The social efficiency of electricity transition policies based on renewables:

Which ways of improvement?

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Chaire European Electricity Markets (CEEM)
Université Paris-Dauphine

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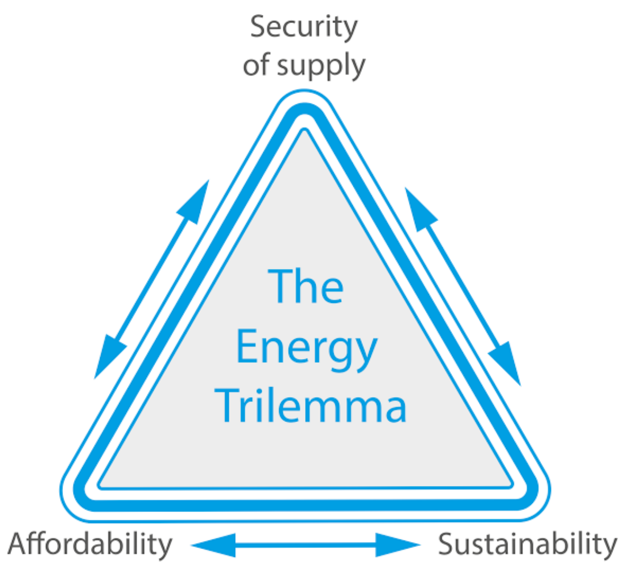
Today's Climate & Energy policies are based on the "The Energy Trilemma":



In the EU, the "***Clean Energy Transition***" strategy focuses on reducing highly CO_2 emissions by:

a. **Electrification** of energy uses (i.e. electric heating, EV, etc…"*The race to electrifying EU is on*"), and,

b. **Promoting energy efficiency** (EE) and **renewable energy sources** (RES)

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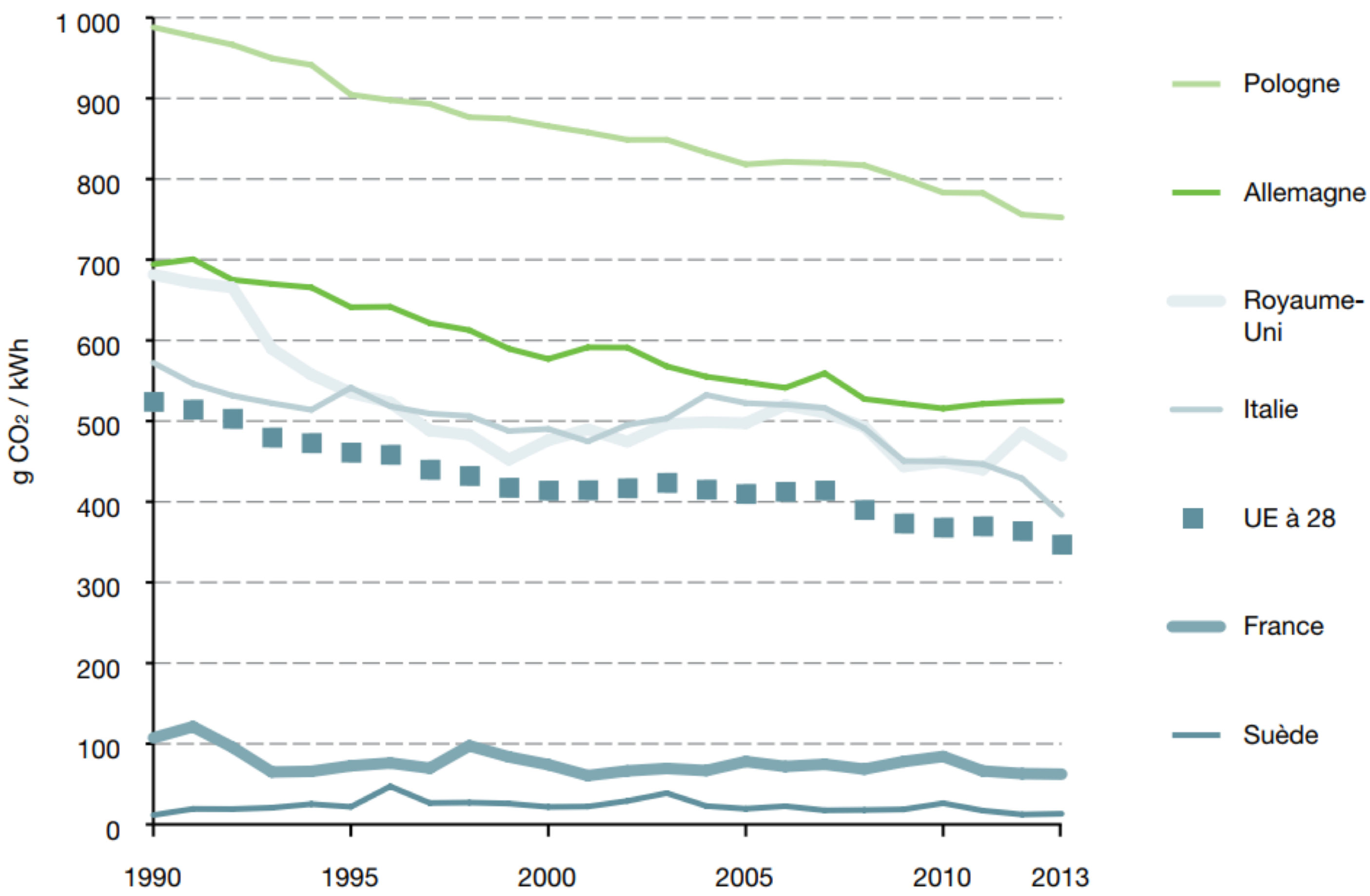
A focus on specific emissions of the power sector in the EU:



CO2 emissions of the power sector of some EU countries. Source: IEA 2015

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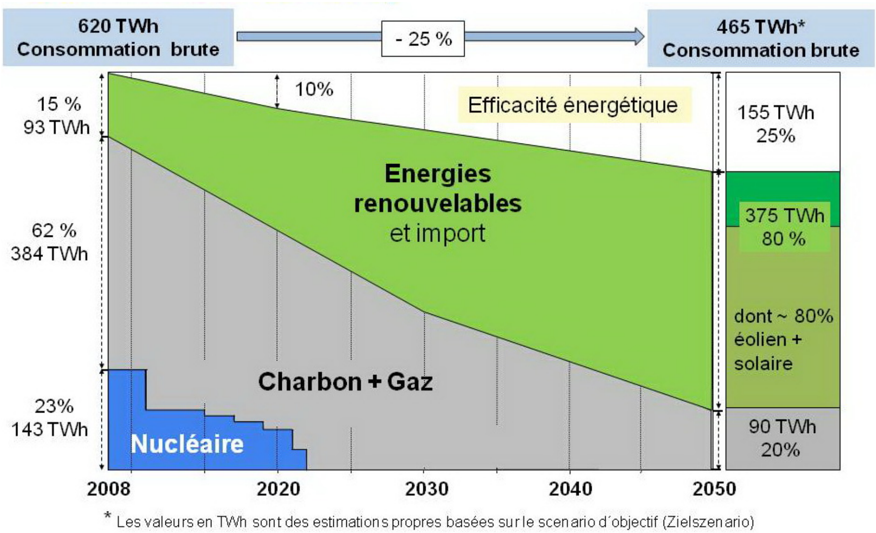
Climate & Energy policies covering the power sector:

***Ex. 1:** The "Energiewende" (Germany)*



Greenhouse gas emissions of the energy sector in France.
Source: Citepa (June 2016).

***Ex. 2:** The "stratégie nationale bas carbonne" (France)*

Declared* targets for the french energy sector by 2050 ("facteur 10"):

- **90-96% CO_2 offset from 1990**
- **At least 80% RES shares**
- **PPE currently under discussion** defining mid-term nuclear policies among others.

*The official communicate stresses that the sectorial targets affecting the power system are still indicative, but gives a clear vision of the very ambitious objectives pretended towards 2050. Further details can be found at: https://unfccc.int/files/mfc2013/application/pdf/fr_snbc_strategy.pdf

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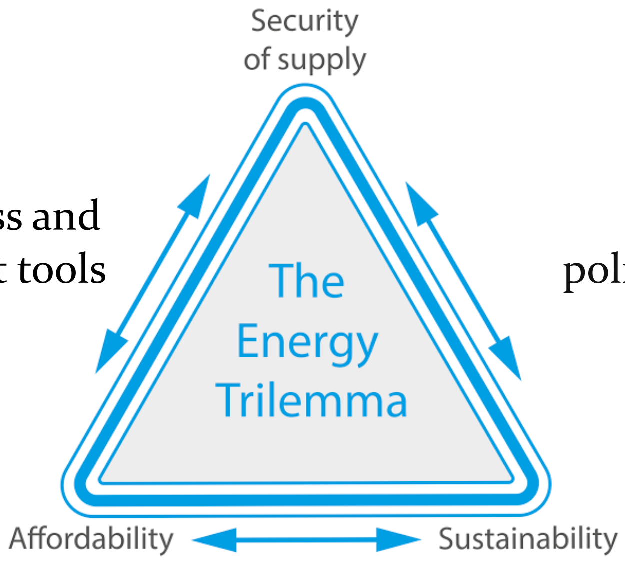
Today's Climate & Energy policies are based on the "The Energy Trilemma":
Two sides of the same coin?

