Introduction to sustainability assessment of energy technologies

RISEnergy
Research Infrastructure Services for Renewable Energy

Part II – How sustainability assessment is carried out on a technology level

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Targets of this module

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Provide an overview of:

- Motivation and challenges for sustainability assessment (Part I)
- **How sustainability assessment is carried out on a technology level (Part II) – *this presentation***
- How HELDA web tool can be used for comprehensive sustainability assessment of energy technologies (Part III)

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Part II - How sustainability assessment is carried out on a technology level

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What will I learn in this presentation?

After working through this material, you should be able to **remember*** and **understand***

- Important steps to perform sustainability assessment of energy technologies.
- How to create an evaluation matrix as a basis for the assessment.
- Important characteristics to choose appropriate aggregation and weighting methods for MCDA sustainability assessment

*Bloom's Taxonomy on intended learning outcomes

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Sustainability assessment

Recap of motivations, challenges and important steps

Different concepts for sustainable development

– Sustainable development goals (SDGs)
– Triple bottom Line model (TBL)

Sustainability assessment of energy technologies

– Life cycle thinking
– Selection of criteria/indicators
– Selection of assessment methods

Multi-criteria decision analysis (MCDA)

– Integrated consideration of assessment criteria
– Aggregation and weighting methods for ranking of alternatives

MCDA Sustainability assessment

Important steps:

- Goal and problem definition
- Identification of relevant stakeholders
- Selection of alternatives
- Selection of criteria/indicators
- Elaboration of performance matrix
- Selection of proper MCDA methods
- Weighting and aggregation of criteria
- Analysis of results
    - Ranking of alternatives
    - Sensitivity analysis

Training material Part I

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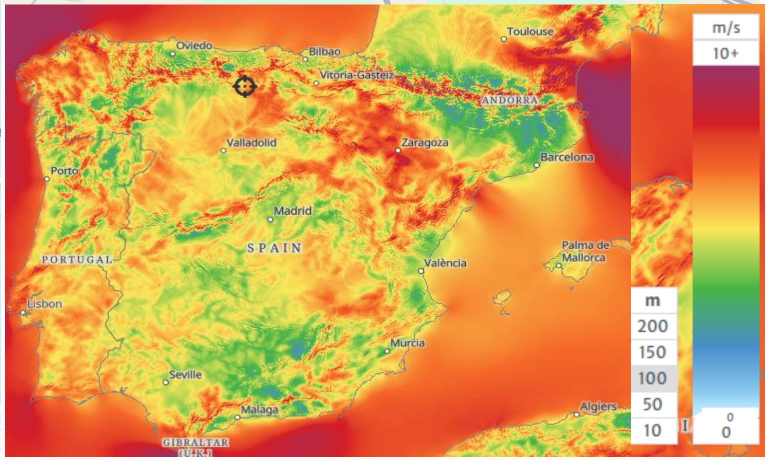
Use case: Mechanical energy storage
Theoretical study case

In the autonomus community of **Castile and León** in the north of Spain there is located the Aguilar reservoir with a power plant of 9,86 MW. Castile and León possesses a big wind potential, which makes it an attractive location to **increase the installed capacity of wind turbines**.

Castile and León autonomus región in Spain



Wind potential in Spain

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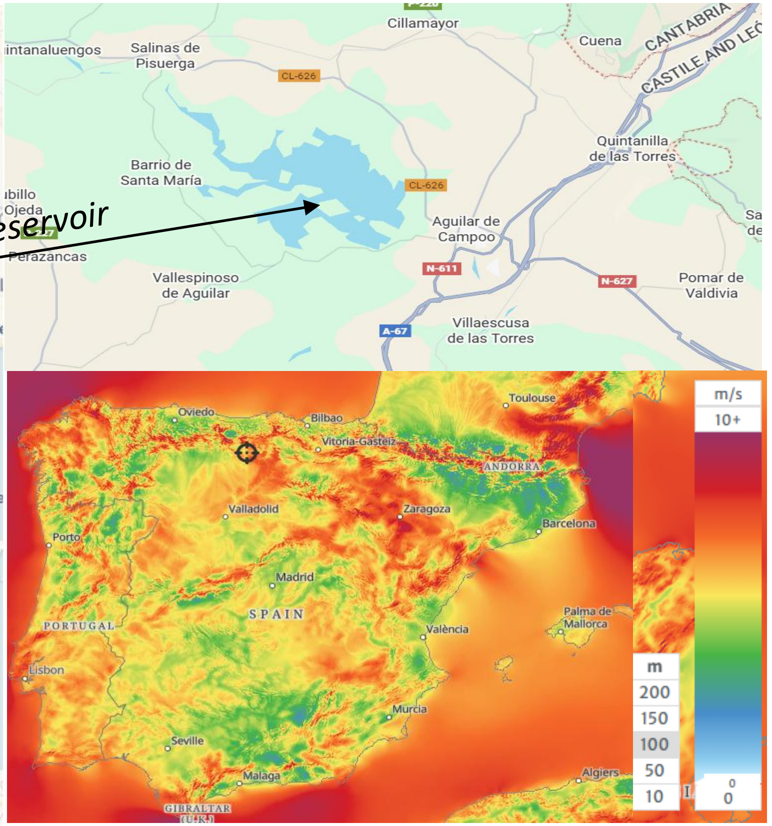
Use case: Mechanical energy storage

Goal and problem definition

Castile and León currently **lacks suitable energy storage technologies** to shift surplus wind power to peak-demand hours or to ensure supply during outages.

The goal of this study is to allow the storage of wind generated electricity for peak demand periods and potential blackouts of around four hours by **identifying the most appropriate large scale energy storage technology for the region**.

Castile and León autonomus región in Spain



Wind potential in Spain

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Use case: Mechanical energy storage

Identification of relevant stakeholders

In order to involve all stakeholders to install new energy storage technologies in the vicinity of the town of Aguilar de Campoo, the identified stakeholders can be divided into four main groups:

Private companies	Public institutions	Civil society	Technology-specific experts
Companies engaged in the development and construction of energy storage technologies.	National and/or regional energy authorities responsible for planning and regulating the expansion of the electricity sector in Spain.	Residents and local communities living in areas potentially affected by the location of the energy storage alternatives.	Researchers and technical specialists in energy storage technologies who can provide information on the potential impacts of their implementation.

In real-world applications, stakeholders should be involved in as many as possible phases of the assessment process: **1.) Selection of alternatives, 2.) selection of criteria/indicators, 3.) weighting of criteria, 4.) Analysis of results**

Training material
Part I

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Use case: Mechanical energy storage

