is also a valuable result from any trade study, as it helps pinpoint which set of criteria carries the most impact for future studies on the subject.



4 Analysis and selection of end-usages options

As mentioned, the Trade Study method has been used within task 6.2 of the ENDURANCE project. The goal of this task is to identify limitations and opportunities related to the operating conditions and needs of MSR's thermal power end-usages.

4.1 *Composition of the team and formulation of the Trade Study's main question*

The team was composed of 10 members:

- 2 members from Framatome,
- 4 members from PoLiMi,
- 1 member from CEA,
- 3 members from CNRS.

Members reflected a variety of disciplines linked with MSR technology, but mostly centered around plant operation, neutronics and thermal hydraulics.

As mentioned in Section 3, one of the main issues of a trade study is to correctly formulate the main questions to be treated, as well as to identify the *Musts*. In the case tackled here, the first question was a semantic one. The subject originally concerned poly-generation and end-usage. The question was the delimitation of the scope of the study. Are end-usages that require only thermal power to be considered? Is the scope limited to co-generations solutions, for which the nuclear power plant produces both electricity and thermal energy?

The approach adopted in the present trade study is to consider all end-usages possible, *i.e.* both those that can be plugged to an electricity producing MSR's (poly-generation solution) and those that require the full power of an MSR's. This choice was made in order not to constrain too much the subject, on the consideration that in both cases, it opens new markets for MSR's and allows their flexibility of use. However, the subject was restrained to the end-usages that require also thermal power. The end-usages that require only electricity are already well known and do not necessitate any adaptation specifically for MSR.

The following list of end-uses have been gathered by the participants:

- Hydrogen production:
 - Alkaline Electrolysis (AEL): This process needs electricity and water and is already quite developed. Some information on it can be found in the European project NPHyCo. Given that it requires electricity and not heat, it has not been considered for the present trade study.
 - Proton Exchange Membrane electrolysis (PEM): This process also needs electricity and water but is less developed than AEL. Some information on it can be found in the European project NPHyCo. Given that it requires electricity and not heat, it has not been considered for the present trade study.
 - Solid Oxide Electrolysis Cell: This process needs heat and electricity and is supposed to have a better efficiency than the previous solutions of hydrogen production.



Some information on it can be found in the European project Tandem. Its main drawback is its relatively low TRL (~3).

- Sulphur-Iodine (S-I) or Copper-Chlorine (Cu-Cl): These processes are thermo-chemical processes. Their efficiency is supposed to be intermediate (better than AEL or PEM but not better than Solid Oxide Electrolysis Cell), but its TRL remains relatively low (~4/5). Some information concerning this process can be found in the European project Gemini 4.0.
- Heat generation for industrial steel production: Steel production is heat-expensive, and requires very high temperatures ($\geq 1000^{\circ}\text{C}$).
- Heat generation for industrial non-steel production:
 - Paper production: paper production requires medium amount of heat, mainly for the drying phase of the paper. It can be considered both as an end usage (if the paper production plant is relatively large) or as a co-generation solution.
 - Chemical industry: many chemical processes require heat and/or steam to be achieved. It can be considered either as end usage or as a co-generation solution depending on the size of the chemical plant.
 - Oil refining: Oil refining needs a phase of distillation to separate the heavier molecules in petroleum from the lighter ones. The temperature needed is within a reasonable range ($\sim 450^{\circ}\text{C}$). It can again be considered either as end usage or as a co-generation solution depending on the size of the refinement plant.
 - Fertilizers production: some processes for fertilizer production can rely on heat, such as the Haber-Bosch process. It needs temperatures between 350°C and 500°C and consumes a lot of H_2 . Once again, it can again be considered either as end usage or as a co-generation solution depending on the size of the production plant.
- District heating: This is a relatively well-known case of co-generation. This already exists to use the combustion heat from waste burning plants, or to recover the heat released by the cooling of computing centers.
- Water desalination: This is also a well-known case of co-generation.
- Data centers electricity supply: This end usage is becoming increasingly popular as society rely more and more on IA powered by massive data and computing centers. However, as previously mentioned, this end-usage only uses electricity, and does not necessitate any adaptation specifically for MSR. Thus, it has not been considered for the present trade study.

The final list of end-usages considered is hydrogen production (with both Solid Oxide Electrolysis Cell, Sulphur-Iodine and Copper-Chlorine), steel production, paper production, chemical industry, oil refining, fertilizer production, district heating and water desalination.



The second question that arises quite directly after the previous one is the questions of the kind of MSR considered. In task 6.1 [5], three types of MSR have been considered for flexibility, but no preferable solution has emerged. In order to get rid of this complexity and to avoid redoing the first task, the working hypothesis was made that a MSR that can respond to the needs exists. From this theoretical reactor, the same power output as for the MSFR-type can be expected with the same controllability as for the ARAMIS-type. Thus, the choice of the end-usage is partially decorrelated from the choice of the MSR. Partially only because, as presented in the following parts, the maximal temperatures and power outputs condition some of the must.