The technical rationale

Enhancing technical progress and improving grid management tools



The economical rationale

Designing "Climate & Energy policy packages" targeting multi-objective goals.

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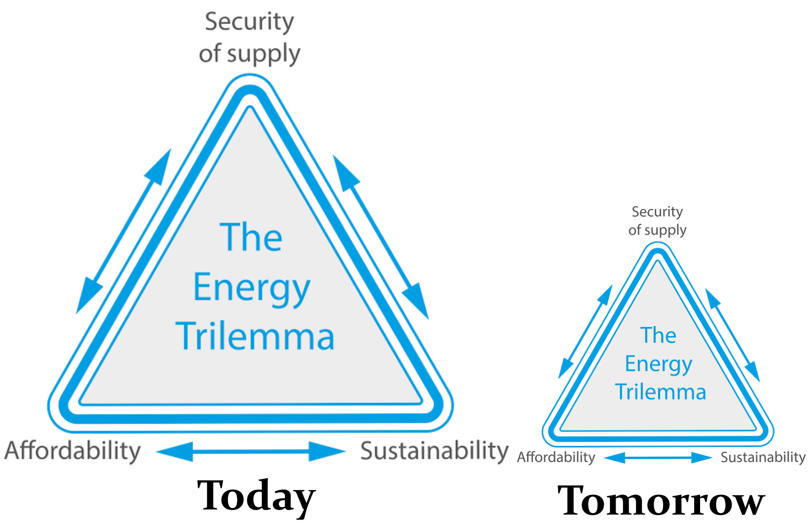
Reviewing "The Energy Trilemma": two complementary approaches

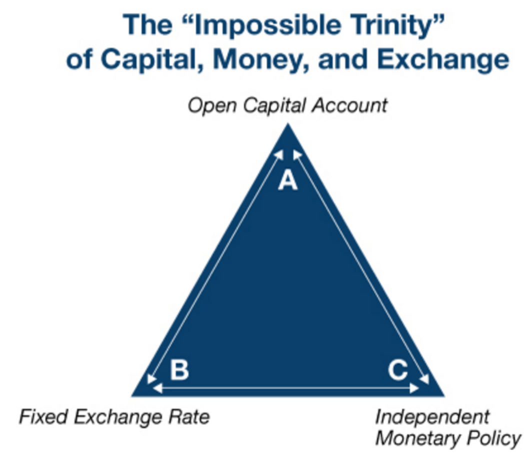
The technical rationale

A technical challenge on how to make the vertex of the triangle come closer.



The economical rationale

A problem of trade-off given that only satisfying two of the three objectives is possible. Ex:



"..a country must choose between free capital mobility, exchange-rate management and an independent monetary policy.."

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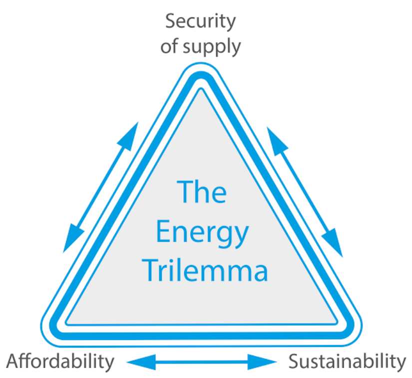
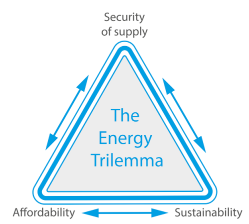
Reviewing "The Energy Trilemma": two complementary approaches

The technical rationale

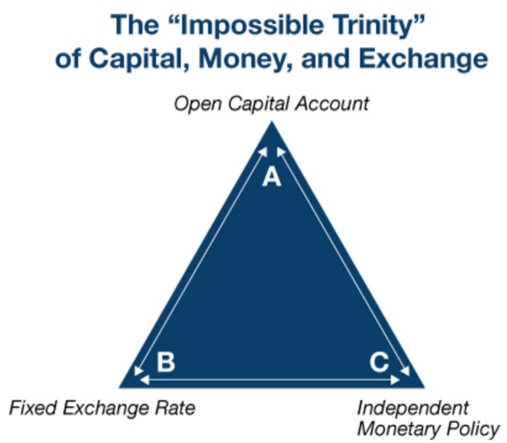


Today



Tomorrow

The economical rationale



Main issues:

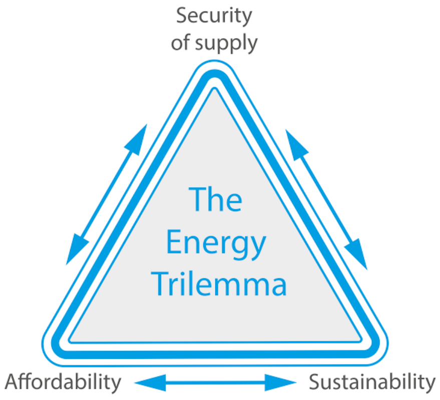
- Developing cleaner and more sustainable technologies at lower costs
- Improving flexibility capabilities and monitoring of the system

Main issues:

Designing sound policies ("proper planning") by accounting for:

- Economic efficiency
- Environmental effectiveness
- Joint objective's coherence

Research questions:



Given current "**Clean Energy Transition**" goals:

1. **Propose a theoretical framework** for assessing climate & energy policies

2. **Propose a consistent methodology** for understanding the interplays between climate & energy policies on the power sector ("proper planning" methodology)

3. **Design and evaluate (i.e. "Rank") climate & energy policies** in terms of their economic efficiency, environmental effectiveness and joint coherence.

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The Timbergen's golden rule on political economics:

"Variables are targets, instruments, data, and so on. Relations are structural ones (model) and restrictions. Consistent economic policy requires that the number of instruments equal the number of targets. Otherwise, targets are incompatible or instruments alternative." (Tinbergen 1952).

These concepts were further developed by Thiel (1964) and others.

This offers:

- *A **FRAMEWORK** of analysis: Given a set of targets and policy instruments, capturing their interplays is only possible by modeling their structural relationships.*

- *A **RULE** for policy assessment:*
  One target => One instrument ("and not more")

Theil, H, A P Barten, and P J M Van den Bogaard. 1964. *Optimal decision rules for government and industry*. Amsterdam: North-Holland. http://lib.ugent.be/catalog/rug01:000071658.

Tinbergen, J. 1952. *On the Theory of Economic Policy*. Amsterdam: Amsterdam: North-Holland. https://doi.org/10.1017/S1373971900100800.

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The "Proper Planning" methodology: extending the Tinbergen's Golden Rule to asses climate & energy policies

- ***FRAMEWORK****: Define set of targets, possible Climate & Energy instruments (one goal => one policy "and not more") and the structural model to simulate them:*
  - *Define targets consistent with current CO2 emissions goals and VRE shares.*
  - *Find the equilibrium states by jointly optimizing capacity expansion and operations (SRMC = AC = LRMC). => e.g. DIFLEXO*
  - *Obtain fuel transition diagrams and phase diagrams describing the interplays between variability, flexibility needs and CO_2 emissions.*
- ***RANK:*** *class the optimums by using Pareto-efficiency curves considering social efficiency and environmental effectiveness (first, second and third bests).*
- ***RULE: Evaluate the Golden rule and quantify trade-offs*** *of multi-policy outcomes. Are policies are in coherence with targets? policy calibration and gap analysis*

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DIFLEXO: an investment model encompassing operational constraints, flexibility issues and energy policies. It is formulated as a system cost minimization problem s.t. multiple constraints.

$$\min Y = \sum_{con}(I_{con} + MB_{con}) + \sum_{con}\sum_{t}\left(O\&M_{con,t} + F_{con,t} + CO2_{con,t} + \Delta G_{con,t}\right)$$

$$+ \sum_{VRE}(I_{VRE} + MB_{VRE}) + \sum_{VRE}\sum_{t}\left(O\&M_{VRE,t} + VREC_{VRE,t}\right)$$