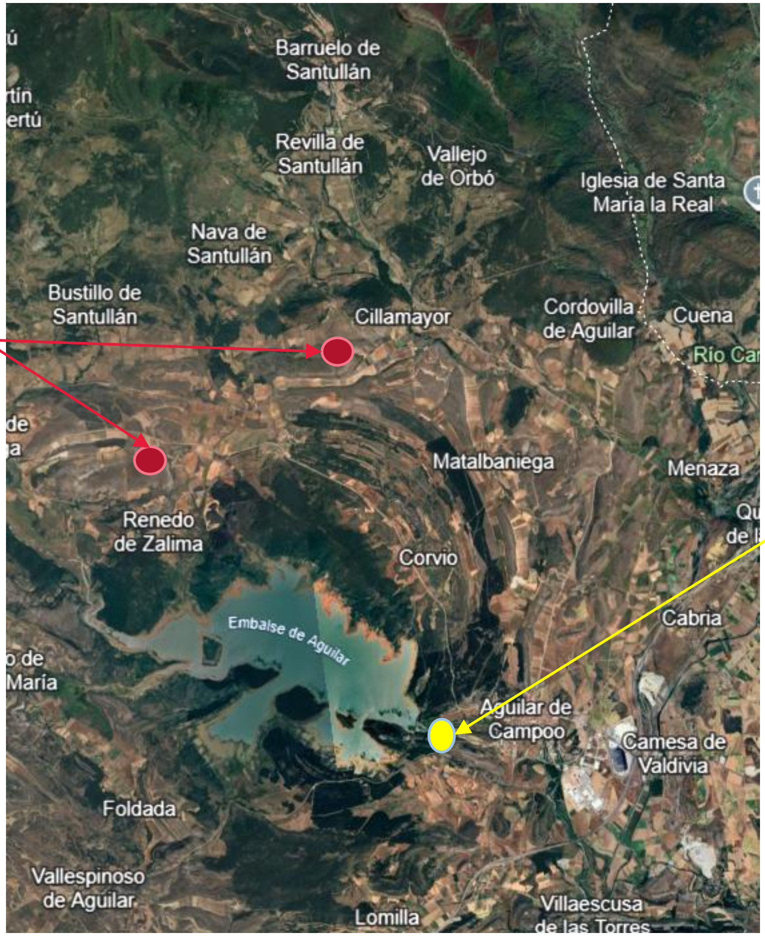
Selection of alternatives

Given the presence of a hydroelectric power plant with a reservoir, the location sufficiently far from nearby cities, and the availability of flat land, the following mechanical energy storage technologies represent suitable options to consider in this theoretical case study:

- **Pumped hydro energy storage,**
- **Solid gravity energy storage, and**
- **Compressed air energy storage.**

For more information on the three mechanical energy storage alternatives please compare **Annex A.**

In these surrounding areas, **tower solid gravity energy storage or diabatic compressed air energy storage** could be built



A second reservoir could be built in the down stream of the river Pisuerga and pump the water upstream for **pumped hydro energy storage**.

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Use case: Mechanical energy storage

Selection of sustainability criteria and indicators

The criteria for sustainability assessment are selected based on the RISEnergy White Paper "White paper on relevant sustainability KPIs" which summarizes sustainability **Key Performance Indicators (KPIs)** relevant to different types of energy technologies (see **Annex B**). As a result, four main groups of criteria were identified: technical, environmental, economic, and social indicators. In total, **11 key performance indicators (KPIs) are considered** in this case study for the comparison of mechanical energy storage technologies. For more information on the selected KPIs please compare **Annex C**.

Selected criteria for sustainability assessment of mechanical energy storage technologies

Technical	**Economic**	**Environmental**	**Social**
Technology Readiness Level (TRL) Efficiency Lifetime Distribution infrastructure	Levelized Cost of Energy (LCOE) Capital Expenditure (CAPEX)	CO_2 footprint Land use Ecosystem impact	Visual impact Impact on human health

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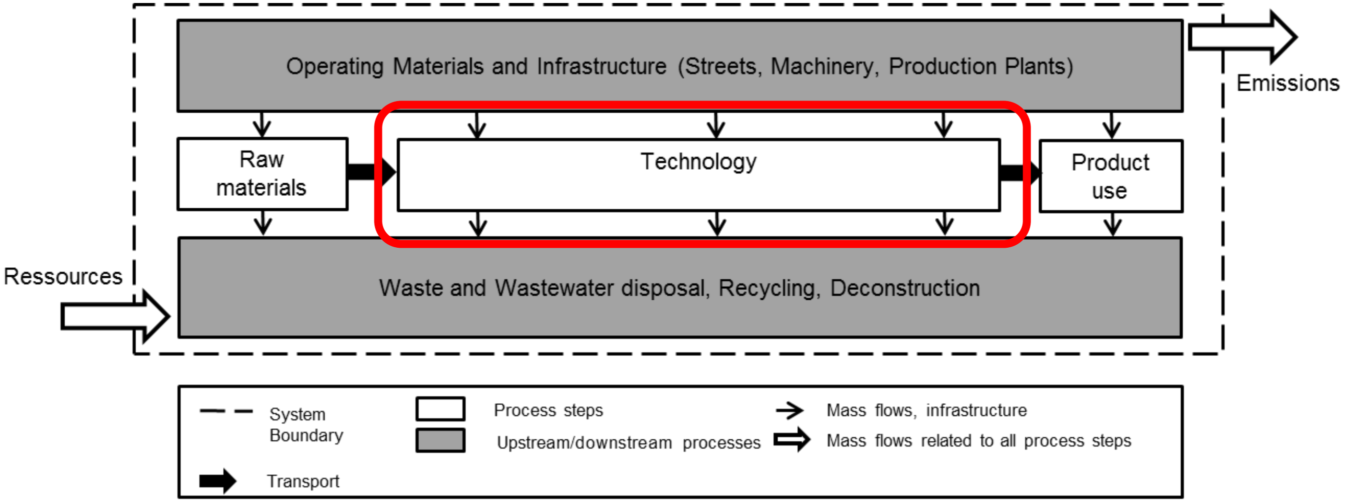
Use case: Mechanical energy storage

Elaboration of performance matrix (1)

For the elaboration of the performance matrix, a consistent assessment framework (e.g. base year, spatial reference) and system boundaries need to be defined [3] .



System boundaries for sustainability assessment of energy technologies (Cradle-to-grave assessment) based on [3] and subject of study of mechanical energy storage use case (red rectangle)

The consideration of the entire value chain or product life cycle includes **1) raw materials provision, 2) the technology itself, 3) use of product** as well as related upstream (operating materials, infrastructure) and downstream (waste and Wastewater disposal, recycling, deconstruction) processes.

In our use case example, **system boundaries** include **the storage technologies themselves,** along with the related **upstream and downstream processes,** while wind electricity generation as well as distribution and use of stored energy are not included.
Base year for the assessment is **2025**, **spatial reference** is **Castile and León**, Spain.

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Use case: Mechanical energy storage
Elaboration of performance matrix (2)

The **performance matrix** lists **1.) KPIs, 2.) Preferred directions**, **3.) Units, 4.) considered alternatives**. For each alternative, the **performance data**, i.e. quantitative or qualitative assessments for each KPI need to be gathered from e.g. literature or technology experts. For some KPIs, site-specific information is needed (see **Annex D**). For more detailed information on performance data gathering please refer to **Annex E**.

Training material Part I

Exemplary performance matrix for sustainability assessment of mechanical energy storage

KPIs	Prefered direction	unit	Pumped hydro	Solid gravity	Compressed air
TRL	max	-	9	6	9
Efficiency	max	%	85	90	70
Lifetime	max	years	100	50	60
Distribution infrastructure	max	-	Bad	Good	Good
LCOE	min	€/kWh	low	high	medium
CAPEX	min	€/kW	709	664	775
CO_2 footprint	min	$kgCO_{2eq}$/kWh	0.12094	0.2074	0.3306
Land use	min	m2/MW	2300	400	1800
Ecosystem impact (ecotoxicity freshwater)	min	CTUe/kWh	1.18E-01	0.64	3.34E-01
Visual impact	min	-	low	high	low
Impact on human health (human toxicity cancer)	min	CTUh/kWh	1.60E-11	1.05E-10	3.47E-11

Please note: These are indicative data, based on secondary literature which depend largely on location. For specific data, we recommend that you conduct your own sustainability assessment.

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Use case: Mechanical energy storage

Assessment based on KPIs

Based on the performances and preferred directions, one can assess the alternatives criterion-/KPI-wise e.g. by using a colour-scheme (**best**, **medium**, **worst**). In our example, none of the exemplary alternatives performs best with respect to all considered criteria. MCDA methods for weighting and aggregation can help to rank the alternatives.