With these considerations in mind, the main question governing the trade study is the following:

Among all the solutions considered, which of them is the best suited to a non-electrical end-usage of an MSR?

The goal of the Trade Study is to provide elements of an answer to this question by distinguishing between the listed end-usages. The Trade Study process will help identify to which extent these end-usages are suited to receive thermal energy from a nuclear power plant.

4.2 Identification of the Musts

As previously stated, the formulation of *Musts* is the preliminary phase consisting in defining non-negotiable requirements for the selection (or rejection) of candidate solutions. *Musts* were collectively chosen around the following themes:

- Performance scope: End-usage solution must be compliant with the technical capacities of the nuclear power plant. For example, the end usage solutions must not need a temperature outside of the range that the MSR power plant can produce.
- Safety: The end-usage solutions must not reduce the safety of the nuclear power plant. Moreover, the regulatory authority must allow this use of the nuclear power plant. It is important to note that this trade study is extremely theoretical, without any feedback from the regulatory authority. This second *Must* from the Safety subpoint is thus entirely theoretical too.
- Social acceptance: The end-usage solution must be socially acceptable, and for the greater good. This is part of a wider concept of nuclear acceptability and is not only related to co-generation and end-usages.

Based on these core principles, a set of *Must* requirements was established, summed up in the following table.

Table 1: *Must* requirements

Category	Must Requirement
Performance scope	End-usage solution must be compliant with the technical capacities of the nuclear power plant. The temperature needed, for instance, must be lower than 550°C.



Safety	The end-usage solutions must not reduce the safety of the nuclear power plant. The safety margins must remain sufficient.
Safety	The regulatory authority must allow this use of the nuclear power plant.
Social acceptance	The end-usage solution must be socially acceptable, and for the greater good.

4.3 Agreement between the solutions and the Musts

All the solutions except for steel production present a good agreement with the identified *Musts*. Concerning Steel production, the only drawback concerns the performance scope. Steel production needs a temperature higher than 1000°C, which is largely superior to the maximal temperatures that the MSR can provide (~550°C).

All the solutions except heat generation for steel productions are thus retained.

4.4 Identification, comparison and ranking of the Wants

Following the workflow previously defined, the next step of the Trade Study was dedicated to the formulation and comparison of the *Wants* criteria pairwise to generate a matrix. These criteria were established collectively by the team during dedicated sessions. As for the *Musts*, the identified criteria can be gathered under categories, labelled as follows:

- Economic viability
- Initial investment
- Resources utilization/efficiency of the technology
- TRL
- Cohabitation
- Flexibility
- Availability of existing structures
- Demand for the solution
- Integrability of power plant to the solution
- Decarbonation
- Life-time compatibility
- Power demand and supply compatibility

As previously described, the *Wants* criteria were collectively chosen and then compared during dedicated meetings. It is important to underline here that the outcome of a Trade Study at every step is unique since it reflects the composition of the team as well as the different discussions occurring during its successive phases. It should also be noted that none of the following criteria



are accompanied by quantified values. Indeed, the role of these criteria is to serve as a basis of relative comparison between candidate solutions, to determine which of them leans the closest to one or many *Wants*.

A total of 12 criteria were collectively described and labelled. A 13th criterion, named “Efficiency of the BoP” was originally considered. It was finally discarded due to its proximity with the “efficiency of the technology” criterion. Keeping it would have been redundant. The 13 criteria are summed up in the following table.

Table 2: *Wants* criteria

	Category	Description
A	Economic viability	How much the use of this solution costs compared with others.
B	Initial investment	How much investment is needed initially to put such a solution in place.
C	Resources utilization/efficiency of the technology	How efficient is this solution compared with the others.
D	TRL	How mature is the technology of the solution.
E	Efficiency of the BoP	How efficient is the thermal interface for this solution compared with other solutions. Discarded. Already included in C.
F	Cohabitation	To what extent can the solution be used with other (co-gen or end usages) solutions on the same site / with the same MSR system.
G	Flexibility	Operational constraints (e.g. ramping limits, minimal power requirements, ...) and need for off-design operation. Impact on the components (degradation) of the flexible operation (e.g. for desalination, ageing important if too many variations). Sensitivity to the power plant shut down.
H	Availability of existing structures	Existence of infrastructures of which the power plant can be plugged (e.g. district heating in northern European countries).
I	Demand for the solution	Existence of a market for the solution and perspective of growth.
J	Integrability of power plant to the solution	How the solution is adapted with the fact that a power plant needs an exclusion area. If the solution needs an exclusion area (e.g. chemical plants), how is it compatible with the presence of a nuclear power plant.