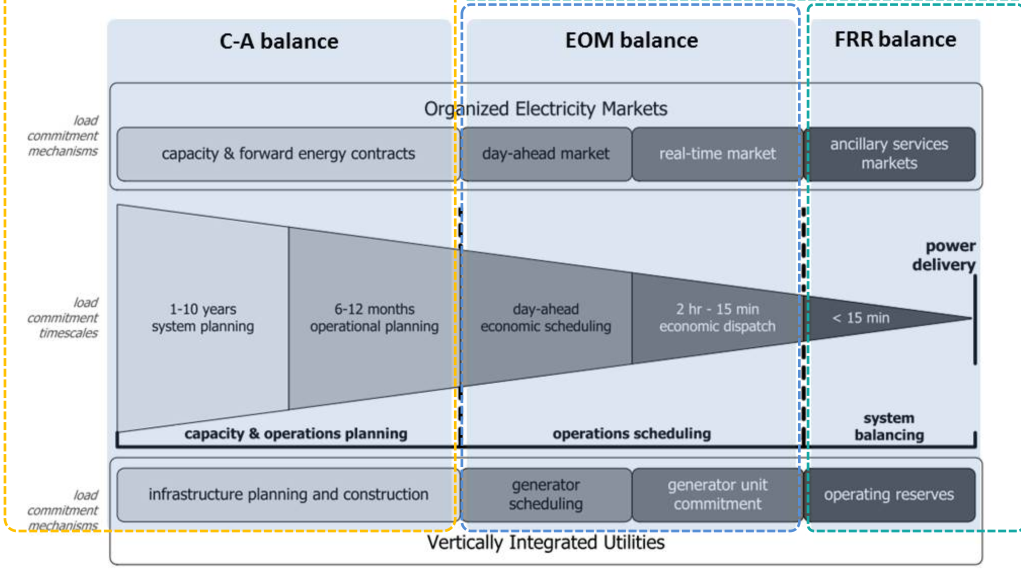
$$+ \sum_{ees}(I_{ees} + MB_{ees}) + \sum_{ees}\sum_{t} O\&M_{ees,t}$$

$$+ \sum_{dsm} I_{dsm} + \sum_{lc}\sum_{t} DSM_{lc,t} + \sum_{ls}\sum_{t} DSM_{ls,t}$$

ST

LT

RT



Schematic representation of power markets in DIFLEXO.
Source: Own elaboration from the scheme of (US DOE. 2006).

FRR: Frequency restoration reserve
EES: Electric energy storage
DSM: demand-side management

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Due to different types of externalities:
"the cheapest power generation technologies might not be the ones delivering the greatest value to the system"

Model inputs:

- *Costs: Investment, fuel, O&M,*
- *Technical characteristics: min levels, ramp capabilities, CO2 factors, etc.*
- *Wind, solar and load hourly profiles*

DIFLEXO

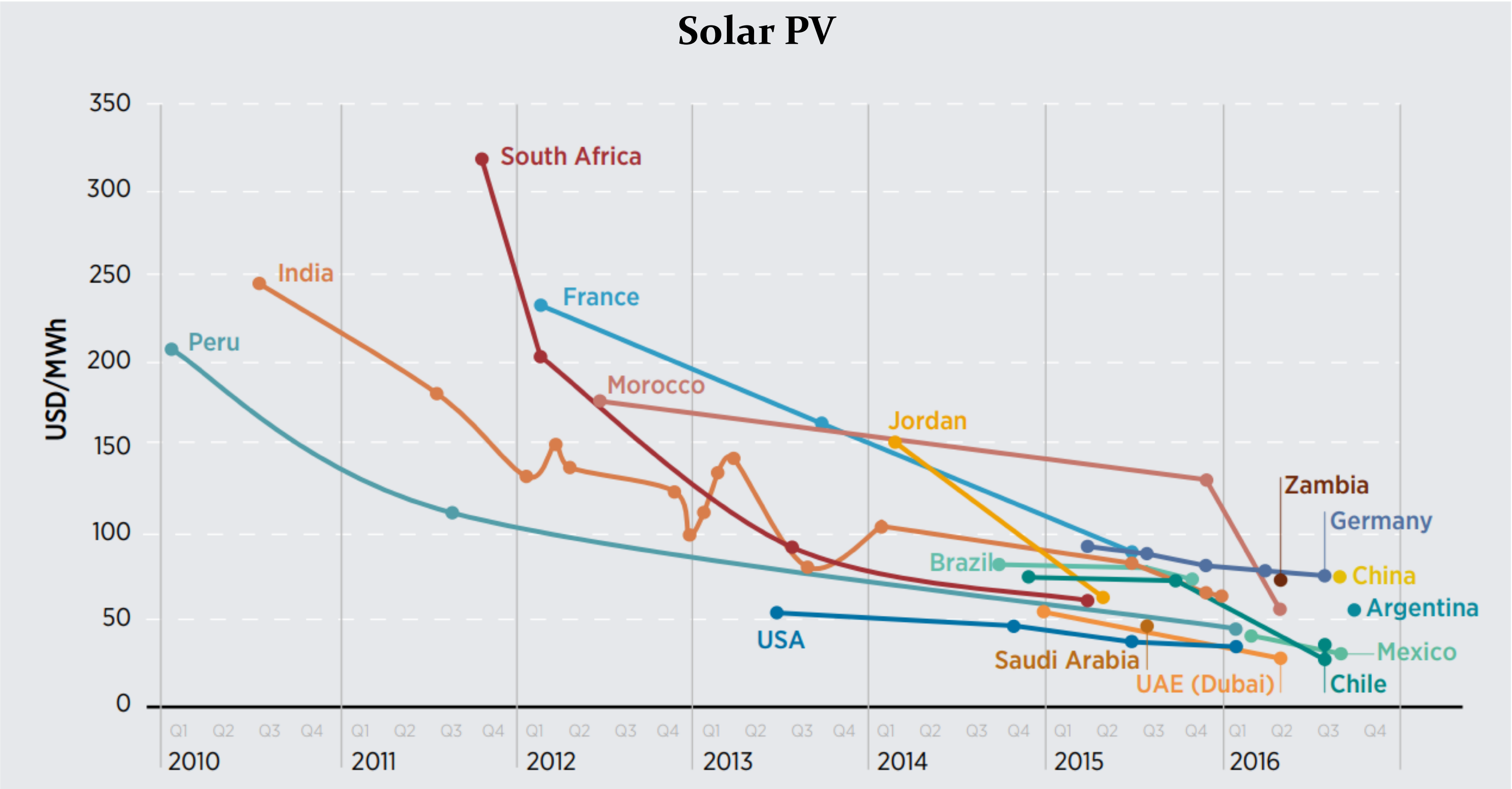
$$\textbf{min } Y = \sum_{con}(I_{con} + MB_{con}) + \sum_{con}\sum_{t}(O\&M_{con,t} + F_{con,t} + CO2_{con,t} + \Delta G_{con,t})$$
$$+ \sum_{VRE}(I_{VRE} + MB_{VRE}) + \sum_{VRE}\sum_{t}(O\&M_{VRE,t} + VREC_{VRE,t})$$
$$+ \sum_{ees}(I_{ees} + MB_{ees}) + \sum_{ees}\sum_{t} O\&M_{ees,t}$$
$$+ \sum_{dsm} I_{dsm} + \sum_{lc}\sum_{t} DSM_{lc,t} + \sum_{ls}\sum_{t} DSM_{ls,t}$$

LT ST RT

Model outputs:

- *Optimal investments, dispatch, inventory decisions of EES and DSM, and reserve scheduling*
- *Optimal system cost and CO2 emissions*

Good news 1/3: "Technical progress drives LCOE down[1]"



Evolution of average auctions prices for solar PV, January 2010-September 2016. Source: IRENA 2017