Training material Part I

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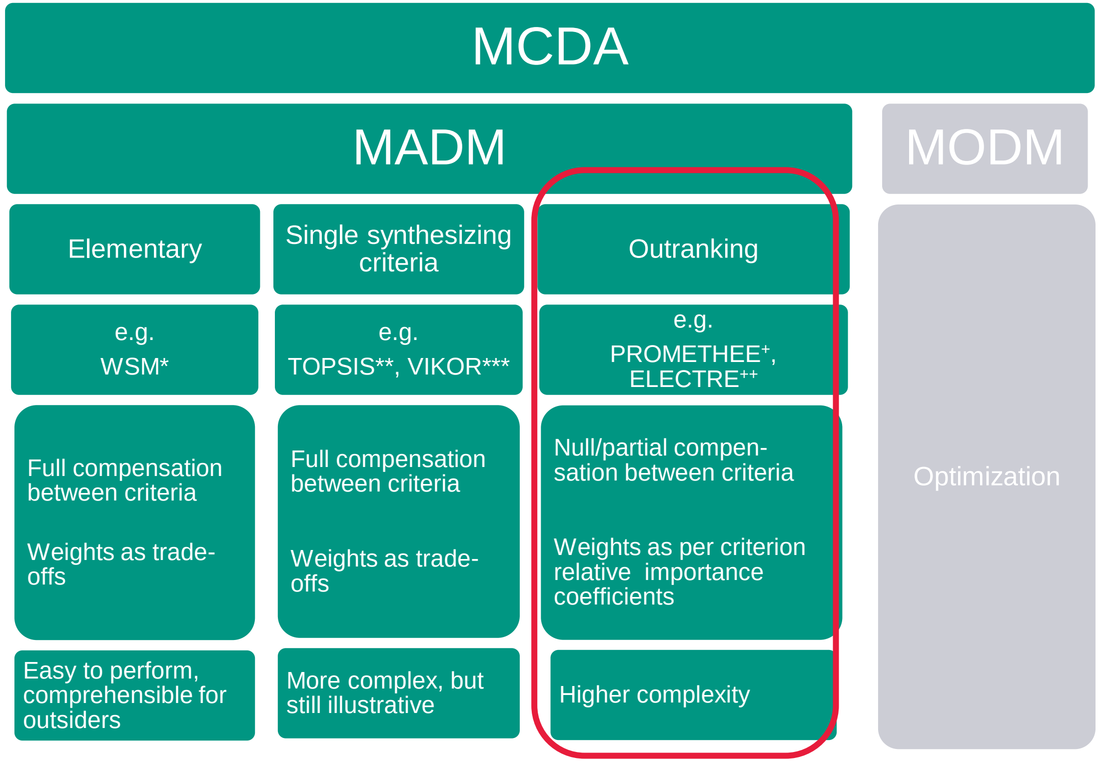
Use case: Mechanical energy storage

Selection of MCDA methods

1. Selection of aggregation method



Methods for criteria aggregation (based on [4] and [8])

Choice of method depending on decision problem and type of information available

In our example, the evaluation matrix shows **1.) quantitative and qualitative criteria.** Furthermore, in order to consider **2.) the concept of strong sustainability,** methods with low degree of compensation between criteria are preferred. Therefore, outranking methods are most suitable, e.g. PROMETHEE and ELECTRE. For our example, we choose the **ELECTRE III aggregation method**.

Training material Part I

*Weighted Sum Method **Technique for Order Preference by Similarity to Ideal Solution ***Multicriteria Optimization and Compromise Solution $^{+}$Preference ranking organization method for enrichment evaluation $^{++}$ELimination and Choice Expressing REality

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Use case: Mechanical energy storage
Selection of MCDA methods

2. Selection of weighting method

Category#	Description	Method (examples)	Description
Objective	• weights elicitation by using measured data and information • reflect the difference degree of data and information	Entropy method	Relative importance of each criterion is assessed according to the difference between the observed values of each criterion.
Subjective	• weights elicitation by using stakeholders' preferences • reflect the judgments and knowledge of stakeholders	Pairwise comparison	Importance of two criteria is compared at a time and the relative importance is scored (Pairwise comparison ratios).
		AHP*	Builds on the pair-wise comparison model with a scale scale from 1 to 9 (Pairwise comparison ratios).
		SMART**	Direct assignment of importance on a 0-100 scale (Per criterion relative importance).
		SIMOS (Deck of cards)	Ranking of cards (criteria) from the least important to the most important according to their importance (Per criterion relative importance).
		n-point scale	Importance coefficients on a scale from 1 to 10 (Per criterion relative importance).
		Trade-offs	Trade-offs as percentages for each criterion summing up to 100%

Methods for criteria weighting (based on [8])

For **ELECTRE III aggregation method**, weights need to be elicited as per criterion relative **importance coefficients**. A suitable weighting method is e.g. the n-point scale to elicit relative **weights on a scale from e.g. 1 to 10**.

*Analytical hierrarchy process **Simple multi-attribute rating technique

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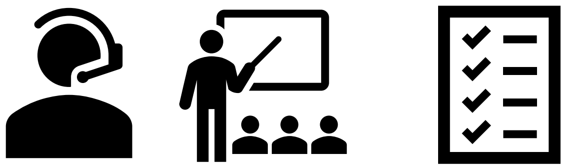
Use case: Mechanical energy storage

Weighting of criteria (1)

In a real-world application, the weighting of criteria should be derived from the **preferences of relevant stakeholders**, as their input is essential for a meaningful and transparent assessment of technologies. These preferences can be obtained through surveys, interviews, or workshops, in which actors are asked to express the importance they assign to each criterion.



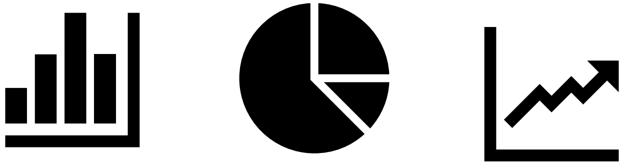
Given that the presented exemplary study is purely theoretical, weighting is analysed through **three illustrative weighting scenarios** in order to examine how different perspectives influence the ranking of mechanical energy storage alternatives:

1.) All criteria are assigned the same weight.

2.) Technical criteria are assigned higher importance than all other criteria

3.) Economic criteria are assigned higher importance than all other criteria.

4.) Environmental criteria are assigned higher importance than all other criteria.



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Use case: Mechanical energy storage
Weighting of criteria (2)

Proposed weighting scenarios

KPIs	Prefered direction	unit	1 Equal Weights	2 Technical	3 Economic	4 Environmental
TRL	max	-	0.091	0.165	0.037	0.043
Efficiency	max	%	0.091	0.165	0.037	0.043
Lifetime	max	years	0.091	0.165	0.037	0.043
Distribution infrastructure	max	-	0.091	0.165	0.037	0.043
LCOS	min	€/kWh	0.091	0.048	0.33	0.043
CAPEX	min	€/kW	0.091	0.048	0.33	0.043
CO2 footprint	min	gCo2eq/kWh	0.091	0.048	0.037	0.22
Land use	min	m2/MW	0.091	0.048	0.037	0.22
Ecosystem impact (ecotoxicity freshwater)	min	CTUe/kWh	0.091	0.048	0.037	0.043
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Use case: Mechanical energy storage