K	Decarbonation	How many tons of CO ₂ can be avoided with the implementation of the solution. Considerations are only for the operational cost in term of CO ₂ and not the full life cycle.
L	Life-time compatibility	Are the lifetime of the reactor and the facility of the same order of magnitude. If not, to what extent are they compatible.
M	Power demand and supply compatibility	Are the needs, in term of power, of the solution compatible with the amount of power that the power plant can provide.

The following step of the Trade Study method consists in ranking these Wants by comparing them two by two. To this end, a triangular matrix is filled, as shown in Figure 2 below:

	Category	Description	A	B	C	D	E	F	G	H	I	J	K	L	M
A	Economical viability	How much the use of this solution costs compared with	A1												
B	Initial investment	How much investment is needed initially to put such a solution in place.		B1											
C	Ressource utilization/efficiency of the technology	How efficient is this solution compared with the others.			C1										
D	TRL	How mature is the technology of the solution.				D1									
E	Efficiency of the BoP	How efficient is the thermal interface for this solution compared with other solutions.					E1								
F	Cohabitation	At what extend the solution can be used with other (co-gen or end usages) solutions on the same power plant.						F1							
G	Flexibility	Operational constraints (e.g. ramping limits, minimal power requirements, ...). Need for off-design operation. Impact on the components (degradation) of the flexible operation (e.g. for desalination, ageing important if too many variations). Sensitivity to the power plant shut down.							G1						
H	Availability of existing structures	Existence of infrastructures of which the power plant can be plugged (e.g. district heating in northern European countries).								H1					
I	Demand for the solution	Existence of a market for the solution. Perspective of growth.									I1				
J	Integrability of power plant to the solution	How the solution is adapted with the fact tha a power plant needs an exclusion area. If the solution needs an exclusion area (e.g. chemical plants), how is it compatible with the presence of a nuclear power plant.										J1			
K	Decarbonation	How many tons of CO ₂ can be avoided with the implementation of the solution Considerations are only for the operational cost in term of CO ₂ and not the full life cycle.											K1		
L	Life-time compatibility	Are the life-time of the reactor and the facility of the same order of magnitude. If not, to what extend are they compatible.												L1	
M	Power demand and supply compatibility	Are the needs, in term of power, of the solution compatible with the amount of power that the power plant can provide.													M1

Figure 2: Wants ranking: empty matrix

As explained in section 3.2.2, each cell must be filled with a grade attributed by the team in a collective manner, on a scale of 1 to 5. This grade reflects how important one criterion is relative to another. For instance, when comparing criterion A with criterion B, grade A5 would mean that criterion A is much more important than criterion B. Reciprocally, grade B1 would mean that criterion B is very slightly more important than criterion A.

This step is capital in the process, as the final weight attributed to each criterion greatly impacts the result of the Trade Study. Directly comparing criteria with sometimes very different



formulations and applications can prove to be a delicate task, hence the need for a collective consensus on each ranking.

The filled matrix with all the rankings is displayed on Figure 3 below:

	Category	Description	A	B	C	D	E	F	G	H	I	J	K	L	M
A	Economical viability	How much the use of this solution costs compared with others.	A1	A2	A3	A1	A0	A5	A2	A1	I1	A4	K1	A3	A3
B	Initial investment	How much investment is needed initially to put such a solution in place.		B1	C2	D1	B0	B4	G4	B1	I3	B4	K4	B4	B1
C	Ressource utilization/efficiency of the technology	How efficient is this solution compared with the others.			C1	D1	C0	C4	G2	C4	I4	C2	K3	C4	M3
D	TRL	How mature is the technology of the solution.				D1	D0	D3	D1	D4	I3	D4	K2	D4	D2
E	Efficiency of the BoP	How efficient is the thermal interface for this solution compared with other solutions.					E0	F0	G0	H0	I0	J0	K0	L0	M0
F	Cohabitation	At what extend the solution can be used with other (co-gen or end usages) solutions on the same power plant.						F1	G3	H2	I5	J2	K4	F1	M2
G	Flexibility	Operational constraints (e.g. ramping limits, minimal power requirements, ...). Need for off-design operation. Impact on the components (degradation) of the flexible operation (e.g. for desalination, ageing important if too many variations). Sensitivity to the power plant shut down.							G1	G3	I1	G3	G1	G3	G1
H	Availability of existing structures	Existence of infrastructures of which the power plant can be plugged (e.g. district heating in northern European countries).								H1	I5	J1	K4	L1	M3
I	Demand for the solution	Existence of a market for the solution. Perspective of growth.									I1	I3	I3	I4	I3
J	Integrability of power plant to the solution	How the solution is adapted with the fact tha a power plant needs an exclusion area. If the solution needs an exclusion area (e.g. chemical plants), how is it compatible with the presence of a nuclear power plant.										J1	K3	J2	M1
K	Decarbonation	How many tons of CO2 can be avoided with the implementation of the solution Considerations are only for the operational cost in term of CO2 and not the full life cycle.											K1	K4	K3
L	Life-time compatibility	Are the life-time of the reactor and the facility of the same order of magnitude. If not, to what extend are they compatible.												L1	M4
M	Power demand and supply compatibility	Are the needs, in term of power, of the solution compatible with the amount of power that the power plant can provide.													M1