[1] LCOE are average costs, it does not include full integration costs of VRE

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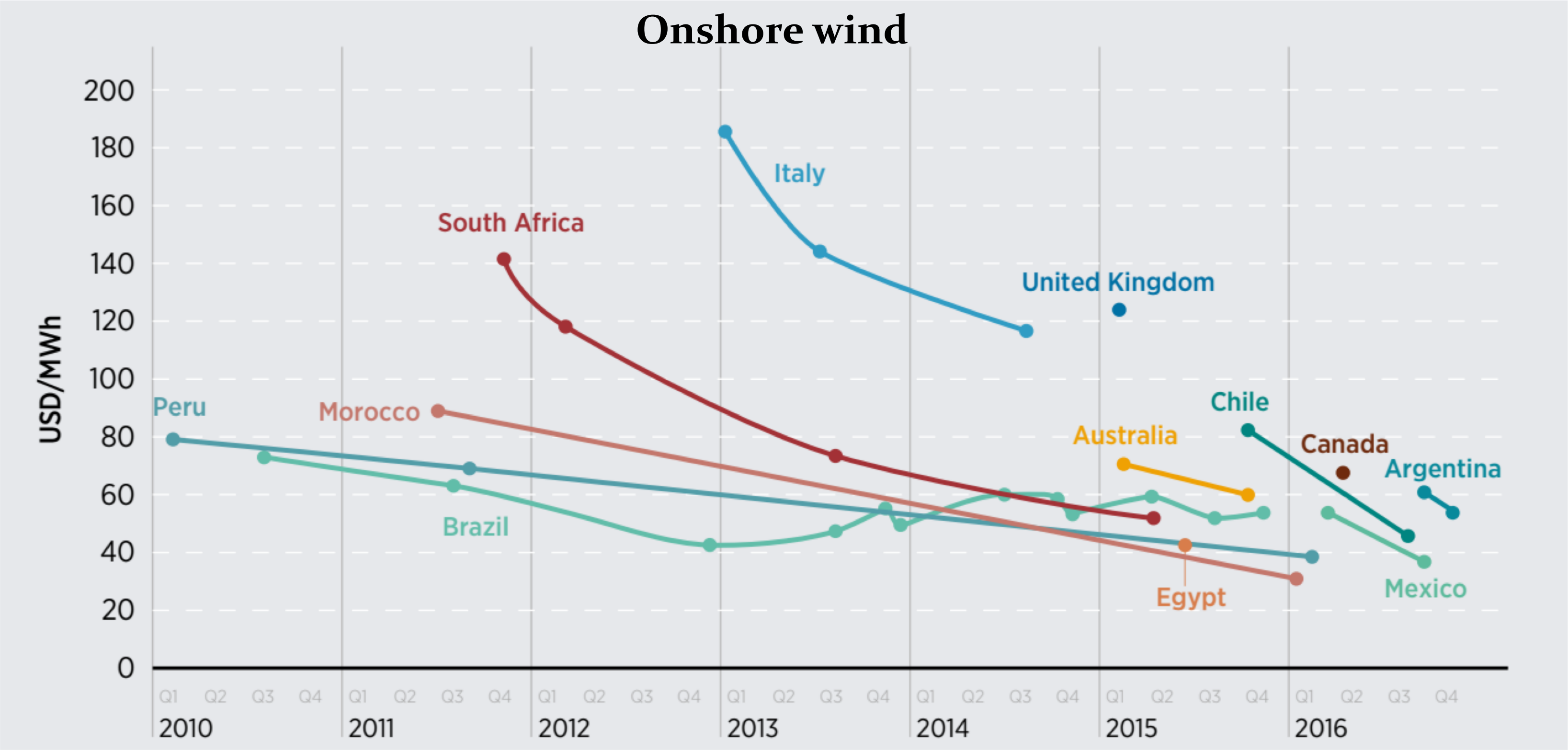
Good news 2/3: "Technical progress drives LCOE down[1]"



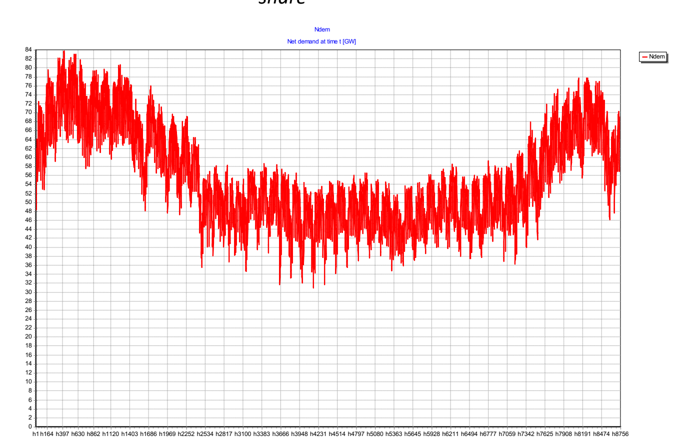
Evolution of average auction prices for onshore wind energy, January 2010-July 2016. Source: IRENA 2017

[1] *LCOE are average costs, it does not include full integration costs of VRE*

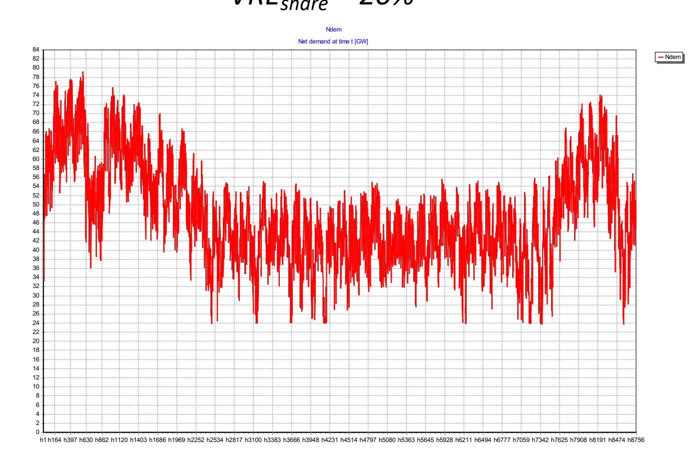
Technological externalities of VRE (Keppler and Cometto (2012) following Scitovsky (1954)):

Increasing variability ("negative externality") => increasing grid integration costs