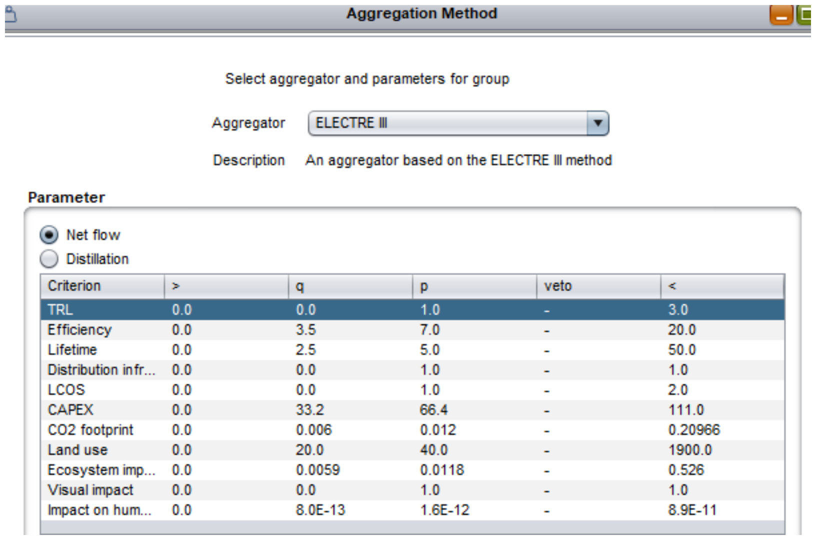
Aggregation of criteria

For criteria aggregation and ranking of alternatives the MCDA method **ELECTRE III Net Flow Score (NFS)** is chosen. ELECTRE III allows for the definition of **discriminating threshold values: Preference (p) and Indifference (q) threshold** for each criterion which are defined by the MCDA analysts and/or technology experts that participated in the performance evaluations of the criteria. The **Veto (v)** threshold is an additional preference parameter that serves to indicate reasons against an outranking relation and can be defined by e.g. a decision-maker. For further information on ELECTRE III and related thresholds please compare **Annex F**.

In our theoretical example, the following **default threshold values are defined: 1) for criteria with quantitative scales**: q: 5% of minimum criterion value, p: 10% of minimum criterion value, no veto, **2) for criteria with qualitative scales**: q = 0, p = 1, no veto value.

Different Software solutions are available to apply ELECTRE methods. Within our case study, the Software **HELDA (Helmholtz MCDA Tool)** is used for alternatives rankings and sensitivity analysis.

HELDA
HELMHOLTZ MCDA TOOL


Aggregation Method

Select aggregator and parameters for group

Aggregator: ELECTRE III

Description: An aggregator based on the ELECTRE III method

Parameter

- (•) Net flow
- ( ) Distillation

Criterion	>	q	p	veto	<
TRL	0.0	0.0	1.0	-	3.0
Efficiency	0.0	3.5	7.0	-	20.0
Lifetime	0.0	2.5	5.0	-	50.0
Distribution infr...	0.0	0.0	1.0	-	1.0
LCOS	0.0	0.0	1.0	-	2.0
CAPEX	0.0	33.2	66.4	-	111.0
CO2 footprint	0.0	0.006	0.012	-	0.20966
Land use	0.0	20.0	40.0	-	1900.0
Ecosystem imp...	0.0	0.0059	0.0118	-	0.526
Visual impact	0.0	0.0	1.0	-	1.0
Impact on hum...	0.0	8.0E-13	1.6E-12	-	8.9E-11

https://www.mcda-helmholtz.de/

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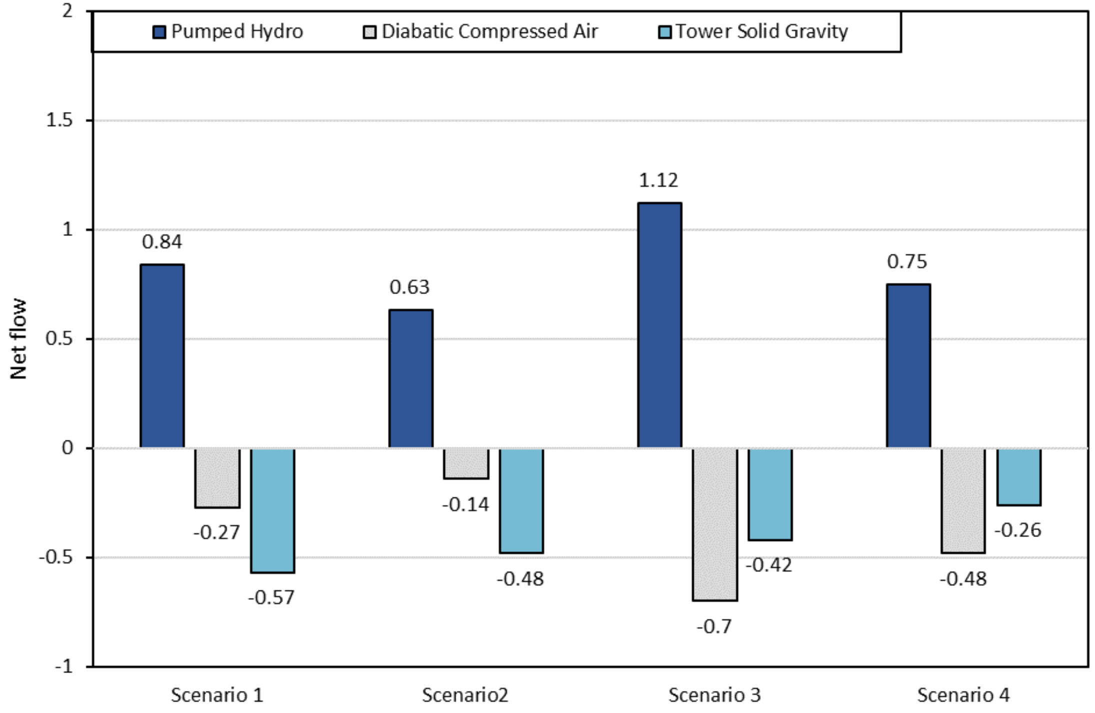
Use case: Mechanical energy storage

Analysis of results

4.1 Ranking of alternatives



Comparison of the ranking of the 3 mechanical energy storage technologies under the 3 proposed weighting scenarios

When all criteria have **equal weights** (**Scenario 1**), meaning same preference is given to all criteria, pumped hydro energy storage is the most preferred option among the three technologies.

When **technical criteria are given higher importance than** economic, environmental, and social criteria (**Scenario 2**), pumped hydro energy storage perform better than the other two storage technologies. However, diabatic compressed air, even with a negative flow, perform better than in scenario 1.

When **economic criteria are given higher importance than** technical, environmental, and social criteria (**Scenario 3**), pumped hydro energy storage obtains positive net flow, meaning that its performance is better than the other two technologies. However, tower solid gravity energy storage with a negative flow, perform better than in scenarios 1 and 2.

When **environmental criteria are given higher importance than** technical, economic, and social criteria (**Scenario 4**), pumped hydro energy storage obtains again positive net flow, meaning that its performance is better than the compressed air and tower solid gravity technologies.

In all four weighting scenarios, **pumped hydro energy storage technology** obtains a positive overall score and consistently ranks better compared to the other two storage technologies, representing that this technology is the most suitable option for implementation in this theoretical case study.

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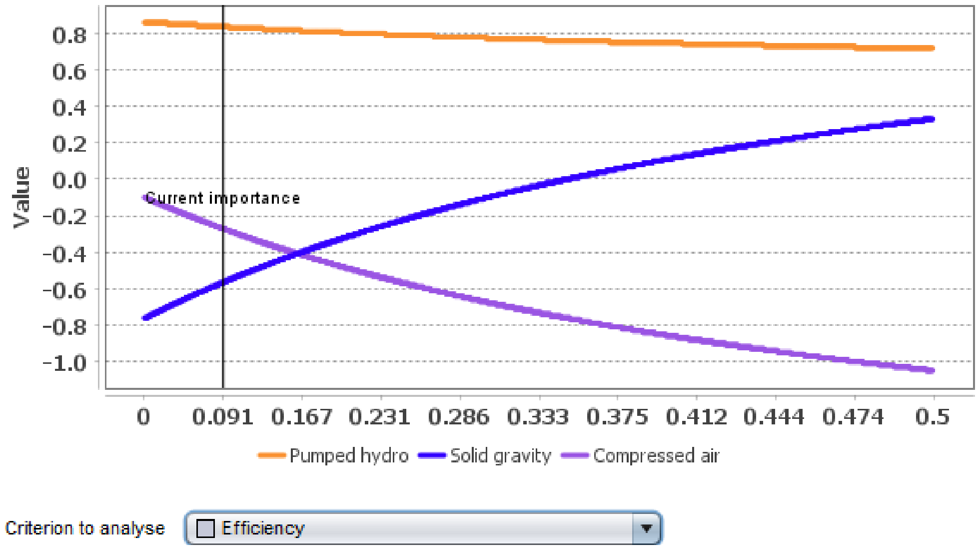
Use case: Mechanical energy storage