Figure 3: Wants ranking: filled matrix

As mentioned before, criterion E has been discarded due to its proximity with criterion C. This discarding occurred during the Wants classification meeting. To do so, the line has been put to 0. This way, the overall weighing process is not impacted. It is as if criterion E has never been considered in the first place.

In order to better visualize the main tendencies of this ranking, Figure 4 shows the total score raised by each criterion, corresponding to the sum of the weights it was given in the matrix.

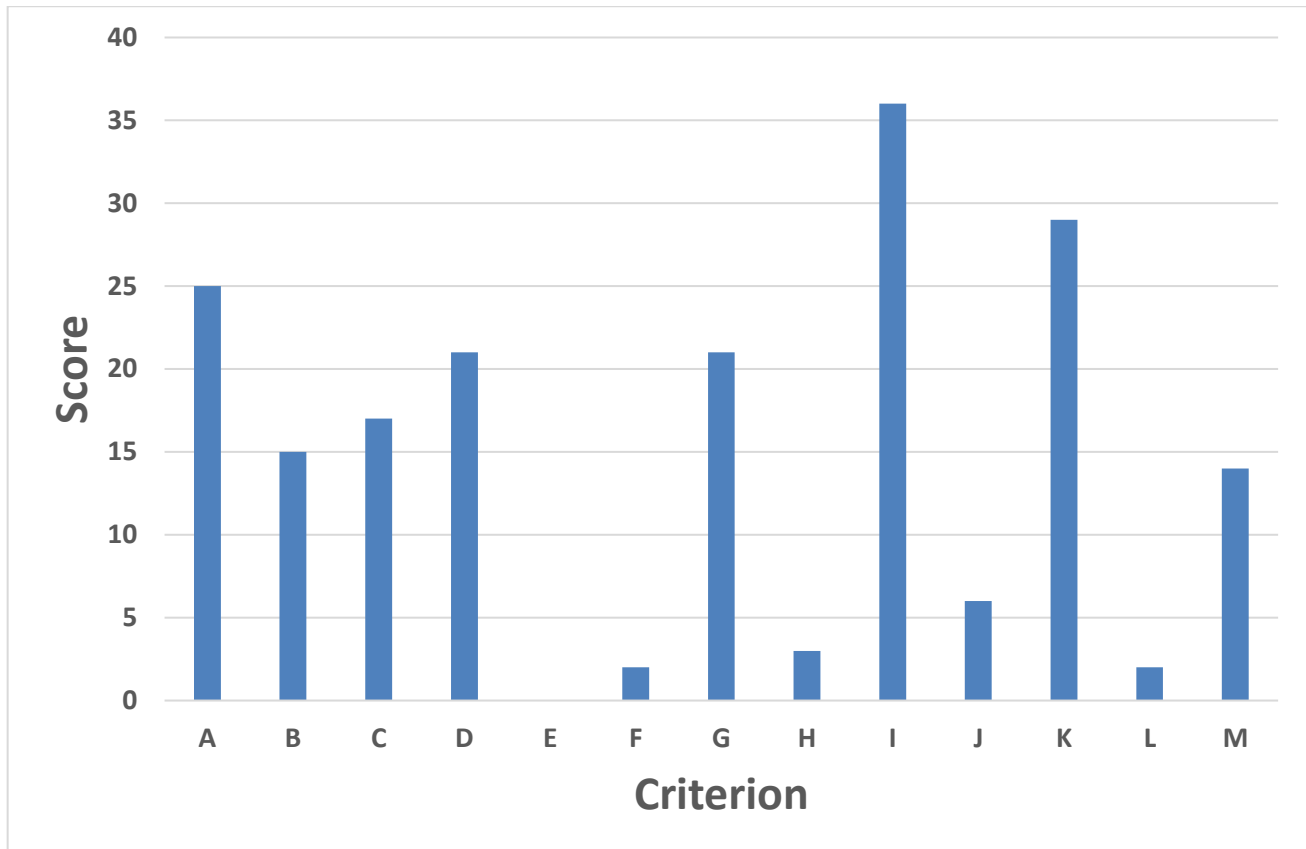


Figure 4: Total weights achieved by each criterion

The following points can be underlined:

