International Conference on

small modular reactors

and their applications

21–25 October 2024, Vienna, Austria

Economic Analysis of Thermal Energy Storage Integration in Small Modular Reactors Balance of Plant

F. Tassone, G. Locatelli, S. Lorenzi, M. E. Ricotti

POLITECNICO MILANO 1863

NRGroup

ANSELMUS

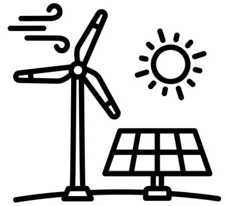
Agenda

- **Introduction**
  - Storage and nuclear technologies
  - Power plant configurations
  - Hypotheses and notes

- **Methodology and results**
  - Estimation of costs
  - Estimation of revenues
  - Discounted cash flow

- **Comments and conclusions**

Introduction



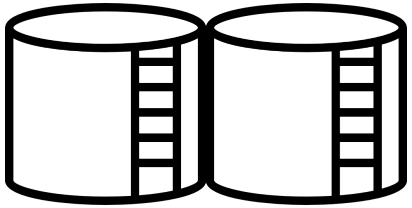
- In 2022 alone, share of **renewable energy sources** increased by 340 GWe.
- The **ability to modulate electricity output** is becoming increasingly valuable, especially for base load power plants, like nuclear (NPPs).
- **Load-following** with NPPs is possible but usually avoided:
  - increased thermo-mechanical stresses among reactor components;
  - reduced power output (loss in revenues) with constant operational costs.

- **Energy storage** could enhance load-following capabilities of NPPs.
- **Constant power output**:
  - Price arbitrage;
  - Operational easiness.

Introduction

Energy storage technologies:

- **Mechanical** - e.g., pumped hydro, compressed air;
- **Chemical** - e.g., batteries;
- **Electrical** - e.g., capacitors;
- **Thermal** - e.g., molten salt.
  - ***Molten salt thermal energy storage*** *(MSTES).*
  - ***Solar salt*** *(40% KNO_3, 60% $NaNO_3$).*
  - *Working temperatures:* ***290°C for cold tank, 400°C for hot tank.***

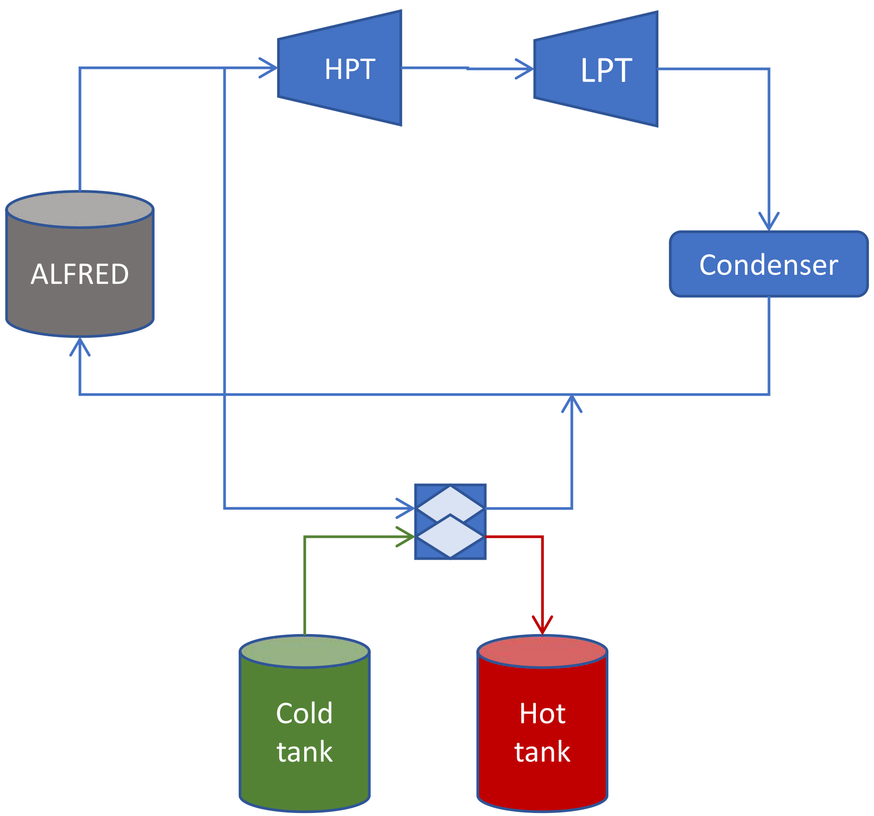


Nuclear technologies:

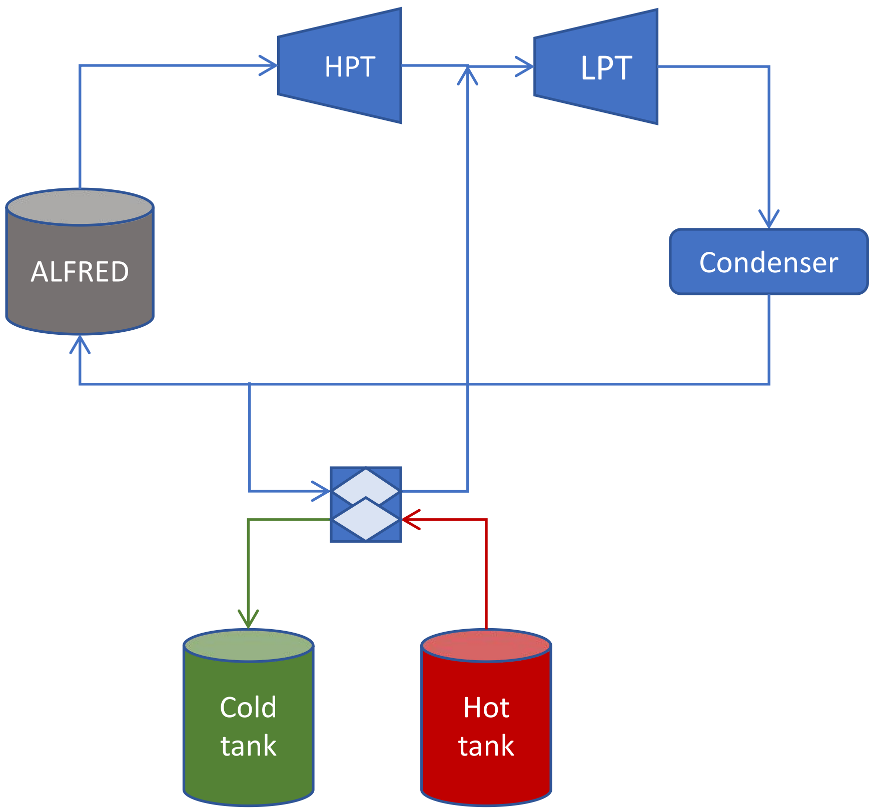
- **Gen IV technologies** would be more suitable for such coupling given the higher temperatures reached with respect to typical Gen II, III/III+ NPPs;
- One of the most advanced in research is the **lead-cooled fast reactor** (LFR);
- **ALFRED**, European demonstrator for lead technology, given its advanced design status and temperature compatibility (450°C in the steam loop), is the reactor selected for this study.