Analysis of results

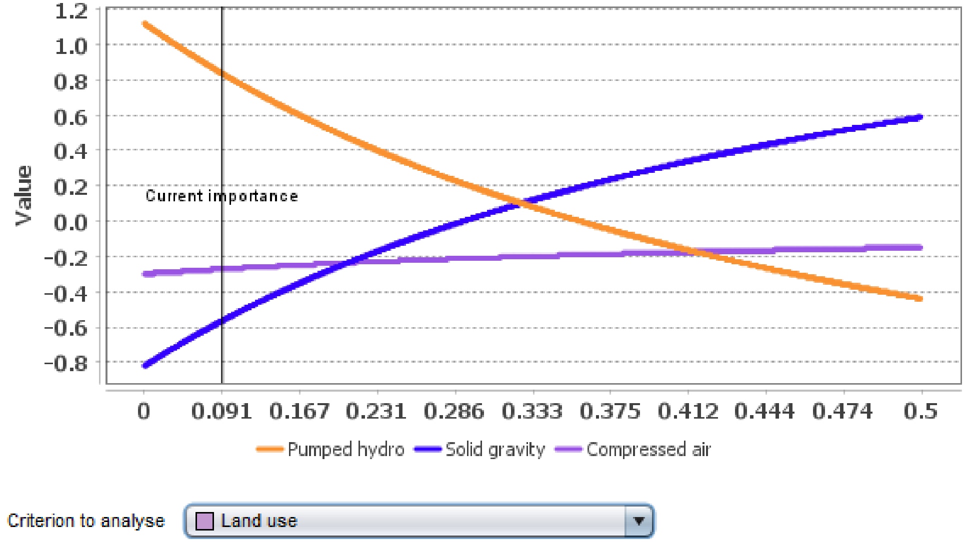
The sensitivity analysis shows how responsive final ranking is to changes in the weight or performance of each criterion.

4.2 Sensitivity analysis for weights (Equal weights scenario)



If the weight of the criterion efficiency is increased from 0.091 to higher values than 0.167, the performance of the tower solid gravity energy storage technology will improve and a change in the ranking will occur.

If the weight of the criterion land use increases to a value higher than 0.333, the performance of tower solid gravity energy storage will further increase, and even with higher weight values (higher than 0.412), the diabatic compressed air will perform better than the pumped hydro energy storage technology.



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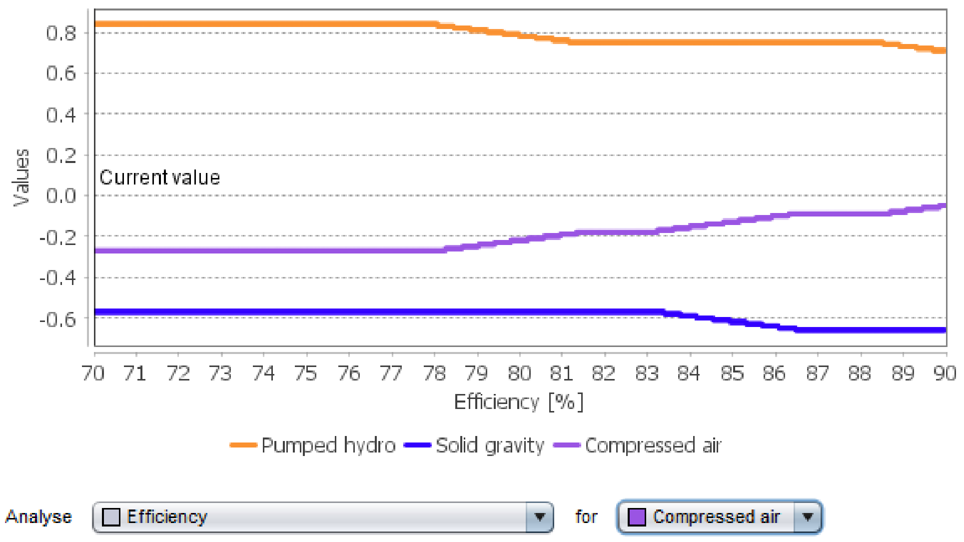
Use case: Mechanical energy storage
Analysis of results

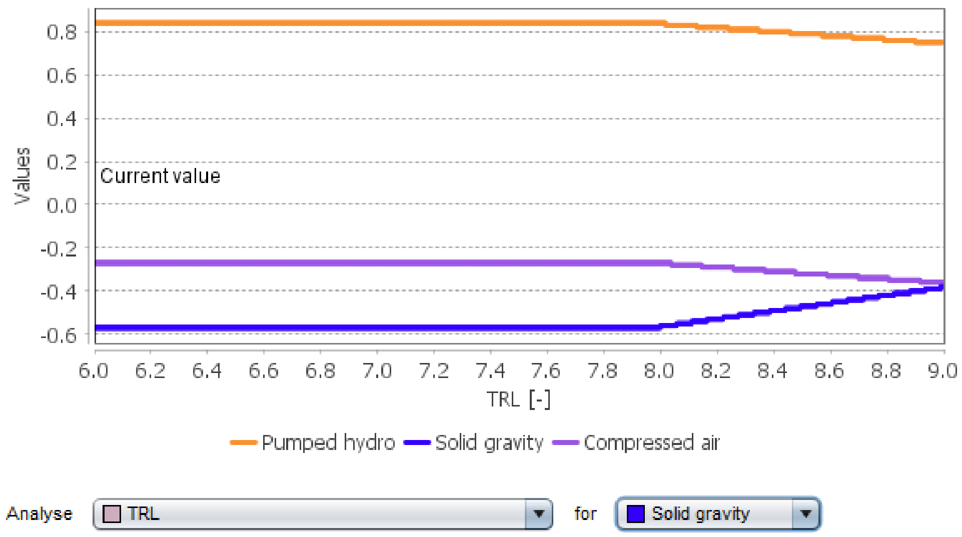
The sensitivity analysis shows how responsive final ranking is to changes in the weight or performance of each criterion.

4.2 Sensitivity analysis for performance (Equal weights scenario)



Currently, the efficiency of compressed air energy storage is the lowest compared to the other two technologies. In the case its efficiency increases significantly (to over 78%), its overall performance will also improve.

Currently, the TRL for solid gravity energy storage is 6. If this TRL increases to 8 or higher, which would indicate higher technological maturity, its overall performance is expected to improve.



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Self-testing

Questions

1. What are important steps to follow to perform sustainability assessment of energy technologies?
2. For which steps of real world sustainability assessment of energy technologies stakeholders should be included?
3. Is ELECTRE the only method for criteria aggregation in MCDA sustainability assessment?

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Self-testing

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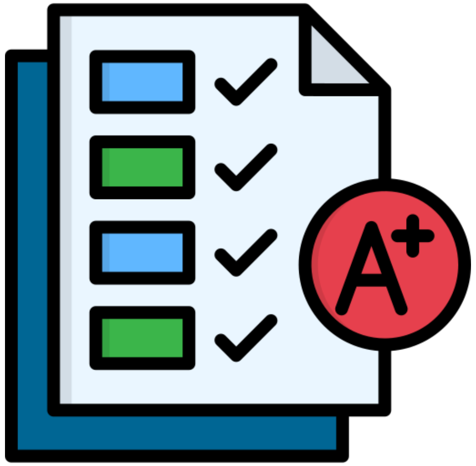

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Answers

1. Identification of relevant stakeholders, Selection of alternatives, Selection of criteria/Indicators, Elaboration of performance matrix, Selection of appropriate weighting and aggregation methods, Weighting of criteria, Aggregation of criteria, Analysis of results.
2. Selection of alternatives, selection of criteria/indicators, weighting of criteria, analysis of results.
3. No, ELECTRE is one possible method for criteria aggregation in a MCDA. The chosen method depends on the characteristics of the decision problem at hand e.g. on the type of data available for technology evaluation.