- Criterion I, corresponding to the existence of a demand for the solution – *i.e.* the existence of a potential market – ranks the highest. Even though the Trade Study was done by a panel of technical experts, with little commercial objectives, it was acknowledged that for a solution to have a chance to be achieved, it has to respond to a commercial demand. This point can be considered *a posteriori* quite obvious, so it is not incongruous to find it ranking the highest.
- Criterion K, corresponding to the decarbonation capacity of the solution, comes second, and not too far from the first one. It was considered primordial by the participants that the solution helps to reduce the carbon footprint of society.
- On the other hand, both criteria F and L rank the lowest: the capacity of the solution to be as long lived as the power plant and its capacity to cohabit with another solution was not considered primordial.
- The ranked criteria can be roughly separated in three categories of lower , middle and higher ranks:
 - Criteria F, H and J and L with lower weight values.
 - Criteria B, C, D, G and M with middle weight values.
 - Criteria A, I and K with higher weight values.



A lower weight value does not necessarily mean that the corresponding criterion is overall irrelevant; Indeed, the integrability of the end usage solution to the power plant is key in the design process. This limits the feasibility of such a project. But in the frame of this Trade Study, criteria related to economical viability and decarbonation have been judged of higher importance. The participants considered that if the market exists, the solution is thus economically viable and helps reduce the carbon footprint of society, a solution will be found to realize it.

4.5 Final ranking

The last step of the Trade Study analysis is the cross-comparison of the candidate solutions with the set of weighed criteria. Each solution is given a grade (from 1 to 5) when confronted with each of the 12 criteria previously described.

The final ranking matrix to be filled by each participant (or group of participants) is described in Figure 5 below:

Alternatives	Criteria	A	B	C	D	F	G	H	I	J	K	L	M	Total score
	Score	25	15	17	21	2	21	3	36	6	29	2	14	
	Percentage score	13.09	7.85	8.90	10.99	1.05	10.99	1.57	18.85	3.14	15.18	1.05	7.33	
Hydrogen : Solid Oxide Electrolysis Cell	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen : Sulfur-Iodine	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen : Copper-Chlorine	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Generation : Paper production	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Generation : Chemical industry	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heat Generation : District heating	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water Desalination	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oil refining	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fertilizer production	Grade by criterion													0
	Weighted score	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 5: Final results: empty matrix

The grade attributed by the participant to the candidate solution regarding a given criterion will be multiplied by the weight of the corresponding criterion. The final grade of the solution will be the sum of these components over the criteria, allowing for comparison between the solutions.

Contrary to the weighing process of the criteria, this phase was performed by each entity (Framatome, CEA, CNRS, PoLiMi) separately, and without communication with the rest of the team before comparison of the results. The corresponding result matrices were then compared between entities. A summary of the results is shown in Table 3.

The grades allocated by each entity were chosen based on the expected performance of the solution regarding the different criteria, as well as the current knowledge of these possible performances. It should be noted that for the criterion D, the “TRL”, all the solutions except three got the maximal mark. The three solutions with lower TRL are the hydrogen production solution. This denotes the fact that for the solutions selection, the participants focused on realistic, already existing solutions, in order to have the maximum amount of information to class them. As a consequence, even though criterion D is quite important, with a quite important weight, it does not participate strongly in the discrimination of the best solution.



Table 3: Final ranking of candidate end-use applications.

Candidate end-use application	Framatome	CEA	CNRS	PoliMi
District heating	2nd — 3.98	1st — 4.28	2nd — 4.42	3rd — 3.60
Water desalination	9th — 2.19	5th — 3.22	1st — 4.79	8th — 3.19
Oil refining	1st — 4.25	9th — 2.55	3rd — 4.08	5th — 3.27
Chemical industry	3rd — 3.85	4th — 3.28	3rd — 4.08	1st — 3.76
Paper production	5th — 3.20	2nd — 3.85	6th — 3.89	9th — 3.13
Fertilizer production	4th — 3.54	7th — 2.86	5th — 4.01	4th — 3.59
Hydrogen — Solid Oxide Electrolysis Cell	6th — 3.16	3rd — 3.42	7th — 3.42	2nd — 3.67
Hydrogen — Sulfur-Iodine	7th — 2.73	8th — 2.69	8th — 3.32	6th — 3.26
Hydrogen — Copper-Chlorine	8th — 2.62	6th — 3.19	9th — 3.20	6th — 3.26

All grades provided by participants are summarized in Appendix A. Even though the final ranking has been done by the participants independently, the results present interesting similarities. District heating emerges as the most robust option overall, as it is consistently ranked within the top three by all participating entities: first for CEA, second for Framatome and CNRS, and third for PoliMi. This indicates a strong convergence on its relevance, profiting from the fact that it is an already existing technology, with a clear possible market and a very easily measurable impact.