ALFRED-MSTES plant configurations

Simplified loading scheme



Simplified unloading scheme



Notation:

- **U1**, **U2**, **U3** - unloading scheme and turbine size;
- **L1**, **L2** - loading scheme;
- **S1**, **S2**, **S3** - storage size.

M. Celador Lera et al. Main components definition: definition and sizing of the main components, including sensitivity analysis of both BOP configurations. *ANSELMUS, D5.2, 2023.*

ALFRED-MSTES plant configurations

Reactor	LFR	ALFRED: 300 MWt, **118 MWe**.
Loading and Unloading Schemes	U1-L1	Plant net power when loading and unloading: **80.6** and **136.0 MWe**. Unloading/loading time ratio: 1.44.
	U1-L2	Plant net power when loading and unloading: **41.5** and **136.0 MWe**. Unloading/loading time ratio: 2.87.
	U2-L1	Plant net power when loading and unloading: **73.6** and **153.6 MWe**. Unloading/loading time ratio: 0.72.
	U2-L2	Plant net power when loading and unloading: **35.0** and **153.6 MWe**. Unloading/loading time ratio: 1.43.
	U3-L1	Plant net power when loading and unloading: **68.3** and **187.1 MWe**. Unloading/loading time ratio: 0.36.
	U3-L2	Plant net power when loading and unloading: **30.1** and **187.1 MWe**. Unloading/loading time ratio: 0.72.
Tanks	S1	Total salt: 12000 ton. Diameter: 24.2 m. Height: 14 m.
	S2	Total salt: 15000 ton. Diameter: 27.1 m. Height: 14 m.
	S3	Total salt: 20000 ton. Diameter: 31.3 m. Height: 14 m.

3 countries: **Germany**, **Italy**, and **Romania**.

Total scenarios: 18 configurations × 3 countries = **54 possibilities**.
Examples: U2-L1-S2 in Italy, U3-L2-S1 in Romania, etc.

ALFRED-MSTES plant configurations

Reactor	LFR	ALFRED: 300 MWt, **118 MWe**.
Loading and Unloading Schemes	U1-L1	Plant net power when loading and unloading: **80.6** and **136.0 MWe**. Unloading/loading time ratio: 1.44.
	U1-L2	Plant net power when loading and unloading: **41.5** and **136.0 MWe**. Unloading/loading time ratio: 2.87.
	U2-L1	Plant net power when loading and unloading: **73.6** and **153.6 MWe**. Unloading/loading time ratio: 0.72.
	U2-L2	Plant net power when loading and unloading: **35.0** and **153.6 MWe**. Unloading/loading time ratio: 1.43.
	U3-L1	Plant net power when loading and unloading: **68.3** and **187.1 MWe**. Unloading/loading time ratio: 0.36.
	U3-L2	Plant net power when loading and unloading: **30.1** and **187.1 MWe**. Unloading/loading time ratio: 0.72.
Tanks	S1	Total salt: 12000 ton. Diameter: 24.2 m. Height: 14 m.
	S2	Total salt: 15000 ton. Diameter: 27.1 m. Height: 14 m.
	S3	Total salt: 20000 ton. Diameter: 31.3 m. Height: 14 m.

3 countries: **Germany**, **Italy**, and **Romania**.

Total scenarios: 18 configurations × 3 countries = **54 possibilities**.
Examples: U2-L1-S2 in Italy, U3-L2-S1 in Romania, etc.

ALFRED-MSTES plant configurations

Reactor	LFR	ALFRED: 300 MWt, **118 MWe**.
Loading and Unloading Schemes	U1-L1	Plant net power when loading and unloading: **80.6** and **136.0 MWe**. Unloading/loading time ratio: 1.44.
	U1-L2	Plant net power when loading and unloading: **41.5** and **136.0 MWe**. Unloading/loading time ratio: 2.87.
	U2-L1	Plant net power when loading and unloading: **73.6** and **153.6 MWe**. Unloading/loading time ratio: 0.72.
	U2-L2	Plant net power when loading and unloading: **35.0** and **153.6 MWe**. Unloading/loading time ratio: 1.43.
	U3-L1	Plant net power when loading and unloading: **68.3** and **187.1 MWe**. Unloading/loading time ratio: 0.36.
	U3-L2	Plant net power when loading and unloading: **30.1** and **187.1 MWe**. Unloading/loading time ratio: 0.72.
Tanks	S1	Total salt: 12000 ton. Diameter: 24.2 m. Height: 14 m.
	S2	Total salt: 15000 ton. Diameter: 27.1 m. Height: 14 m.
	S3	Total salt: 20000 ton. Diameter: 31.3 m. Height: 14 m.

3 countries: **Germany**, **Italy**, and **Romania**.

Total scenarios: 18 configurations × 3 countries = **54 possibilities**.
Examples: U2-L1-S2 in Italy, U3-L2-S1 in Romania, etc.