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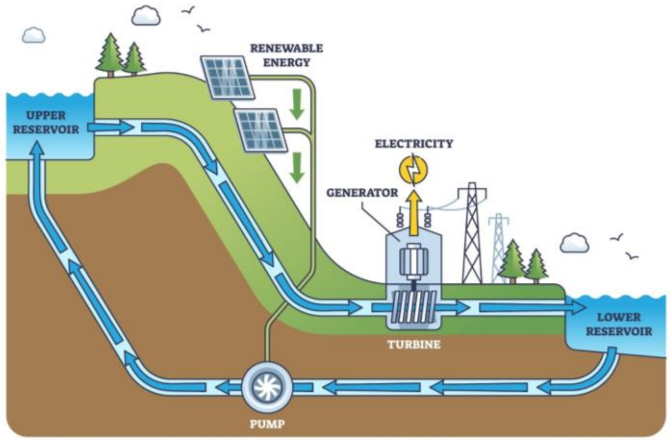
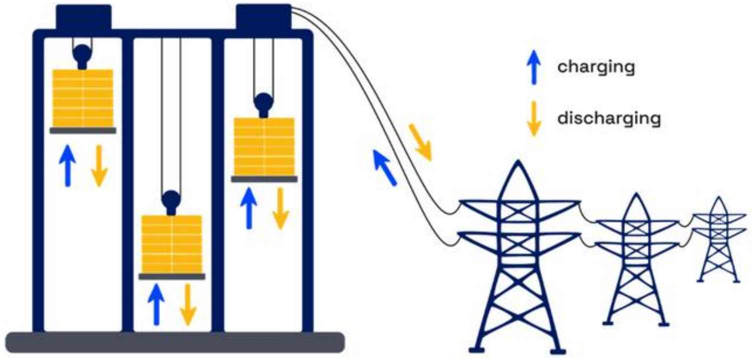
Annex A
Considered mechanical energy storage alternatives



[18]

Pumped hydro energy storage (PHES)

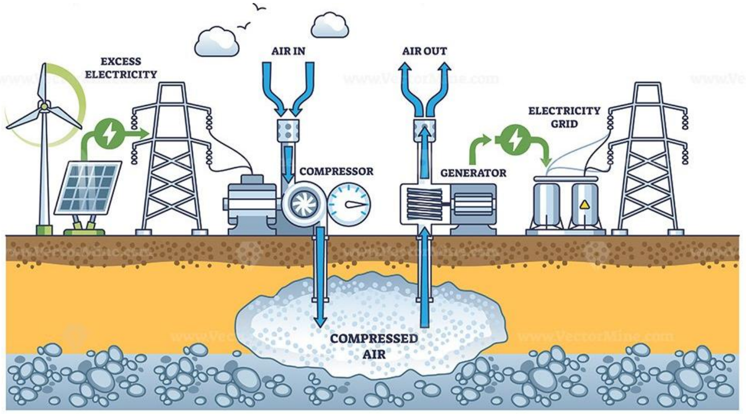
Electricity surplus: Excess electricity powers pumps.
Water is pumped: From a lower reservoir to an upper reservoir.
Energy is stored: As gravitational potential energy in elevated water.
Electricity demand rises: Water is released back to the lower reservoir.
Water flows through turbines: Driving generators to produce electricity.
Cycle repeats.



[21]

(Tower) Solid gravity energy storage ((T)SGES)

Electricity surplus: Powers motors to lift heavy solid blocks (e.g., concrete).
Blocks are raised: Vertically to build a tower or stacked in height.
Energy is stored: As gravitational potential energy in elevated masses.
Electricity demand rises: Blocks are lowered under controlled descent.
Descent drives generators: Using motors in reverse to produce electricity.
Cycle repeats.



[22]

Compressed air energy storage (CAES)

Electricity surplus: Powers compressors to pressurize air.
Air is stored: In underground caverns, tanks, or pipelines.
Energy is stored: As potential energy in compressed air.
Electricity demand rises: Stored air is released.
Air expands: Drives a turbine connected to a generator.
Electricity is produced: Mechanical energy from expanding air is converted to electricity.

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Annex B

Sustainability KPIs for energy technologies

Technical			Economic	Environmental	Social
(Conversion) Efficiency	*Module power output*	*Energy balance*	**Capital Expenditure (CAPEX)**	**CO_2 footprint**	**Safety perception and public trust**
Reliability	*Spectral Response / Quantum Efficiency*	*Nutrient recycling potential*	**Operational Expenditure (OPEX)**	**Ecosystem impact**	**Impact on human health**
Distribution infrastructure	*Receiver thermal efficiency*	*Survivability*	**Levelized cost of X (LCOX)**	**Circularity**	**Job creation**
Degradation rate (losses over time)	*Gravimetric Energy Density (storage stage)*	*Electricity yield*	**Payback period**	*Land-use (intensity)*	**Visual impact**
Durability/Lifetime	*Volumetric Energy Density (storage stage)*	*Bifaciality*	**Return on investment**	*Water consumption*	*Resettlement*
Technology readiness level (TRL)	*Compression Energy*	*Incidence Angle Modifier factor*	**EU production share in the value chain**	*Food security risk*	*Impact on other marine users*
Grid connection and energy system integration	*Cycle life*	*Deployment Logistics*	**Decommissioning Expenditure (DECEX)**	*Critical raw materials*	
Maintenance accessibility	*Pipeline efficiency (delivery stage)*	*Unique Selling Point*	*GHG mitigation costs*		
Process safety	*Leakage Rate (delivery stage)*	*Underwater noise*	*Hydrogen delivery cost*		
Decommissioning	*Fuel Cell Efficiency (utilization stage)*	*Instantaneous energy storage efficiency*	*Hydrogen storage cost*		
Device control (ICT)	*Power Density (utilization stage)*	*Charging/discharging time*	*Water costs*		
Auxiliary power consumption	*Feedstock flexibility*	*Storage exergy efficiency*	*Business case*		
Maximum operating temperature	*Back-end application compatibility*	*Technology adaptability*			

List of sustainability KPIs from RISEnergy "White paper on relevant sustainability KPIs", KPIs applicable to all renewable energy target areas are marked in **bold**, technology-specific KPIS are marked in *italics*, KPIs selected for the assessment of our use case on mechanical energy storage are marked in **blue**

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Annex C
Description of selected sustainability KPIs

Cluster	KPI	Prefered direction*	Description
Technical	TRL	max	Measures how close a technology is to commercial deployment.
	Efficiency	max	Ratio of useful energy output to initial energy input, indicating how well a device uses the resource to produce energy.
	Durability/Lifetime	max	Indicates the operational lifespan of the technology.
	Distribution infrastructure	max	Infrastructure available to transport/distribute energy.
Economic	LCOS	min	Total cost per unit of energy stored over lifetime .
	CAPEX	min	Initial investment cost per installed killowatt.
Environmental	CO2 footprint	min	Greenhouse gas emissions throughout the life cycle of the technology.
	Land use	min	Refers to the area of land required to produce a unit of electricity or per installed capacity
	Ecosystem impact (ecotoxicity, freshwater)	min	Toxic impacts of pollutants on freshwater ecosystems (plants, animals)
Social	Visual impact	min	The visual impact that the installation of the technology and complementary components may have on its surroundings, particularly in terms of aesthetic perception by the public.
	Impact on human health (human toxicity, cancer)	min	Risk of cancer from chronic exposure to toxic substances in air, water, and soil.