Chemical industry applications also appear as a robust candidate, ranking within the top four for all participants and first for PoliMi. This suggests that industrial heat supply to chemical processes should be considered among the priority applications for further assessment. Other options show much stronger dispersion. Water desalination ranges from first place for CNRS to ninth for Framatome and eighth for PoliMi, indicating a strong dependence on assumptions regarding geographical context, market demand, decarbonization impact and integration conditions. Oil refining also shows a highly variable ranking, from first for Framatome to ninth for CEA, which suggests that its relevance depends strongly on assumptions concerning industrial demand, decarbonization benefit and the long-term evolution of fossil-fuel-related industries.

Hydrogen production routes should be discussed separately. Thermochemical routes such as Sulfur-Iodine and Copper-Chlorine generally rank in the lower part of the assessment, mainly due to lower maturity and limited available information, although they are not ranked last by all participants. Solid Oxide Electrolysis Cell hydrogen production shows more contrasted results, ranking second for PoliMi and third for CEA, but lower for Framatome and CNRS. This suggests that hydrogen production remains potentially relevant but requires further analysis of technology maturity, thermal/electric integration and expected market development.

The completion of the Trade Study did not result in complete agreement on the overall ranking of all the identified candidate solutions. Nevertheless, the weighted rankings show that district heating is the most robust option overall, as it is consistently ranked within the top three by all participating entities. The discrepancies on the remaining solutions still allowed us to pinpoint the opportunities related to the implementation of flexibility solutions for MSRs. Indeed, the ranking



of the criteria and their impact on solution ranking help identify the most impactful fields for future studies: the existence of a market should be assessed, as much as the capacity of the solution to decrease the carbon footprint of society. Moreover, the solution must be economically viable, which suggests a good efficiency of the process and a TRL not too low.



5 Conclusion

A Trade Study was conducted to identify and compare the most promising end-use applications, other than electricity production, for exploiting the flexible use of Molten Salt Reactors (MSRs). The method led to the identification and assessment of nine candidate solutions covering a broad range of thermal energy applications, including hydrogen production routes, water desalination, district heating, oil refining, fertilizer production, paper production and other industrial heat uses.

The objective of the study was to assess which of these applications are best suited to use thermal energy from MSRs, taking into account both technical compatibility and broader implementation factors. A set of twelve selection criteria was defined by the team, covering aspects such as end-use performance, market demand and growth potential, economic viability, initial investment, technology readiness level, flexibility, decarbonization potential and compatibility between the heat demand and the expected MSR operating conditions. The candidate solutions were then ranked against these weighted criteria by the participating entities.

The Trade Study did not lead to a unique final ranking shared by all participants. However, the comparison of the weighted scores shows that district heating emerges as the most robust option overall, as it is consistently ranked within the top three by all participating entities. Chemical industry applications also appear promising, with consistently high rankings across the participant matrices. Other options, such as water desalination, oil refining and hydrogen production routes, show more dispersed rankings, reflecting differences in assumptions regarding market potential, decarbonization impact, technology maturity and integration constraints.

Overall, the study provides a first structured screening of non-electric applications for flexible MSR operation rather than a definitive techno-economic ranking. It highlights several priority fields for future work, including economic viability, decarbonization potential, technology readiness, process efficiency, and compatibility between industrial heat demand and MSR operating conditions. Further analyses should refine these results through more quantitative assessments, including case-specific evaluations of market demand, CO₂ reduction potential, thermal integration constraints and the maturity of the considered technologies.



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Appendix A. Final Matrices from Trade Study Participants

Alternatives	Criteria	A	B	C	D	F	G	H	I	J	K	L	M	Total score
	Score	25	15	17	21	2	21	3	36	6	29	2	14	
	Percentage score	13.09	7.85	8.90	10.99	1.05	10.99	1.57	18.85	3.14	15.18	1.05	7.33	
Hydrogen : Solid Oxide Electrolysis Cell	Grade by criterion	2.5	2	2	5	1	4	1	3	4	4	4	2	34.5
	Weighted score	0.33	0.16	0.18	0.55	0.01	0.44	0.02	0.57	0.13	0.61	0.04	0.15	3.16
Hydrogen : Sulfur-Iodine	Grade by criterion	2.5	1	4	3	1	2	1	3	1	4	4	2	28.5
	Weighted score	0.33	0.08	0.36	0.33	0.01	0.22	0.02	0.57	0.03	0.61	0.04	0.15	2.73
Hydrogen : Copper-Chlorine	Grade by criterion	2.5	1	4	2	1	2	1	3	1	4	4	2	27.5
	Weighted score	0.33	0.08	0.36	0.22	0.01	0.22	0.02	0.57	0.03	0.61	0.04	0.15	2.62
Heat Generation : Paper production	Grade by criterion	2	3	4	5	3	5	5	2	4	2	4	4	43
	Weighted score	0.26	0.24	0.36	0.55	0.03	0.55	0.08	0.38	0.13	0.30	0.04	0.29	3.20
Heat Generation : Chemical industry	Grade by criterion	4	3	5	5	1	4	5	4	1	3	3	4	42
	Weighted score	0.52	0.24	0.45	0.55	0.01	0.44	0.08	0.75	0.03	0.46	0.03	0.29	3.85
Heat Generation : District heating	Grade by criterion	3	5	4	5	5	2	5	4	5	4	5	5	52
	Weighted score	0.39	0.39	0.36	0.55	0.05	0.22	0.08	0.75	0.16	0.61	0.05	0.37	3.98
Water Desalination	Grade by criterion	1	3	1	5	4	2	3	1	5	1	1	5	32
	Weighted score	0.13	0.24	0.09	0.55	0.04	0.22	0.05	0.19	0.16	0.15	0.01	0.37	2.19
Oil refining	Grade by criterion	5	4	4	5	1	4	5	4	2	4	5	5	48
	Weighted score	0.65	0.31	0.36	0.55	0.01	0.44	0.08	0.75	0.06	0.61	0.05	0.37	4.25
Fertilizer production	Grade by criterion	4	4	3	5	1	3	4	3	2	4	3	3	39
	Weighted score	0.52	0.31	0.27	0.55	0.01	0.33	0.06	0.57	0.06	0.61	0.03	0.22	3.54