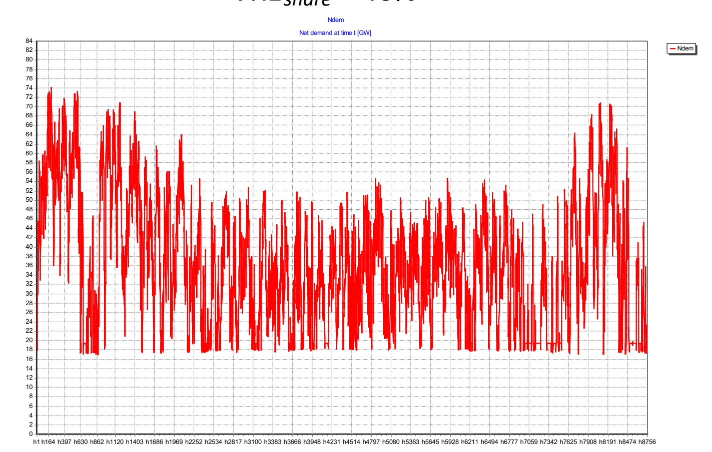
VRE_{share} = 0%



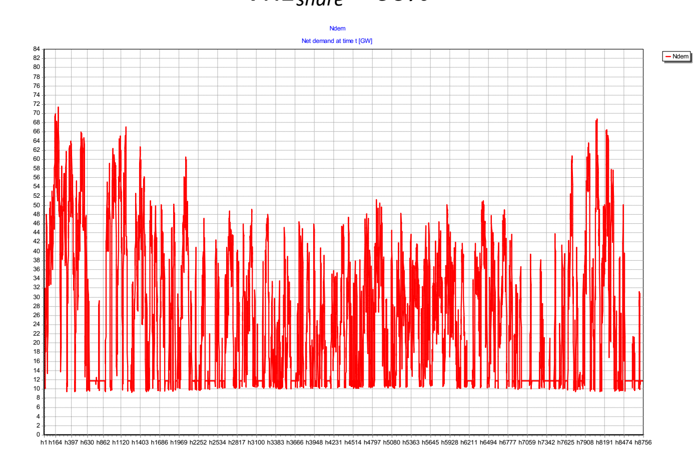
VRE_{share} = 20%



VRE_{share} = 40%

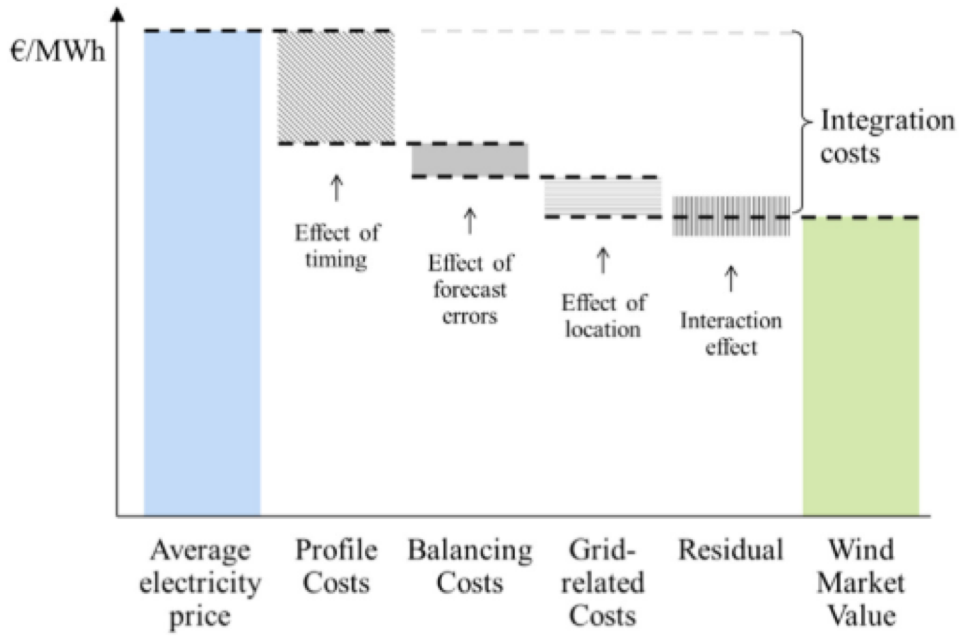


VRE_{share} = 60%



Integrating variability from RES may be costly

Integration costs reduce the system value of VRE



Components of integation costs.
Source: Hirth, Ueckerdt and Edenhofer 2015

Reference

Hirth, Lion, Falko Ueckerdt, and Ottmar Edenhofer. 2015. "Integration Costs Revisited - An Economic Framework for Wind and Solar Variability." *Renewable Energy* 74. Elsevier Ltd: 925–39. doi:10.1016/j.renene.2014.08.065.

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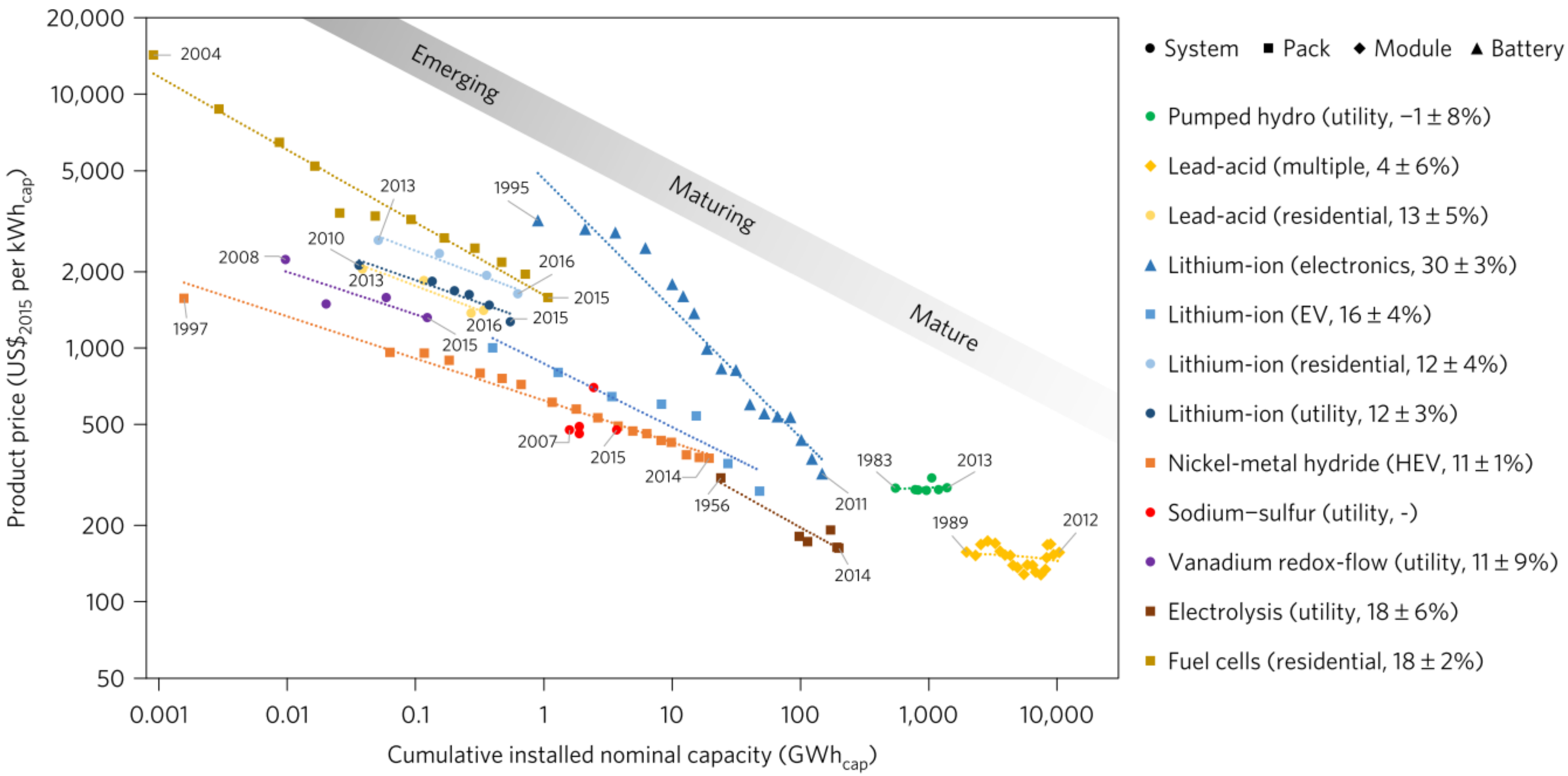
Good news 3/3: "Technical progress drives LCOS down"

Increasing flexibility ("positive externality") reduce grid integration costs of VRE



Learning curves of some EES technologies. Source: Schmidt et al. 2017

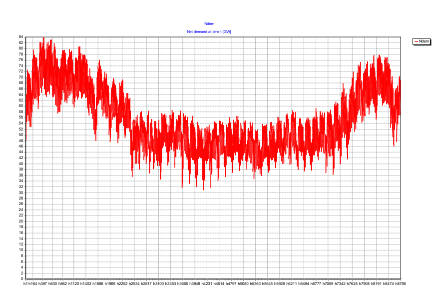
The system must balance demand and supply of:

I. Capacity, power and energy (traditional problem of power systems), but also,

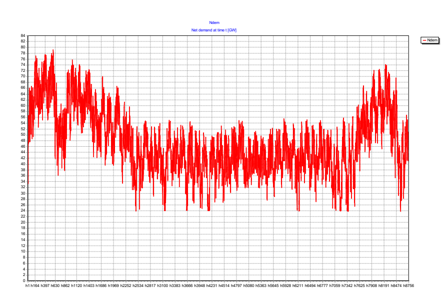
II. Increasing flexibility, short-term reliability needs and grid management due to variable & uncertain supply (new power system challenges)

While maximizing social welfare (i.e. minimizing system costs)

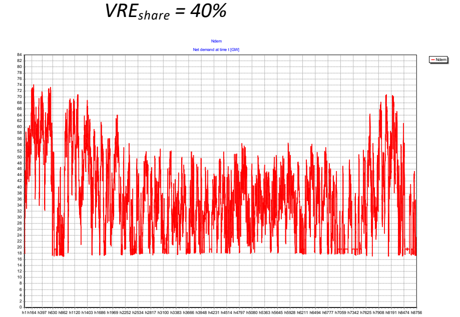
VRE_{share} = 0%



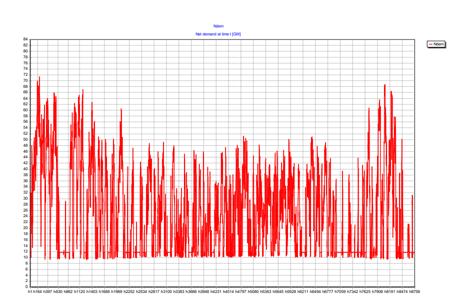
VRE_{share} = 20%

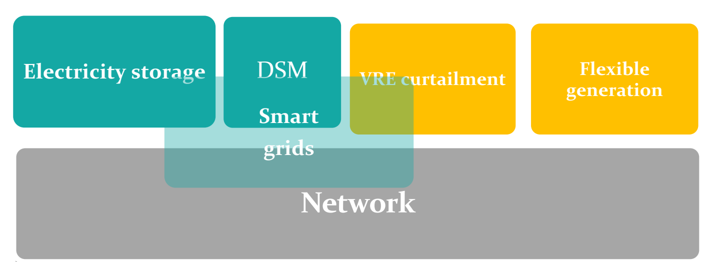


VRE_{share} = 40%



VRE_{share} = 60%





Flexibility reduce integration costs of VRE but it may also increase total CO_2 emissions:

1. "**for all wind installed, carbon actually increases when storage is added**.", "the emissions from this and the increase in base loaded coal in Ireland outweigh the savings from the fact that more energy is generated from wind." "The emissions seen are obviously dependent on the system and the price of carbon (carbon price at 30€/tonne assumed) - at a higher price or with cleaner base loaded units, **the carbon might be reduced by adding storage**". (Tuohy and O'Malley, 2009).