Hyphotheses and notes

1. ‘***Differential***’ ***analysis***. We are **not considering cost and revenues common to all scenarios** (including e.g., capital investment for the nuclear reactor). We are **estimating the increase in total capital investment (TCI), operational costs (O&M) and revenues generated by the coupling with the MSTES**:
   - MSTES - capital investment and O&M costs;
   - ALFRED - increase in capital cost, increase in O&M assumed zero for the reactor.

2. The plants (ALFRED + MSTES) are considered First-Of-A-Kinds (**FOAKs**).

3. Molten salt is loaded during hours with lowest electricity price, it is unloaded when price is high (**price arbitrage**), also for not consecutive hours. Salts cannot be loaded and unloaded simoultaneously.

4. All costs and prices are expressed in **2022 USD** ($).

Cost estimation

[M$]	MSTES		NPP		MSTES		NPP
	TCI	Annual O&M costs	Increase in NPP costs		TCI	Annual O&M costs	Increase in NPP costs
U1-L1-S1	76	3	9	**U2-L2-S1**	87	3	17
U1-L1-S2	85	3	9	**U2-L2-S2**	97	4	17
U1-L1-S3	106	4	9	**U2-L2-S3**	109	4	17
U1-L2-S1	84	3	9	**U3-L1-S1**	94	4	32
U1-L2-S2	92	4	9	**U3-L1-S2**	101	4	32
U1-L2-S3	114	5	9	**U3-L1-S3**	115	5	32
U2-L1-S1	79	3	17	**U3-L2-S1**	101	4	32
U2-L1-S2	89	4	17	**U3-L2-S2**	109	4	32
U2-L1-S3	102	4	17	**U3-L2-S3**	122	5	32

D. E. Holcomb et al., Advanced high temperature reactor systems and economic analysis. *ORNL/TM-2011/364. 2011.*
M. Shamoushaki et al., Development of cost correlations for the economic assessment of power plant equipment. *Energies 14 (2021), 2665.*
S. Thaker et al., Techno-economic evaluation of solar-based thermal energy storage systems. *Energy Conversion and Management 153 (2017), 423-434.*
B. Kelly and D. Kearney. Thermal storage commercial plant design study for a 2-tank indirect molten salt system. *NREL/SR-550-40166. 2006.*
R. Smith. Chemical process design and integration. *John Wiley and Sons, Ltd. 2005.*
F. Ganda et al., Report on the update of fuel cycle cost algorithms. *NTRD-FCO-2018-000439. 2018.*

Cost estimation

Less expensive configuration
85 M$** and **3 M$ increase in annual O&M

[M$]	MSTES		NPP		MSTES		NPP
	TCI	Annual O&M costs	Increase in NPP costs		TCI	Annual O&M costs	Increase in NPP costs
U1-L1-S1	76	3	9	**U2-L2-S1**	87	3	17
U1-L1-S2	85	3	9	**U2-L2-S2**	97	4	17
U1-L1-S3	106	4	9	**U2-L2-S3**	109	4	17
U1-L2-S1	84	3	9	**U3-L1-S1**	94	4	32
U1-L2-S2	92	4	9	**U3-L1-S2**	101	4	32
U1-L2-S3	114	5	9	**U3-L1-S3**	115	5	32
U2-L1-S1	79	3	17	**U3-L2-S1**	101	4	32
U2-L1-S2	89	4	17	**U3-L2-S2**	109	4	32
U2-L1-S3	102	4	17	**U3-L2-S3**	122	5	32

Most expensive configuration
154 M$** and **5 M$ increase in annual O&M

D. E. Holcomb et al., Advanced high temperature reactor systems and economic analysis. *ORNL/TM-2011/364. 2011.*
M. Shamoushaki et al., Development of cost correlations for the economic assessment of power plant equipment. *Energies 14 (2021), 2665.*
S. Thaker et al., Techno-economic evaluation of solar-based thermal energy storage systems. *Energy Conversion and Management 153 (2017), 423-434.*
B. Kelly and D. Kearney. Thermal storage commercial plant design study for a 2-tank indirect molten salt system. *NREL/SR-550-40166. 2006.*
R. Smith. Chemical process design and integration. *John Wiley and Sons, Ltd. 2005.*
F. Ganda et al., Report on the update of fuel cycle cost algorithms. *NTRD-FCO-2018-000439. 2018.*

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Revenues estimation

- Revenues come solely from the selling of electricity.
- For simplicity:
    - **Daily analysis considering the average electricity price in a day for 2023**;
    - **Each day, the molten salt loaded is equal to the amount unloaded;**
    - **Estimation of the maximum daily increase in revenues.**
- 2023 electricity prices of Germany, Italy, and Romania.