*Preference of the KPI (max. – higher values are preferred, min. – lower values are preferred)

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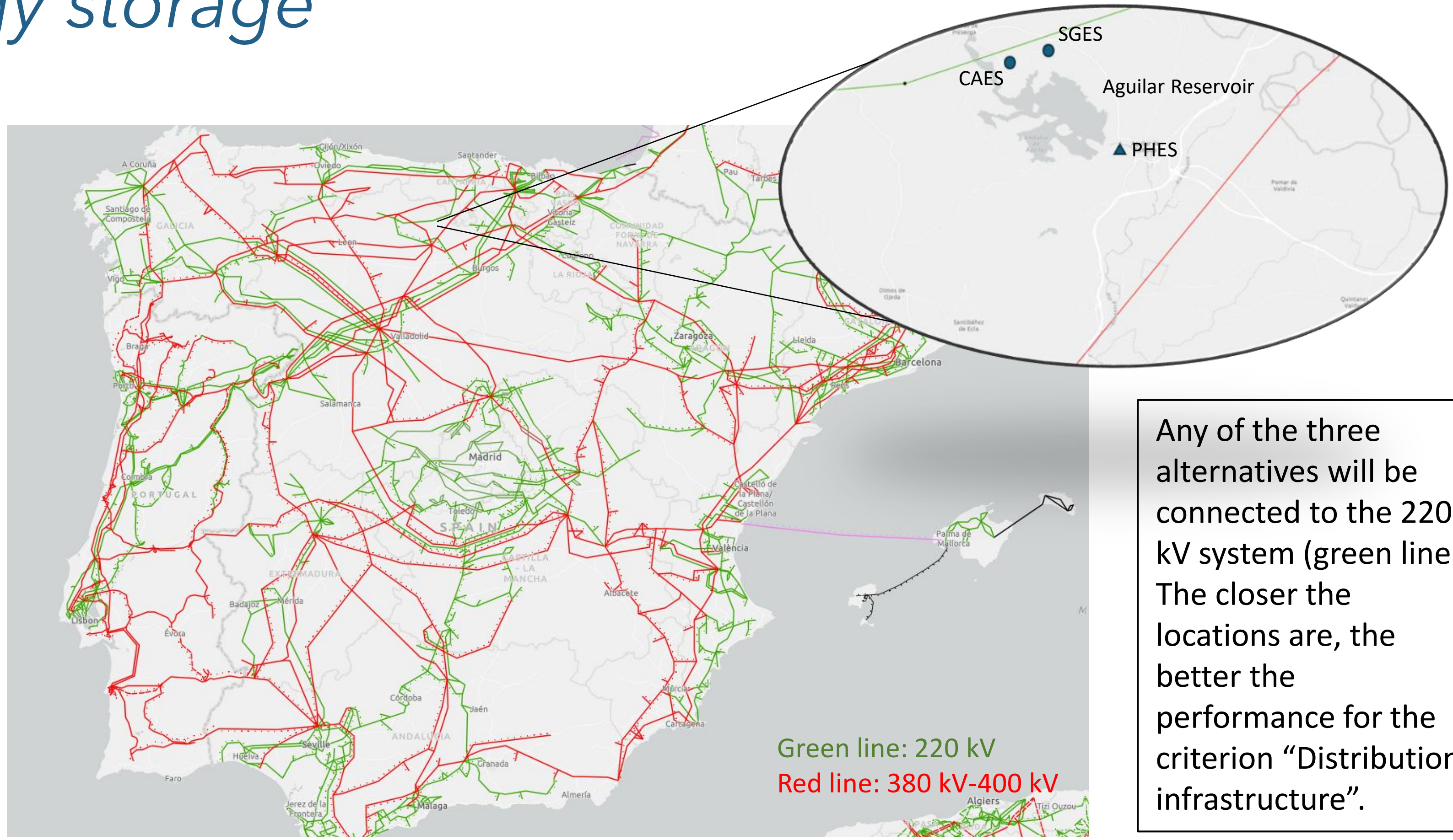
Annex D

Assessment of distribution infrastructure for use case on mechanical energy storage

The KPI distribution infrastructure is location-dependent. To assess this KPI for the theoretical study case on mechanical energy storage alternatives in **Castile and León**, details about the existing transmission line system and distance to connection points are needed.



Transmission system network in Spain [4]

Any of the three alternatives will be connected to the 220 kV system (green line). The closer the locations are, the better the performance for the criterion "Distribution infrastructure".

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Annex E

Database for KPIs for mechanical energy technologies (1)

When developing the evaluation matrix, complete data was not available for all KPIs and/or technologies in one (literature) source; therefore, it was necessary to evaluate different (literature) data sources. In some cases, values from the literature served only as a guideline and needed additional, e.g. spatial, information. In this theoretical use case, the base year for the assessments is 2025. Therefore, costs are given in €2025.

Explanations for selected KPIs

- For **"Efficiency"** and **"Lifetime"** the higher values given in the respective sources are taken.
- The KPI **"Distribution infrastructure"** is highly location-dependent and requires geographic and geospatial information found in [8]. See Annex D. It is assessed as "Good" and "Bad" depending on the distance to the 220 kV transmission system.

KPIs	Unit	References
TRL	-	[1] Tong, W., Lu, Z., Chen, W., Han, M., Zhao, G., Wang, X., & Deng, Z. (2022). Solid gravity energy storage: A review. Journal of Energy Storage, 53, 105226. https://doi.org/10.1016/j.est.2022.105226 [16] Panesar, A., & Sampson, O. (2026). Environmental impact of energy storage technologies and future renewable grids. Journal of Energy Storage, 152, 120501. https://doi.org/10.1016/j.est.2026.120501 [19] Friedel, L., Grenz, J., & Hagist, C. (2026). A comparison of long duration energy storage technologies based on levelized cost of storage. Journal of Energy Storage, 153, 120679. https://doi.org/10.1016/j.est.2026.120679
Efficiency	%	[2] Wang, R., Zhang, L., Shi, C., & Zhao, C. (2025). A review of gravity energy storage. Energies, 18(7), 1812. Academic Editor: Helena M. Ramos https://doi.org/10.3390/en18071812
Lifetime	years	[2] Wang, R., Zhang, L., Shi, C., & Zhao, C. (2025). A review of gravity energy storage. Energies, 18(7), 1812. Academic Editor: Helena M. Ramos https://doi.org/10.3390/en18071812 [19] Friedel, L., Grenz, J., & Hagist, C. (2026). A comparison of long duration energy storage technologies based on levelized cost of storage. Journal of Energy Storage, 153, 120679. https://doi.org/10.1016/j.est.2026.120679 [20] Blakers, A., Stocks, M., Lu, B., & Cheng, C. (2021). A review of pumped hydro energy storage. Progress in Energy, 3(2), 022003. DOI 10.1088/2516-1083/abeb5b
Distribution infrastructure	-	[5] ENERGYDATA.INFO. Available in: https://energydata.info/dataset/global-transmission-network/resource/e0f33c3e-6dab-41d1-919d-d266f300d0bc?inner_span=True

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Annex E

Database for KPIs for mechanical energy technologies (1)

Explanations for selected KPIs

- For the KPI "**LCOS**", the available data are shown in a comparative way in the chosen literature using the pumped hydro values as base line: From the base that the LCOS form PHS is 1, the SGES is 1.5 to 2 times higher, and CAES is 1.1 to 1.4 times the PSH. This data is available in Table 2 in [6].

- For the KPI "**CAPEX**", values are estimated with average data for seasonal pumped hydropower storage, for lift energy storage technology, and for Compressed air energy storage in Table 1 in [9] with the average exchange rate in 2025 of 1€=1.129$.