Figure 6: Final results: Framatome matrix

Alternatives	Criteria	A	B	C	D	F	G	H	I	J	K	L	M	Total score
	Score	25	15	17	21	2	21	3	36	6	29	2	14	
	Percentage score	13.09	7.85	8.90	10.99	1.05	10.99	1.57	18.85	3.14	15.18	1.05	7.33	
Hydrogen : Solid Oxide Electrolysis Cell	Grade by criterion	2	2	5	3	5	3	2	4	4	5	3	2	40
	Weighted score	0.26	0.16	0.45	0.33	0.05	0.33	0.03	0.75	0.13	0.76	0.03	0.15	3.42
Hydrogen : Sulfur-Iodine	Grade by criterion	1	1	3	2	4	2	2	4	1	5	1	2	28
	Weighted score	0.13	0.08	0.27	0.22	0.04	0.22	0.03	0.75	0.03	0.76	0.01	0.15	2.69
Hydrogen : Copper-Chlorine	Grade by criterion	2	3	3	2	3	3	2	4	2	5	2	3	34
	Weighted score	0.26	0.24	0.27	0.22	0.03	0.33	0.03	0.75	0.06	0.76	0.02	0.22	3.19
Heat Generation : Paper production	Grade by criterion	5	1	4	5	1	5	5	3	4	4	5	3	45
	Weighted score	0.65	0.08	0.36	0.55	0.01	0.55	0.08	0.57	0.13	0.61	0.05	0.22	3.85
Heat Generation : Chemical industry	Grade by criterion	2	2	4	5	2	3	5	4	2	4	3	1	37
	Weighted score	0.26	0.16	0.36	0.55	0.02	0.33	0.08	0.75	0.06	0.61	0.03	0.07	3.28
Heat Generation : District heating	Grade by criterion	3	4	4	5	3	5	4	4	3	5	5	5	50
	Weighted score	0.39	0.31	0.36	0.55	0.03	0.55	0.06	0.75	0.09	0.76	0.05	0.37	4.28
Water Desalination	Grade by criterion	2	3	3	5	3	3	4	3	4	3	4	4	41
	Weighted score	0.26	0.24	0.27	0.55	0.03	0.33	0.06	0.57	0.13	0.46	0.04	0.29	3.22
Oil refining	Grade by criterion	1	1	4	5	3	2	4	4	1	1	4	2	32
	Weighted score	0.13	0.08	0.36	0.55	0.03	0.22	0.06	0.75	0.03	0.15	0.04	0.15	2.55
Fertilizer production	Grade by criterion	1	2	3	5	3	2	3	4	2	3	4	2	34
	Weighted score	0.13	0.16	0.27	0.55	0.03	0.22	0.05	0.75	0.06	0.46	0.04	0.15	2.86