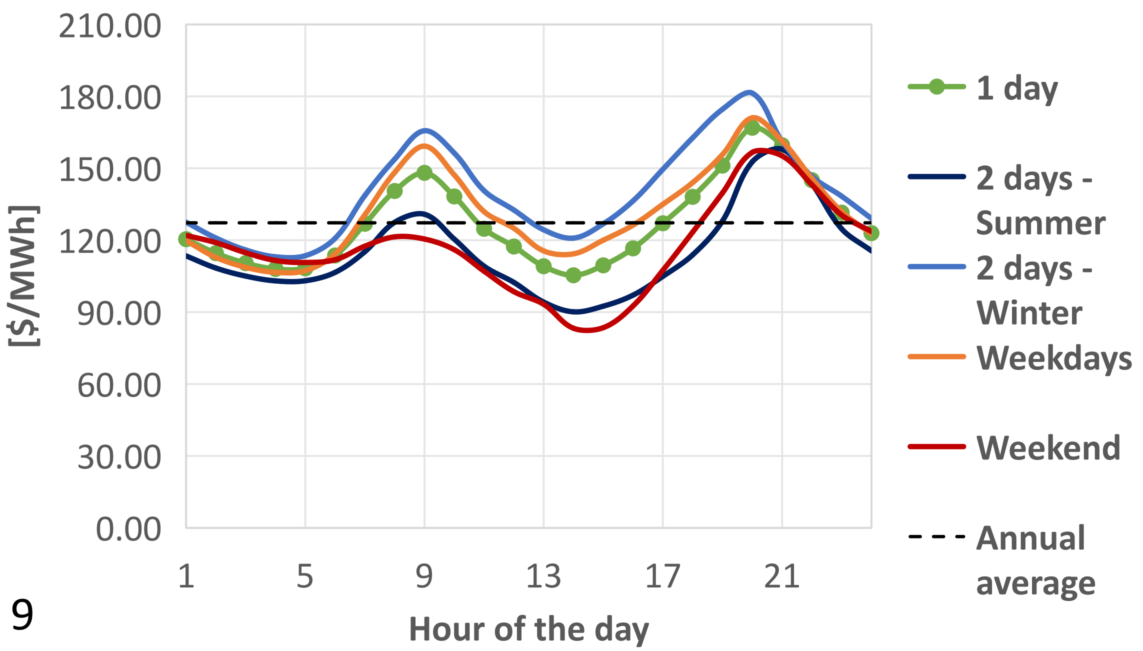
https://transparency.entsoe.eu/

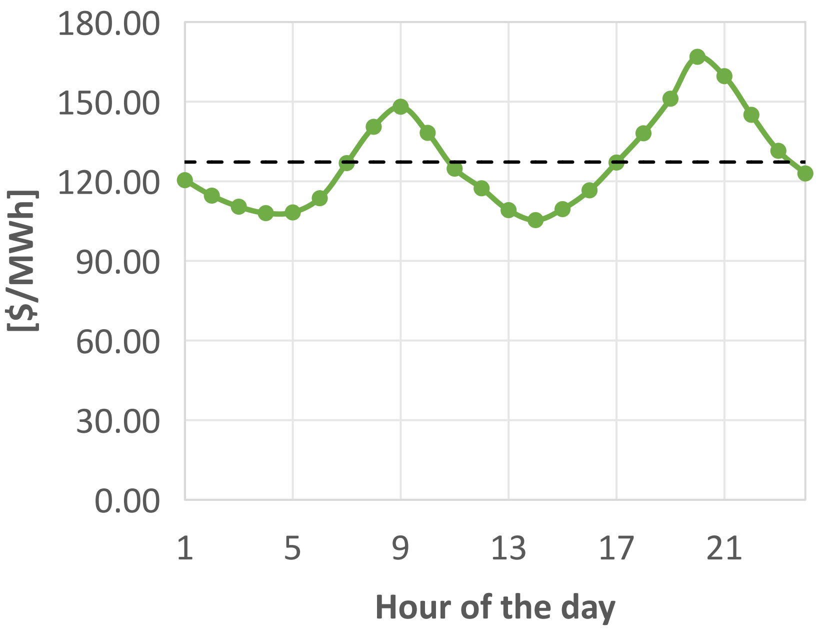
Revenues estimation

- Revenues come solely from the selling of electricity.
- For simplicity:
  - **Daily analysis considering the average electricity price in a day for 2023**;
  - **Each day, the molten salt loaded is equal to the amount unloaded;**
  - **Estimation of the maximum daily increase in revenues.**
- 2023 electricity prices of Germany, Italy, and Romania.

https://transparency.entsoe.eu/

Example: Italy's electricity price in 2023





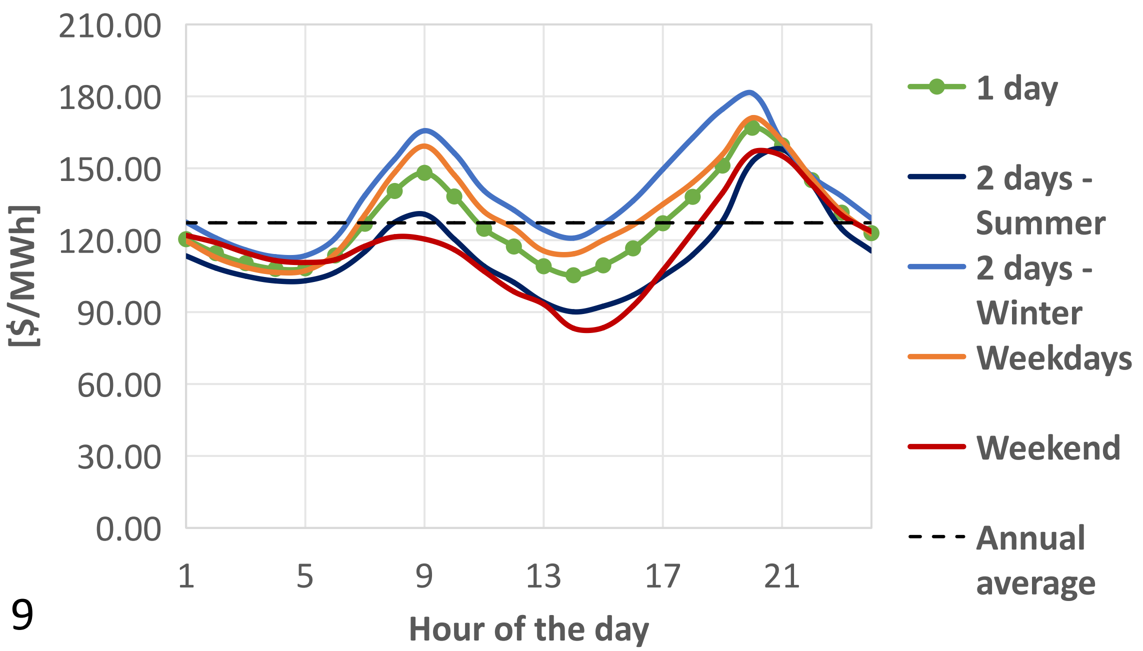
POLITECNICO MILANO 1863 NRGroup ANSELMUS