KPIs	Unit	References
LCOS	-	[6] Wang, X., Yang, H., Li, X., Deng, Z., Fu, G., Wu, Q., & Zhi, H. (2025). Gravitational energy storage: Media taxonomy, efficiency factors, comparison and selection. Applied Energy, 395, 126233. https://doi.org/10.1016/j.apenergy.2025.126233
CAPEX	€/kW	[9] Hunt, J. D., Zakeri, B., Jurasz, J., Wada, Y., Krey, V., & Riahi, K. (2025). The power of sand: Can solid gravity close the energy storage gap?. Journal of Energy Storage, 125, 116839. https://doi.org/10.1016/j.est.2025.116839

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Annex E

Database for KPIs for mechanical energy technologies (2)

Explanations for selected KPIs

- For the KPI **“Land Use”,** technology-specific technical data was required. In the case of CAES, for example, land use data was obtained from a reference plant in Germany [15], and the site area was measured using Google Earth. The land area required for gas storage was then calculated based on technical information regarding the size of the underground caverns where the gas is stored.

- For the KPI **“Visual impact”**, no suitable quantitative data was found in the literature. Therefore, in this case study, it is considered that if the technology can be seen from a great distance, it is considered not the best. As the TSGES is the taller infrastructure among them, this is considered worst compared to the other two technologies. This is a VERY SUBJECTIVE INDICATOR.

KPIs	Unit	References
Land use	m^2/MW	[12] Pang, M., Du, Y., Pei, W., Zhang, P., Yang, J., & Zhang, L. (2025). Pumped hydro energy storage plants in China: Increasing demand and multidimensional impacts identification. Energies, 18(7), 1801. https://doi.org/10.3390/en18071801 [13] Energy Vault. G-VAULT. Evx gravity energy storage for bulk energy shifting. Available in: https://www.energyvault.com/hubfs/G-VAULT_Datasheet-1.pdf [14] Energy Vault. Rudong, China gravity energy storage system. Available in: https://www.energyvault.com/projects/cn-rudong [15] Crotogino, F., Mohmeyer, K. U., & Scharf, R. (2001). Huntorf CAES: More than 20 years of successful operation. Orlando, Florida, USA. Available in: http://www.fze.uni-saarland.de/AKE_Archiv/AKE2003H/AKE2003H_Vortraege/AKE2003H03c_Crotogino_ea_HuntorfCAES_CompressedAirEnergyStorage.pdf
Visual Impact	-	Own assessment.

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Annex E

Database for KPIs for mechanical energy technologies (3)

Explanations for selected KPIs

- For **CO_2 footprint**, **Ecosystem impact**, and **Impact on human health**, we used the report [11] as the initial reference for SGES, since it is the only study that assesses tower solid gravity energy storage, which is the least mature of the three storage technologies evaluated. Based on the system boundaries defined in [11], we performed our own assessment for CAES and PHES in openLCA 2.6.1 and using ecoinvent v3.12. [29]. For all three storage technologies, we applied the environmental footprint methodology with a cradle-to-operation scope, meaning the system boundary extends from raw material extraction to the delivery of 1 kWh of high-voltage electricity at the power plant busbar. Consistent with the approach in [11], the European Union grid mix was used for electricity supply, and only 20% of the total electricity input was attributed to the technology, representing losses.

KPIs	Unit	References
CO_2 footprint	kg CO2 eq/kWh	[11] Szilágyi, A. (2025). Life Cycle Assessment (LCA) Final Report–StoreMore Project. Available in: https://storemore.bcsenergia.hu/wp-content/uploads/2025/06/LCA_StoreMore-FES-GES-Final-2025-05-30.pdf [29] ecoinvent v 3.12 database
Ecosystem impact (ecotoxicity freshwater)	CTUe/kWh	[11] Szilágyi, A. (2025). Life Cycle Assessment (LCA) Final Report–StoreMore Project. Available in: https://storemore.bcsenergia.hu/wp-content/uploads/2025/06/LCA_StoreMore-FES-GES-Final-2025-05-30.pdf [29] ecoinvent v 3.12 database
Impact on human health (human toxicity cancer)	CTUh/kWh	[11] Szilágyi, A. (2025). Life Cycle Assessment (LCA) Final Report–StoreMore Project. Available in: https://storemore.bcsenergia.hu/wp-content/uploads/2025/06/LCA_StoreMore-FES-GES-Final-2025-05-30.pdf [29] ecoinvent v 3.12 database

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Annex F
ELECTRE III Aggregation Method

With ELECTRE III Net flow scores (NFS) calculation of rankings of different alternatives are based on **performance data**, **weights** as importance coefficients and **threshold values**. **Higher NFS indicate better overall performance [10]**

1) Outranking degree between alternatives
(0 ≤ Ck(ai, aj) ≤ 1)

$$C_k(a_i,a_j)=\begin{cases}0 & \text{if} \quad f_k(a_j)-f_k(a_i)>p(f_k)\\ 1 & \text{if} \quad f_k(a_j)-f_k(a_i)\le q(f_k)\\ \dfrac{p(f_k)+f_k(a_i)-f_k(a_j)}{p(f_k)-q(f_k)} & \text{otherwise}\end{cases}$$

p Preference threshold

q Indifference threshold

Reasons FOR

2) Outranking index:

$$C(a_i,a_j)=\frac{\sum_{k=1}^{q} w_k C_k(a_i,a_j)}{\sum_{k=1}^{q} w_k}$$

Criteria weights w_k

[17]

Reasons AGAINST

3) Discordance index:

p Preference threshold

$$D_k(a_i,a_j)=\begin{cases}0 & \text{if} \quad f_k(a_j)-f_k(a_i)\le p(f_k)\\ 1 & \text{if} \quad f_k(a_j)-f_k(a_i)>v(f_k)\\ \dfrac{f_k(a_j)-f_k(a_i)-p(f_k)}{v(f_k)-p(f_k)} & \text{otherwise}\end{cases}$$

v Veto threshold

4) Credibility degree:

$$S(a_i,a_j)=\begin{cases}C(a_i,a_j) & \text{if} \quad D_k(a_i,a_j)\le C(a_i,a_j)\ \forall k\in J\\ C(a_i,a_j)\times\prod_{k\in J(a_i,a_j)}\dfrac{1-D_k(a_i,a_j)}{1-C(a_i,a_j)} & \text{otherwise}\end{cases}$$

$$\phi^+(a_i)=\sum_{x\in A} S(a_i,x) \qquad \phi^-(a_i)=\sum_{x\in A} S(x,a_i)$$

Net flow score

$$\phi(a_i)=\phi^+(a_i)-\phi^-(a_i)$$

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Annex F
ELECTRE III Thresholds

Note: Not necessarily all the criteria are subject to the definition of indifference and preference discriminating thresholds and veto. **Discriminating thresholds p and q** are used to handle imperfect knowledge, i.e. the uncertainty of the data. The **Veto (v)** threshold is a preference parameter that serves to indicate reasons against an outranking relation, i.e. reasons for which one alternative cannot be better than the other.

$0 < q < p < v$

Preference thresholds (p): The preference threshold, p, between two performances, is the smallest performance difference that when exceeded is judged significant of a strict preference in favor of the action with the best performance. This difference (which is by definition non-negative) can be equal to zero (which corresponds to the case of the true-criterion model).

Indifference thresholds (q): The indifference threshold, q, between two performances, is the largest performance difference that is judged compatible with an indifference situation between wo actions with different performances.

Veto threshold (v): The veto threshold, v, represents a level of performance on a particular criterion beyond which an alternative cannot be considered to outrank another, regardless of the performance on other criteria. It is a way to enforce strict disqualifications based on unacceptable performance in certain key areas.

[17], [23]

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Coming soon:

Part III- How HELDA web tool can be used for comprehensive sustainability assessment of energy technologies

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Thank you

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RISEnergy

Research Infrastructure Services for Renewable Energy

QR Code to link to training materials section RISEnergy website

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Further reading

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