Figure 7: Final results: CEA matrix



Criteria		A	B	C	D													
Score		25	15	17	21													
Alternatives	Percentage score	13.09	7.85	8.90	10.99		F	G	H	I	J	K	L	M				
Hydrogen : Solid Oxide Electrolysis Cell	Grade by criterion	2.5	2.5	1.5	2		5	5	0	4	5	4	5	5				41.5
	Weighted score	0.33	0.20	0.13	0.22		0.05	0.55	0.00	0.75	0.16	0.61	0.05	0.37				3.42
Hydrogen : Sulfur-Iodine	Grade by criterion	2.5	2.5	3	3		3.5	2.5	0	4	3.5	4	5	5				38.5
	Weighted score	0.33	0.20	0.27	0.33		0.04	0.27	0.00	0.75	0.11	0.61	0.05	0.37				3.32
Hydrogen : Copper-Chlorine	Grade by criterion	2.5	2.5	4	1		4	2.5	0	4	3.5	4	5	5				38
	Weighted score	0.33	0.20	0.36	0.11		0.04	0.27	0.00	0.75	0.11	0.61	0.05	0.37				3.20
Heat Generation : Paper production	Grade by criterion	4	4	5	5		5	5	2.5	2	4	5	4	1.5				47
	Weighted score	0.52	0.31	0.45	0.55		0.05	0.55	0.04	0.38	0.13	0.76	0.04	0.11				3.89
Heat Generation : Chemical industry	Grade by criterion	4	3.5	5	5		3.5	2.5	2.5	3.5	3	5	5	5				47.5
	Weighted score	0.52	0.27	0.45	0.55		0.04	0.27	0.04	0.66	0.09	0.76	0.05	0.37				4.08
Heat Generation : District heating	Grade by criterion	4	3	5	5		5	2.5	4	5	5	5	5	5				53.5
	Weighted score	0.52	0.24	0.45	0.55		0.05	0.27	0.06	0.94	0.16	0.76	0.05	0.37				4.42
Water Desalination	Grade by criterion	5	5	5	5		5	5	3.5	4	5	5	5	5				57.5
	Weighted score	0.65	0.39	0.45	0.55		0.05	0.55	0.05	0.75	0.16	0.76	0.05	0.37				4.79
Oil refining	Grade by criterion	4	3.5	5	5		3.5	2.5	2.5	3.5	3	5	5	5				47.5
	Weighted score	0.52	0.27	0.45	0.55		0.04	0.27	0.04	0.66	0.09	0.76	0.05	0.37				4.08
Fertilizer production	Grade by criterion	4	3.5	5	5		3.5	2.5	2.5	3.5	1	5	5	5				45.5
	Weighted score	0.52	0.27	0.45	0.55		0.04	0.27	0.04	0.66	0.03	0.76	0.05	0.37				4.01

Figure 8: Final results: CNRS matrix

Criteria		A	B	C	D													
Score		25	15	17	21													
Alternatives	Percentage score	13.09	7.85	8.90	10.99		F	G	H	I	J	K	L	M				Total score
Hydrogen : Solid Oxide Electrolysis Cell	Grade by criterion	4	2	2	3		2	4	1	4	3	5	3	5				38
	Weighted score	0.52	0.16	0.18	0.33		0.02	0.44	0.02	0.75	0.09	0.76	0.03	0.37				3.67
Hydrogen : Sulfur-Iodine	Grade by criterion	3	1	3	2		2	3	1	4	3	5	3	4				34
	Weighted score	0.39	0.08	0.27	0.22		0.02	0.33	0.02	0.75	0.09	0.76	0.03	0.29				3.26
Hydrogen : Copper-Chlorine	Grade by criterion	3	1	3	2		2	3	1	4	3	5	3	4				34
	Weighted score	0.39	0.08	0.27	0.22		0.02	0.33	0.02	0.75	0.09	0.76	0.03	0.29				3.26
Heat Generation : Paper production	Grade by criterion	2	4	5	5		4	1	4	3	4	3	5	2				42
	Weighted score	0.26	0.31	0.45	0.55		0.04	0.11	0.06	0.57	0.13	0.46	0.05	0.15				3.13
Heat Generation : Chemical industry	Grade by criterion	4	3	5	5		3	1	4	5	2	4	4	2				42
	Weighted score	0.52	0.24	0.45	0.55		0.03	0.11	0.06	0.94	0.06	0.61	0.04	0.15				3.76
Heat Generation : District heating	Grade by criterion	3	4	4	5		5	3	5	3	5	3	5	4				49
	Weighted score	0.39	0.31	0.36	0.55		0.05	0.33	0.08	0.57	0.16	0.46	0.05	0.29				3.60
Water Desalination	Grade by criterion	1	4	3	5		5	4	3	2	5	3	3	5				43
	Weighted score	0.13	0.31	0.27	0.55		0.05	0.44	0.05	0.38	0.16	0.46	0.03	0.37				3.19
Oil refining	Grade by criterion	4	4	5	5		3	1	4	2	2	4	4	2				40
	Weighted score	0.52	0.31	0.45	0.55		0.03	0.11	0.06	0.38	0.06	0.61	0.04	0.15				3.27
Fertilizer production	Grade by criterion	4	3	4	4		3	1	4	5	3	4	4	2				41
	Weighted score	0.52	0.24	0.36	0.44		0.03	0.11	0.06	0.94	0.09	0.61	0.04	0.15				3.59

Figure 9: Final results: PoliMi matrix