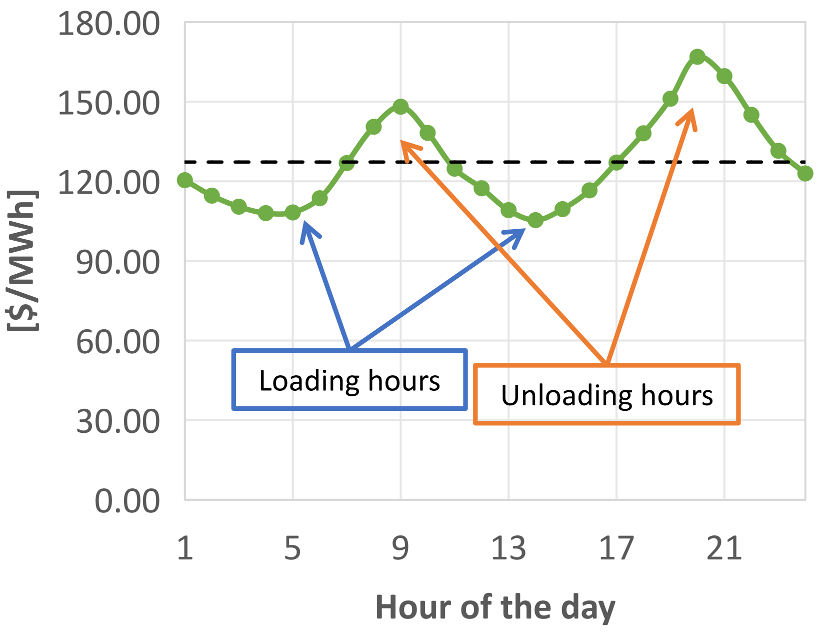
Revenues estimation

- Revenues come solely from the selling of electricity.
- For simplicity:
  - **Daily analysis considering the average electricity price in a day for 2023**;
  - **Each day, the molten salt loaded is equal to the amount unloaded;**
  - **Estimation of the maximum daily increase in revenues.**
- 2023 electricity prices of Germany, Italy, and Romania.

https://transparency.entsoe.eu/

Example: Italy's electricity price in 2023





<u>Note</u>: the increase in revenues is proportional to the area between the curve and its average value.

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Revenues estimation

Maximum increase in daily revenues

$$R = (P_l - P_{nom}) \sum_{i=1}^{L} \left(E_i - \bar{E}\right) + (P_u - P_{nom}) \sum_{j=1}^{U} \left(E_j - \bar{E}\right) k_j$$

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Revenues estimation

Power while loading and nominal power

Maximum increase in daily revenues

$$R = (P_l - P_{nom}) \sum_{i=1}^{L} \left(E_i - \bar{E}\right) + (P_u - P_{nom}) \sum_{j=1}^{U} \left(E_j - \bar{E}\right) k_j$$

Power while unloading and nominal power

Revenues estimation

Power while loading and nominal power

Loading hours (integer)

Unloading hours (integer)

Maximum increase in daily revenues

$$R = (P_l - P_{nom}) \sum_{i=1}^{L} \left(E_i - \bar{E}\right) + (P_u - P_{nom}) \sum_{j=1}^{U} \left(E_j - \bar{E}\right) k_j$$

Power while unloading and nominal power

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Revenues estimation

Power while loading and nominal power

Loading hours (integer)

Unloading hours (integer)

Maximum increase in daily revenues

$$R = (P_l - P_{nom}) \sum_{i=1}^{L} \left(E_i - \bar{E}\right) + (P_u - P_{nom}) \sum_{j=1}^{U} \left(E_j - \bar{E}\right) k_j$$

Power while unloading and nominal power

Electricity price: hour value and average

Revenues estimation

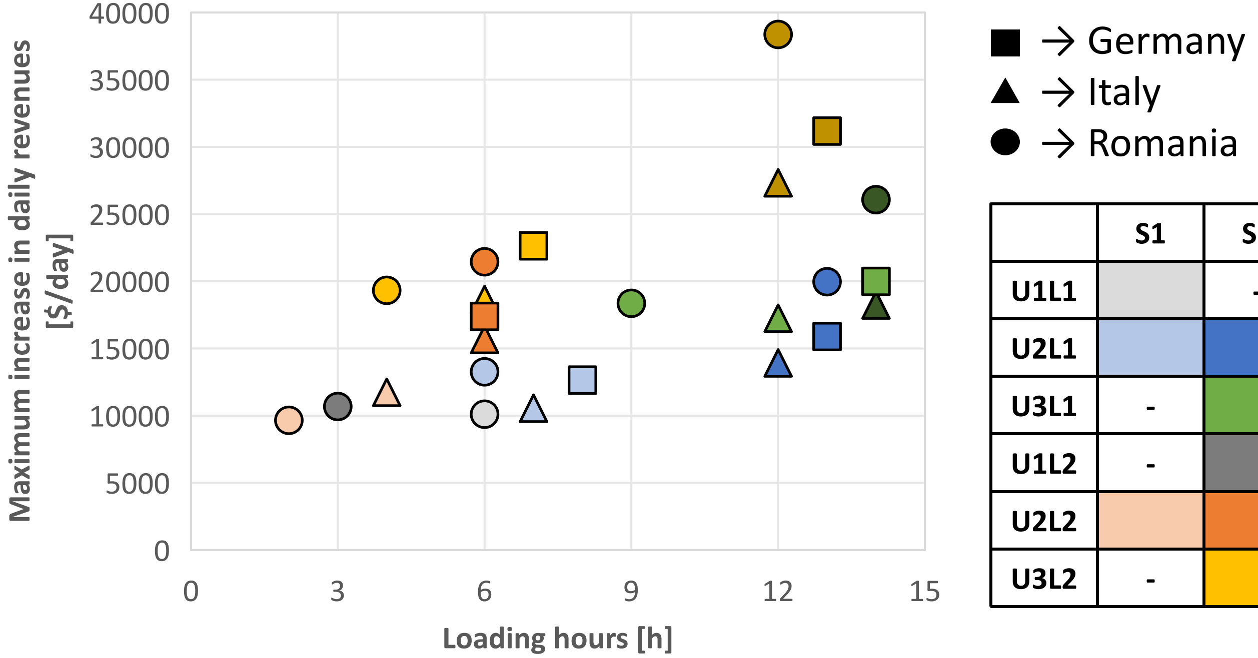
$$R = (P_l - P_{nom})\sum_{i=1}^{L}\left(E_i - \bar{E}\right) + (P_u - P_{nom})\sum_{j=1}^{U}\left(E_j - \bar{E}\right)k_j$$