2. Also, "**storage increases the level of carbon emissions at wind penetration below 60%** (assuming 30€/tonne assumed). With storage available, the cheaper coal units are used more to fill the store ." (Tuohy and O'Malley, 2011)

References

Tuohy, A., O'Malley, M.: Impact of pumped storage on power systems with increasing wind penetration. In: Proceedings of the IEEE Power & Energy Society General Meeting (2009)

Tuohy, A., O'Malley, M.: Pumped storage in systems with very high wind penetration. Energy Policy 39 (2011)

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3. “**without storage, emissions of CO_2, NOX, and SO_2 are lower due to the decrease in coal generation. Adding storage increases emissions of CO_2 and SO_2 in both scenarios.**”(Carson and Novan, 2013)

4. “it has been established that revenue-maximizing grid-level energy storage tends to increase system emissions in current US electricity grids. **The three main factors that affect storage-related emissions are: the marginal emissions of the generator that charged the device, the marginal emissions of the displaced generator when storage discharges, and the roundtrip efficiency of the storage**.” (Hittinger and Azevedo, 2015).

All of these make sense but following the “Energy Trilemma”: How expensive is “Affordable” and how clean is “Sustainable”?

References

Carson and Novan, 2013. The private and social economics of bulk electricity storage. Journal of Environmental Economics and Management 66 (2013) 404–423

E.S. Hittinger, I.M. Azevedo. Bulk energy storage increases United States electricity system emissions. Environ Sci Technol, 49 (5) (2015), pp. 3203-3210

For capturing the interplays between variability, grid integration costs, flexibility and total CO_2 emissions, two cases are considered:

a) “**No Flex**”: systems **without new flexibility** technologies

b) “**Flex**”: systems **with optimal flexibility** (i.e. Storage and DR)

Every climate & Energy goal (i.e. CO_2 offsets and VRE targets) should be analyzed in both cases.

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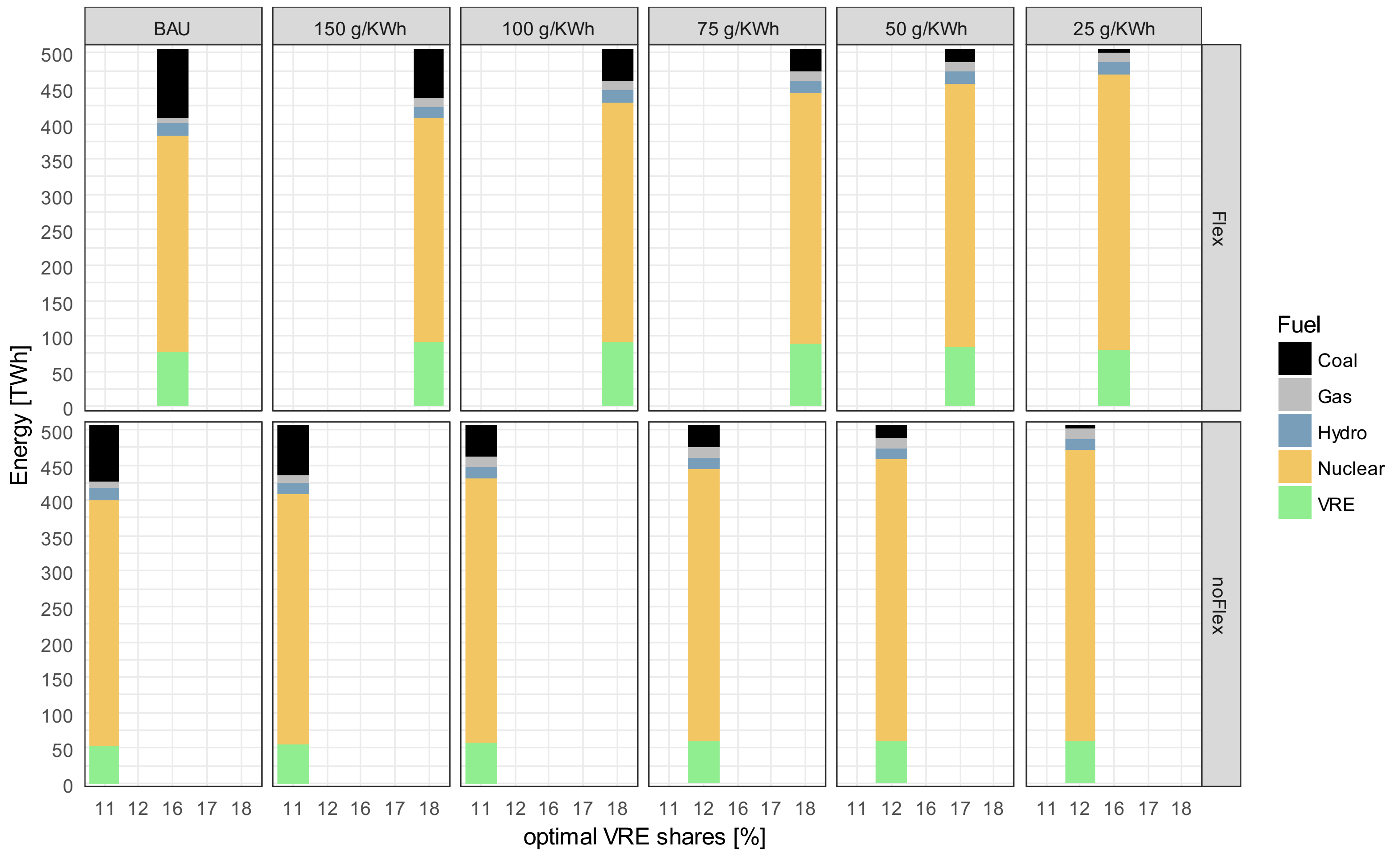
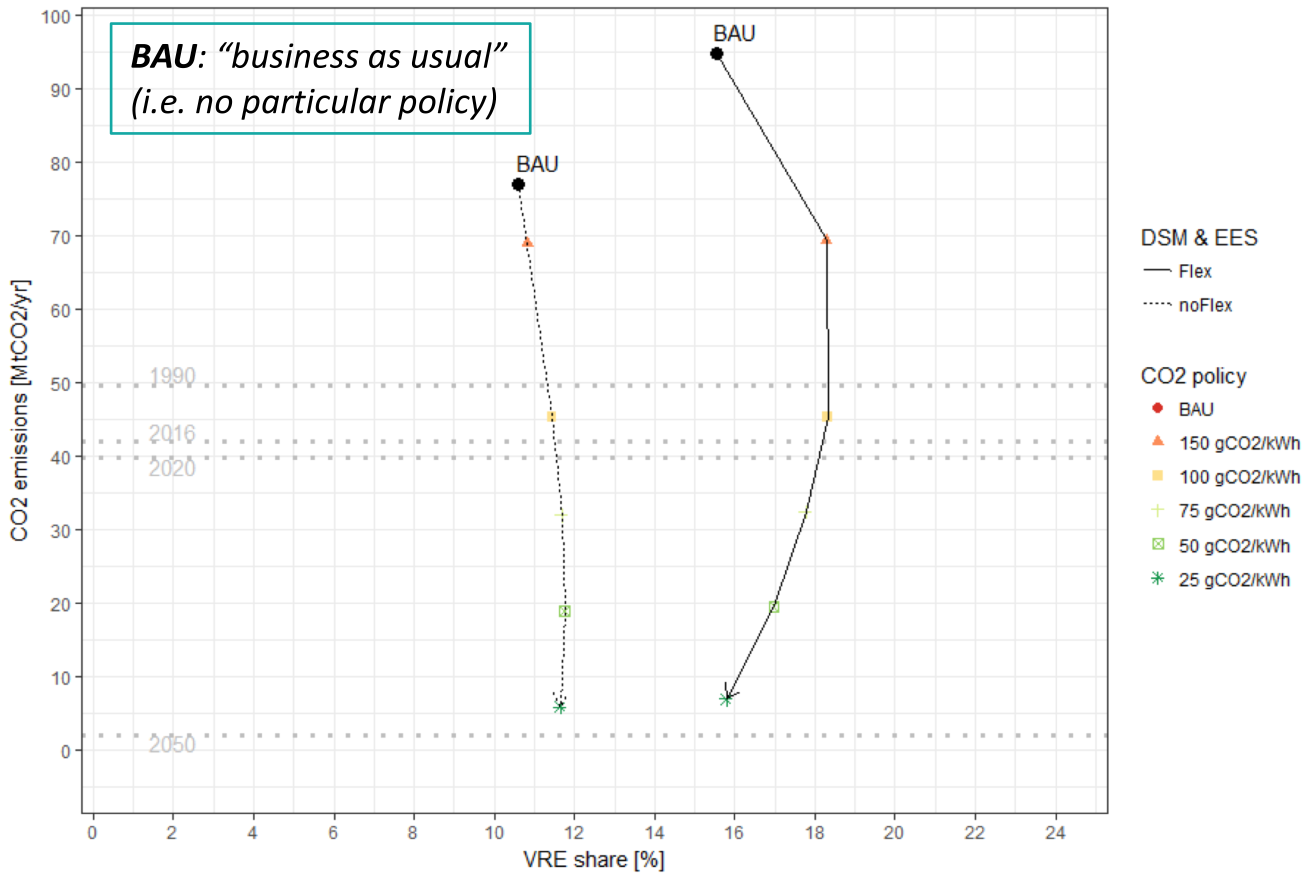
Instrument I: attaining CO_2 offsets by introducing CO_2 caps