- Maximum increase in daily revenues → R
- Power while loading and nominal power → $(P_l - P_{nom})$
- Loading hours (integer) → L
- Unloading hours (integer) → U
- Power while unloading and nominal power → $(P_u - P_{nom})$
- Electricity price: hour value and average → E_i, E_j, $\bar{E}$
- Correcting factor for last unloading hour → k_j

example:
loading time - 2 hours
unloading time - 3.4 hours
$L = 2$
$U = 4$
$k_1 = k_2 = k_3 = 1$
$k_4 = 0.4$

POLITECNICO MILANO 1863 · NRGroup · ANSELMUS

Revenues estimation



	S1	S2	S3
U1L1		-	-
U2L1			-
U3L1	-		
U1L2	-		-
U2L2			-
U3L2	-		

- Total of 54 configurations.
- A configuration is discarded when:
  - **maximum increase in revenues lower than daily increase in O&M**;
  - **revenues equal to the ones of the smaller configuration** (same U and L, but smaller S).
- 30 configurations are discarded.

- **24 remaining configurations**:
  - 10 for Romania;
  - 8 for Italy;
  - 6 for Germany.
- Differences are caused by the electricity price profiles.

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Discounted cash flow

Assumptions to compute Net Present Value (NPV):

- MSTES lifetime of 30 years, with construction and decommissioning;
- 5% interest rate;
- MSTES construction period of 2 years (year 1 and 2);
- 1 year decommissioning (year 30);
- Load factor of 90%.

Discounted cash flow

Assumptions to compute Net Present Value (NPV):

- MSTES lifetime of 30 years, with construction and decommissioning;
- 5% interest rate;
- MSTES construction period of 2 years (year 1 and 2);
- 1 year decommissioning (year 30);
- Load factor of 90%.

NPV [M$]	**Italy**			**Germany**			**Romania**		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
U1-L1							-82		
U2-L1	-92	-92		-83	-83		-80	-65	
U3-L1		-110	-127		-97			-105	-91
U1-L2								-105	
U2-L2	-99	-96			-89		-108	-70	
U3-L2		-116	-97		-97	-80		-112	-47

Discounted cash flow

Assumptions to compute Net Present Value (NPV):

- MSTES lifetime of 30 years, with construction and decommissioning;
- 5% interest rate;
- MSTES construction period of 2 years (year 1 and 2);
- 1 year decommissioning (year 30);
- Load factor of 90%.

NPV [M$]	Italy			Germany			Romania		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
U1-L1							-82		
U2-L1	-92	-92		-83	-83		-80	-65	
U3-L1		-110	-127		-97			-105	-91
U1-L2								-105	
U2-L2	-99	-96			-89		-108	-70	
U3-L2		-116	-97		-97	-80		-112	-47

U3-L2-S3 is the prefereable choice for Germany and Romania. For Italy, it has a worse NPV than others, however, its NPV can increase more easily.
We can state U3-L2-S3 is the preferable choice overall.

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Discounted cash flow

Assumptions to compute Net Present Value (NPV):

- MSTES lifetime of 30 years, with construction and decommissioning;
- 5% interest rate;
- MSTES construction period of 2 years (year 1 and 2);
- 1 year decommissioning (year 30);
- Load factor of 90%.

NPV [M$]	Italy			Germany			Romania		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
U1-L1							-82		
U2-L1	-92	-92		-83	-83		-80	-65	
U3-L1		-110	-127		-97			-105	-91
U1-L2								-105	
U2-L2	-99	-96			-89		-108	-70	
U3-L2		-116	-97		-97	-80		-112	-47

U3-L2-S3 is the prefereable choice for Germany and Romania. For Italy, it has a worse NPV than others, however, its NPV can increase more easily.
We can state U3-L2-S3 is the preferable choice overall.

Comments

All NPVs are negative, however:

- **the largest the configurations are preferable**, U3-L2-S3 has the highest NPV;
- we are considering the plant as a **FOAK**;
- 1-day approximation: **peaks and valleys are smoother and broader, missing highest values**.
- we are considering **only day-ahead market**.

Moreover:

- the maximum increase in revenues is proportional to the area between price curve and its average;
- **is that area proportional to the variation of daily electricity price (max - min)?**

POLITECNICO MILANO 1863 NRGroup ANSELMUS

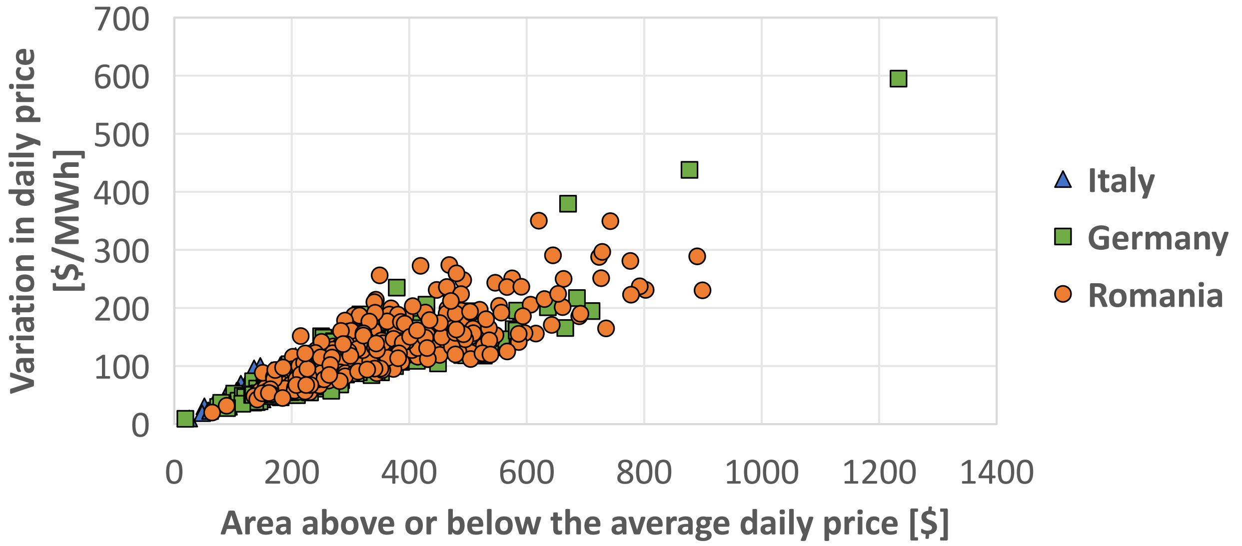
Comments

All NPVs are negative, however:

- **the largest the configurations are preferable**, U3-L2-S3 has the highest NPV;
- we are considering the plant as a **FOAK**;
- 1-day approximation: **peaks and valleys are smoother and broader, missing highest values**.
- we are considering **only day-ahead market**.

Moreover:

- the maximum increase in revenues is proportional to the area between price curve and its average;
- **is that area proportional to the variation of daily electricity price (max - min)?**



POLITECNICO MILANO 1863 NRGroup ANSELMUS

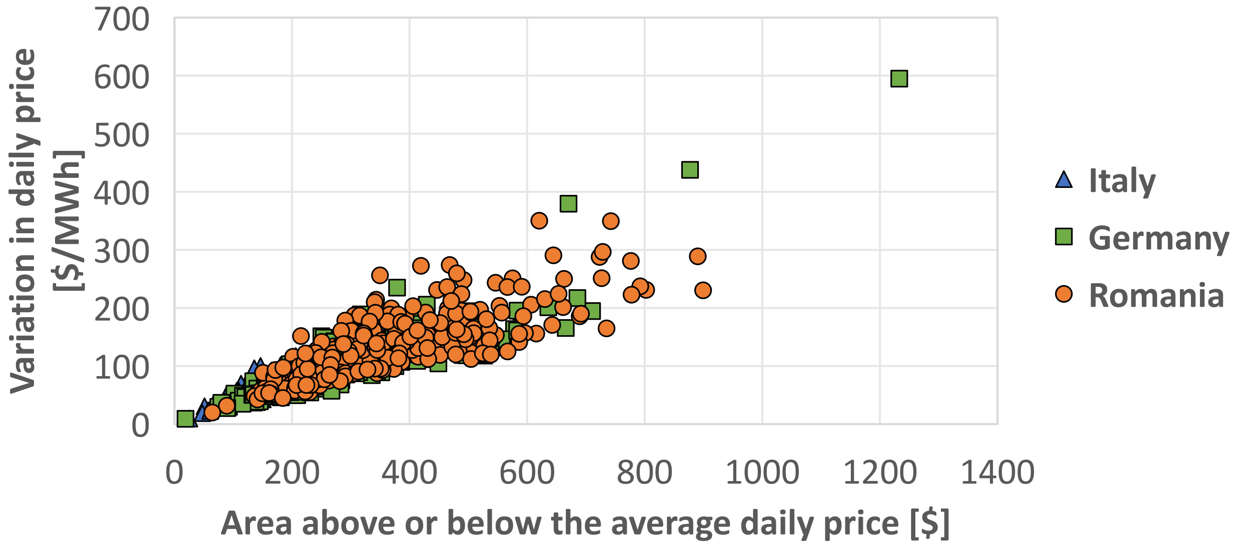
Comments

All NPVs are negative, however:

- **the largest the configurations are preferable**, U3-L2-S3 has the highest NPV;
- we are considering the plant as a **FOAK**;
- 1-day approximation: **peaks and valleys are smoother and broader, missing highest values**.
- we are considering **only day-ahead market**.

Moreover:

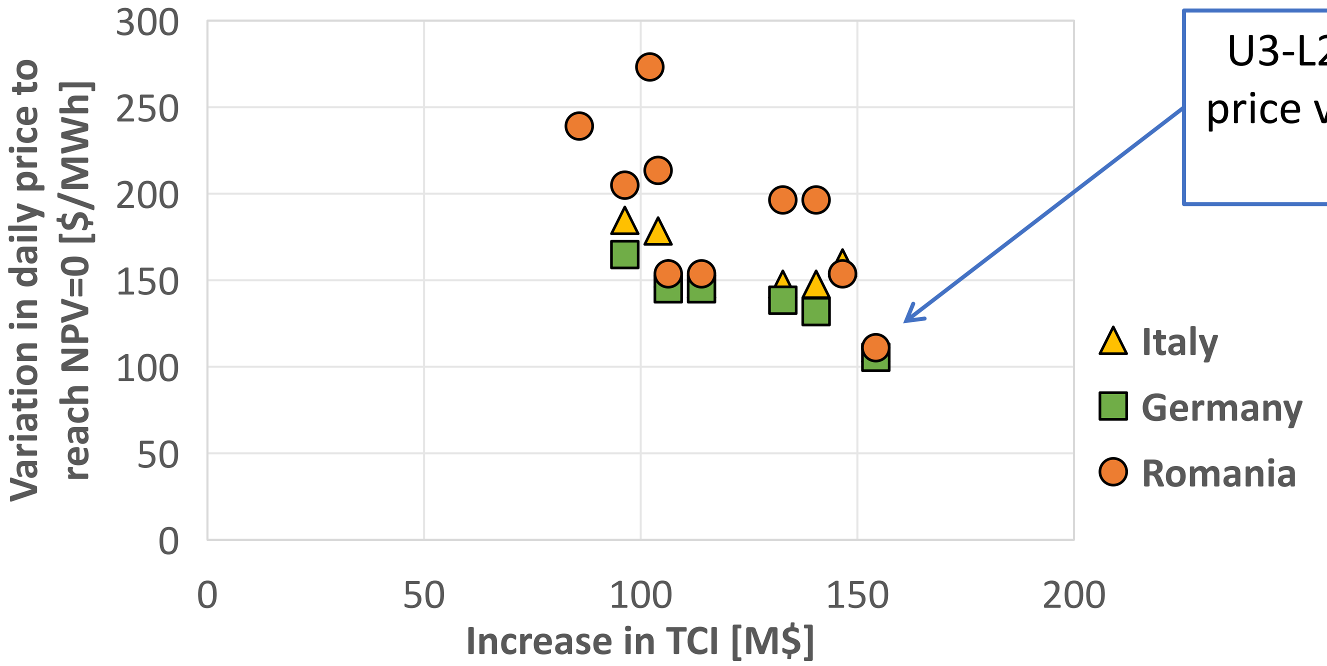
- the maximum increase in revenues is proportional to the area between price curve and its average;
- **is that area proportional to the variation of daily electricity price (max - min)?**