Optimal electricity mix s.t. decreasing CO_2 caps



Instrument I: attaining CO_2 offsets by introducing CO_2 caps

Optimal share of VRE s.t. decreasing CO_2 caps



Optimal shares of VRE are represented by BAU points. No matter the CO_2 policy implemented, market-driven VRE shares (no-subsidies) are below the 20% threshold.

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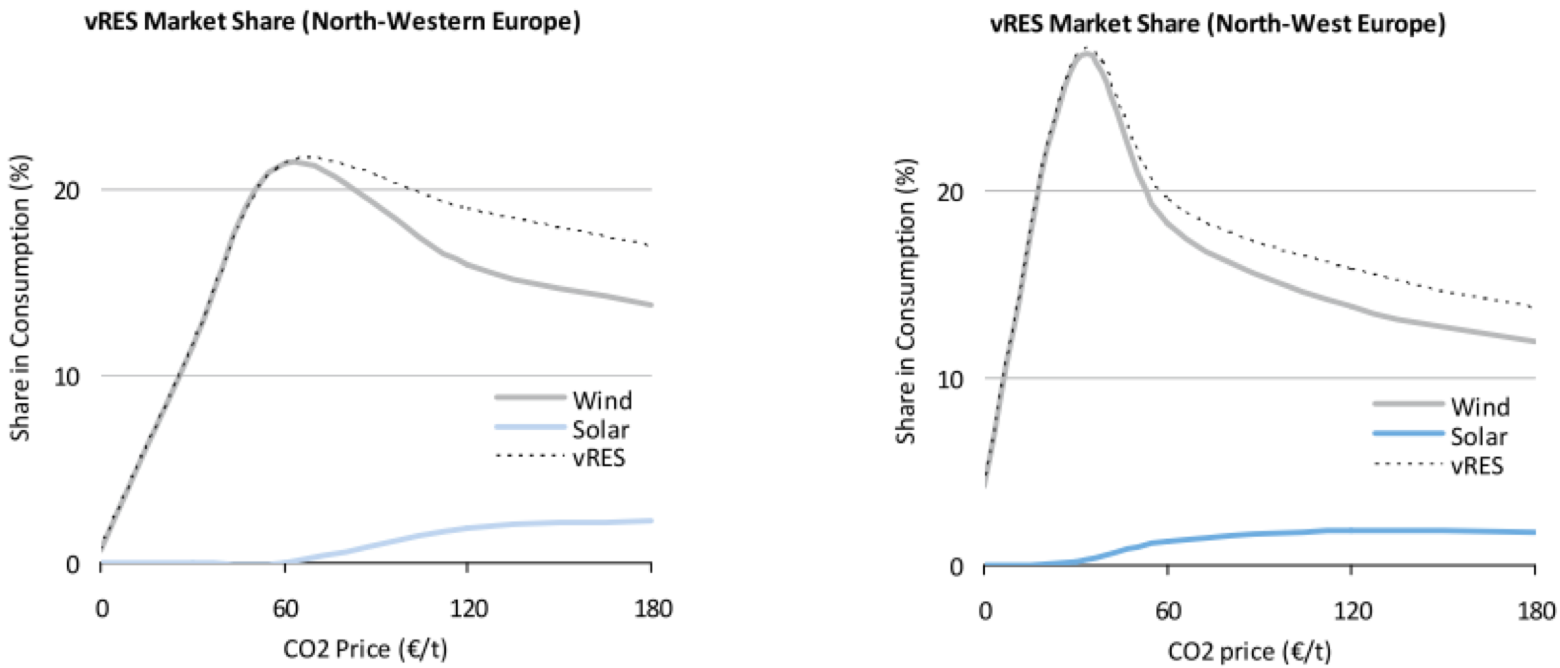
Comparing outcomes from this instrument: CO_2 caps vs CO_2 prices



Optimal VRE shares with sunk baseload technologies (left) and without them (right). Source. Hirth, 2015.

Similar VRE thresholds were found by Hirth (2015) by adopting an increasing CO_2 price approach.

Reference:

Hirth, Lion. 2015. "The Optimal Share of Variable Renewables." *The Energy Journal* 36 (1): 127–62. doi:10.5547/01956574.36.1.6.

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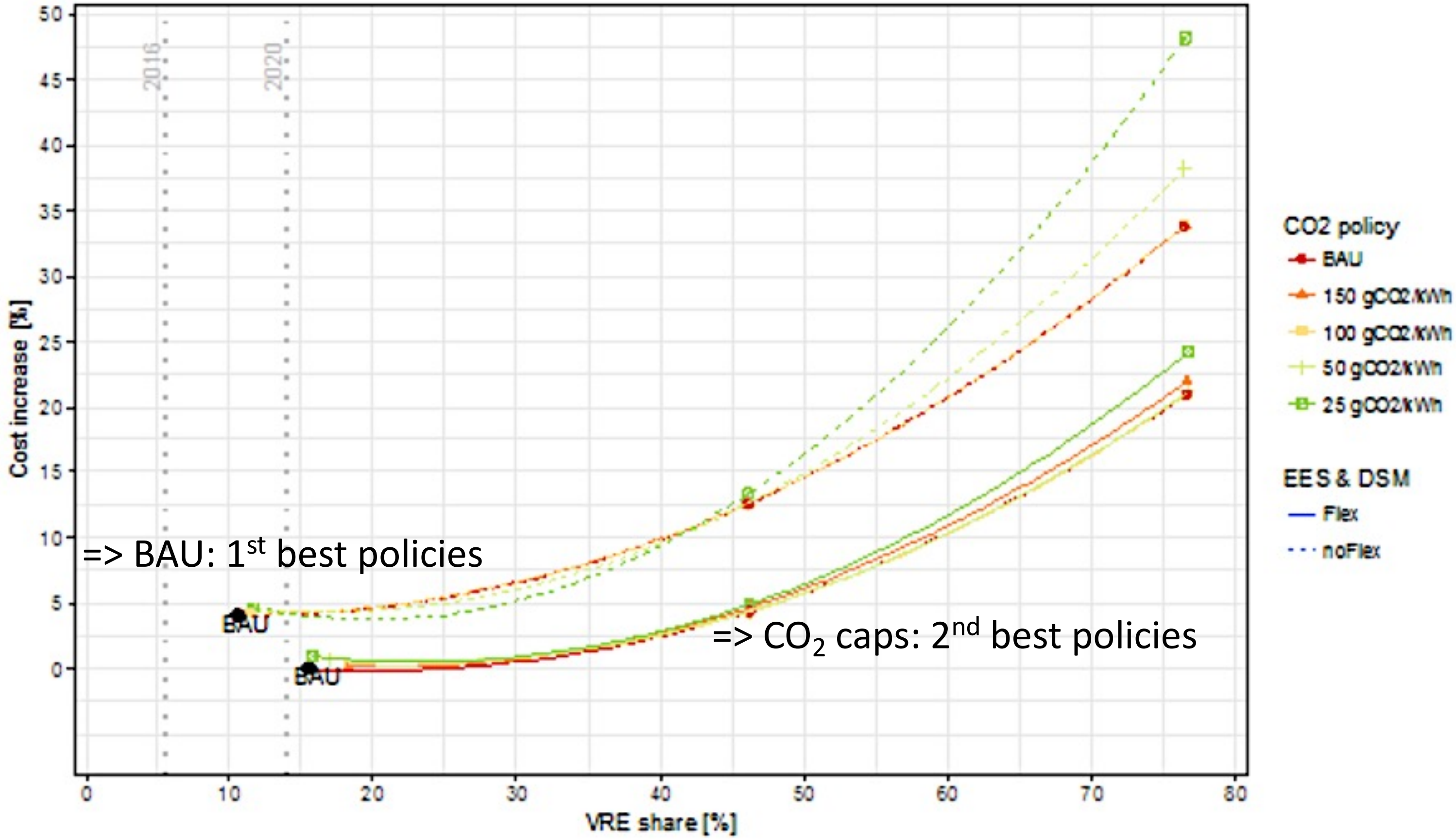
New flexibility technologies are always cost-improving as they allow to better integrate variability