What is the minimum variation in daily electricity price for which the configurations reach NPV = 0?

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Comments

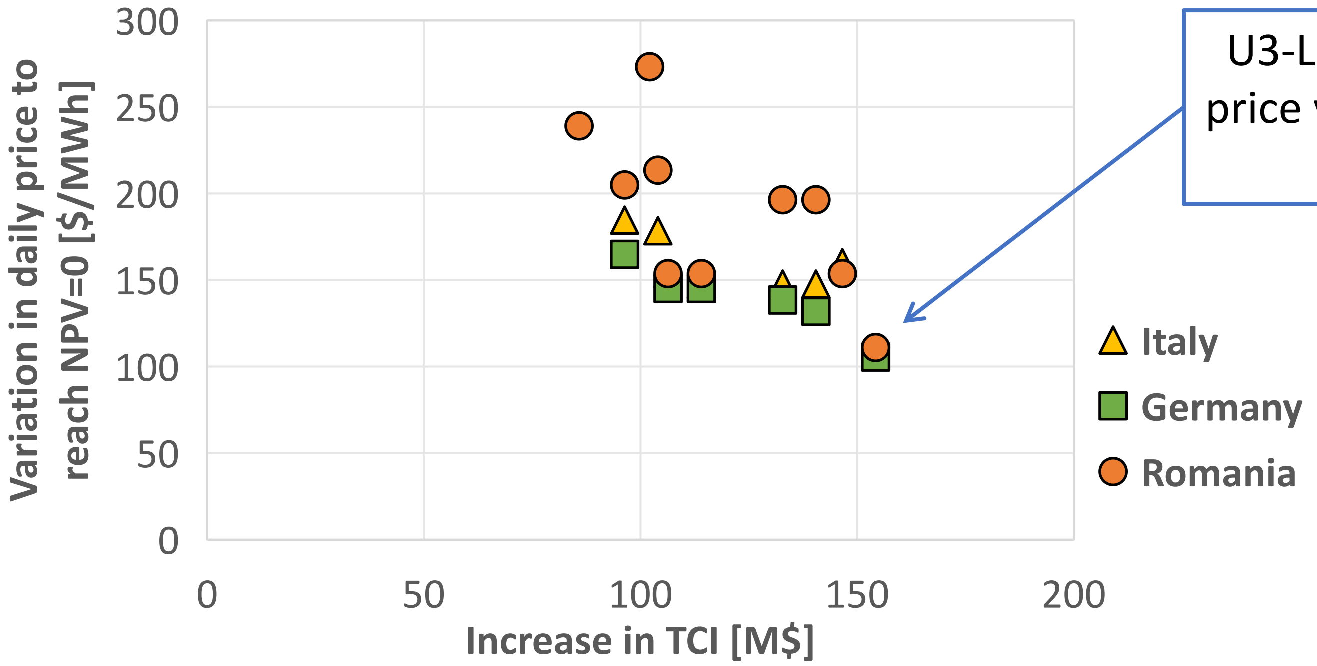


U3-L2-S3 requires a daily electricity price variation of around 100 $/MWh to be profitable

Such daily variations would be increasingly common with an increasing share of renewables

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Comments



U3-L2-S3 requires a daily electricity price variation of around 100 $/MWh to be profitable

Such daily variations would be increasingly common with an increasing share of renewables

Configuration U3-L2-S3		23rd January	8th April	10th August	17th October
Germany	*[k$/day]*	**57**	**22**	**54**	**38**
	Daily variation	124	46	167	94
Italy	*[k$/day]*	**44**	**32**	**20**	**25**
	Daily variation	105	119	61	62
Romania	*[k$/day]*	**105**	**26**	**26**	**80**
	Daily variation	235	70	94	200

Example days from 2023

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Conclusion

- We performed an **economic analysis of MSTES coupled with ALFRED**, considering 18 configurations and 3 countries, for a total of 54 possibilities.
- We evaluated the **increase in capital cost due to MSTES** at around **80-160 M$**, depending on the configuration.
- We performed an average-day analysis for the estimation of the **increase in daily revenues**. The results are around **10-40 k$/day**, depending on the configuration.
- The most promising configuration is **U3-L2-S3**, **requiring a daily electricity price variation of 100 $/MWh to be profitable**. Such variations would be more and more common with an increasing share of renewables.

POLITECNICO MILANO 1863 NRGroup ANSELMUS

Thank you for your attention!

Economic Analysis of Thermal Energy Storage Integration in Small Modular Reactors Balance of Plant

F. Tassone, G. Locatelli, S. Lorenzi, M. E. Ricotti

federico.tassone@polimi.it - giorgio.locatelli@polimi.it - stefano.lorenzi@polimi.it - marco.ricotti@polimi.it

POLITECNICO MILANO 1863

NRGroup

ANSELMUS