Further developing VRE above BAU threshold implies system **COST INCREASES** => **SUBSIDIES**

Similar results obtained by Sioshansi (2014):

"If the generation sector is perfectly competitive, adding storage is always welfare-enhancing.". Sioshansi, R. When energy storage reduces social welfare. Energy Econ. 41 (2014)

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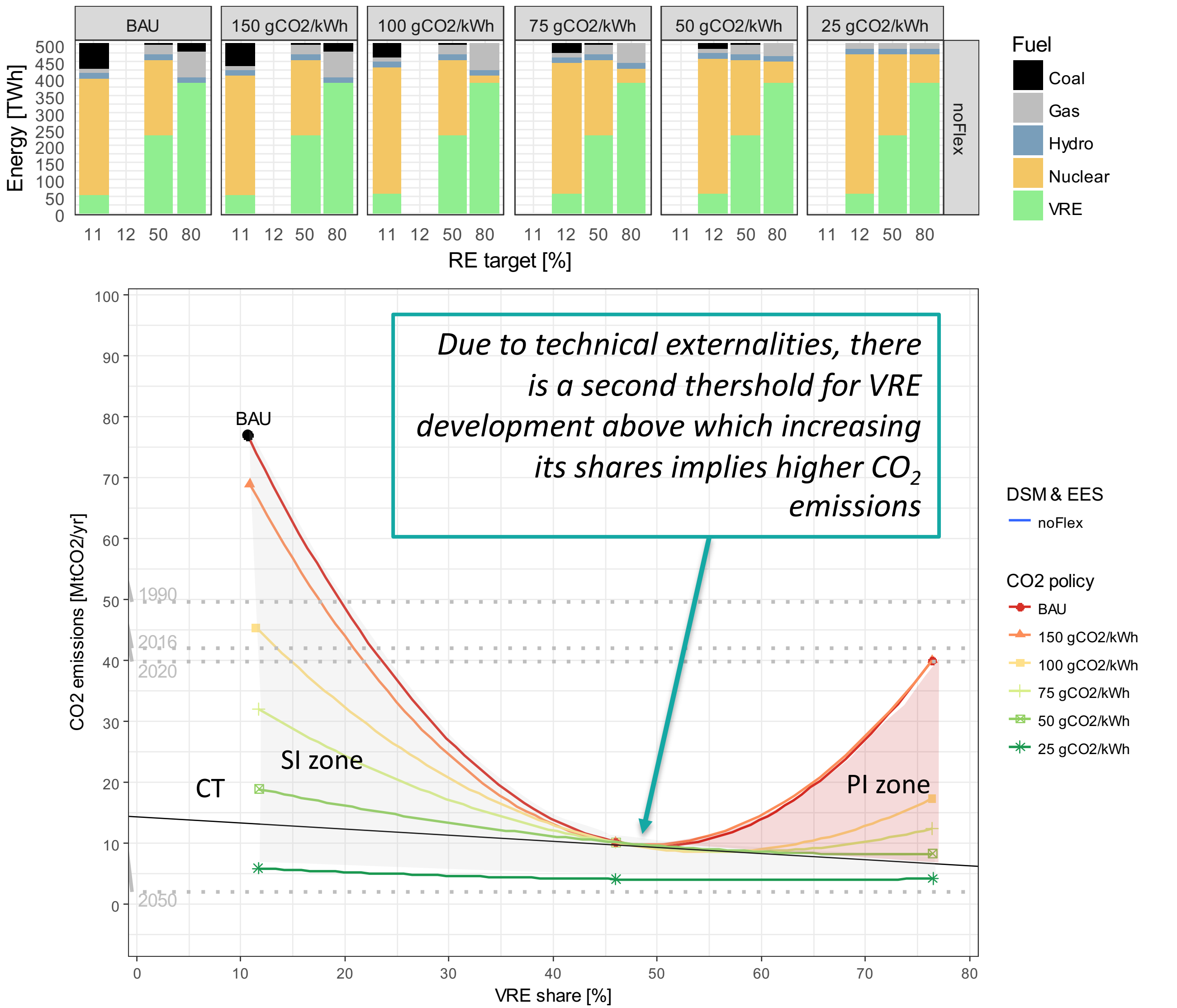
Case a. : Equilibrium states without new flexibility technologies



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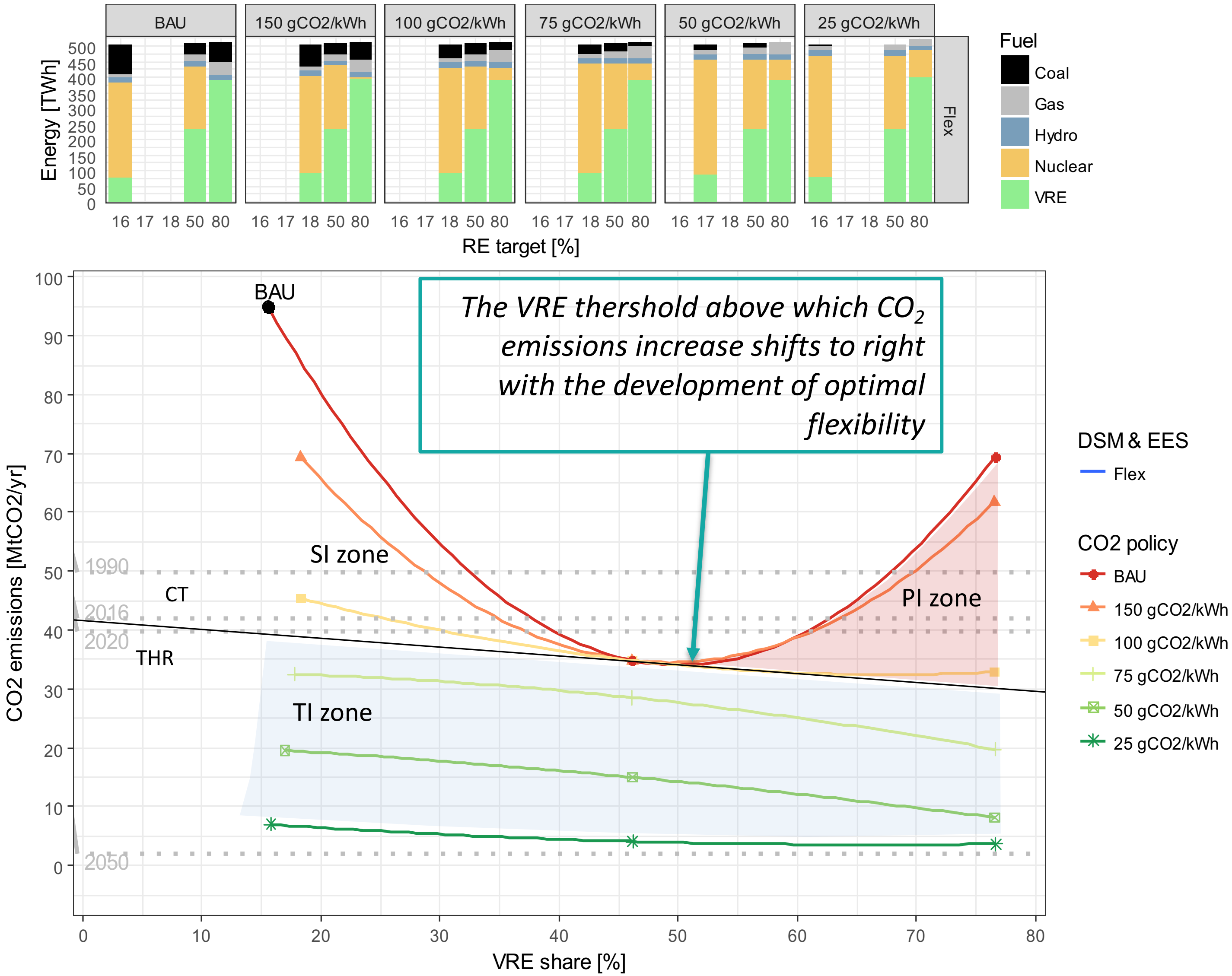
Case b. : Equilibrium states with new flexibility technologies



3. Instrument II: Introducing RE obligations

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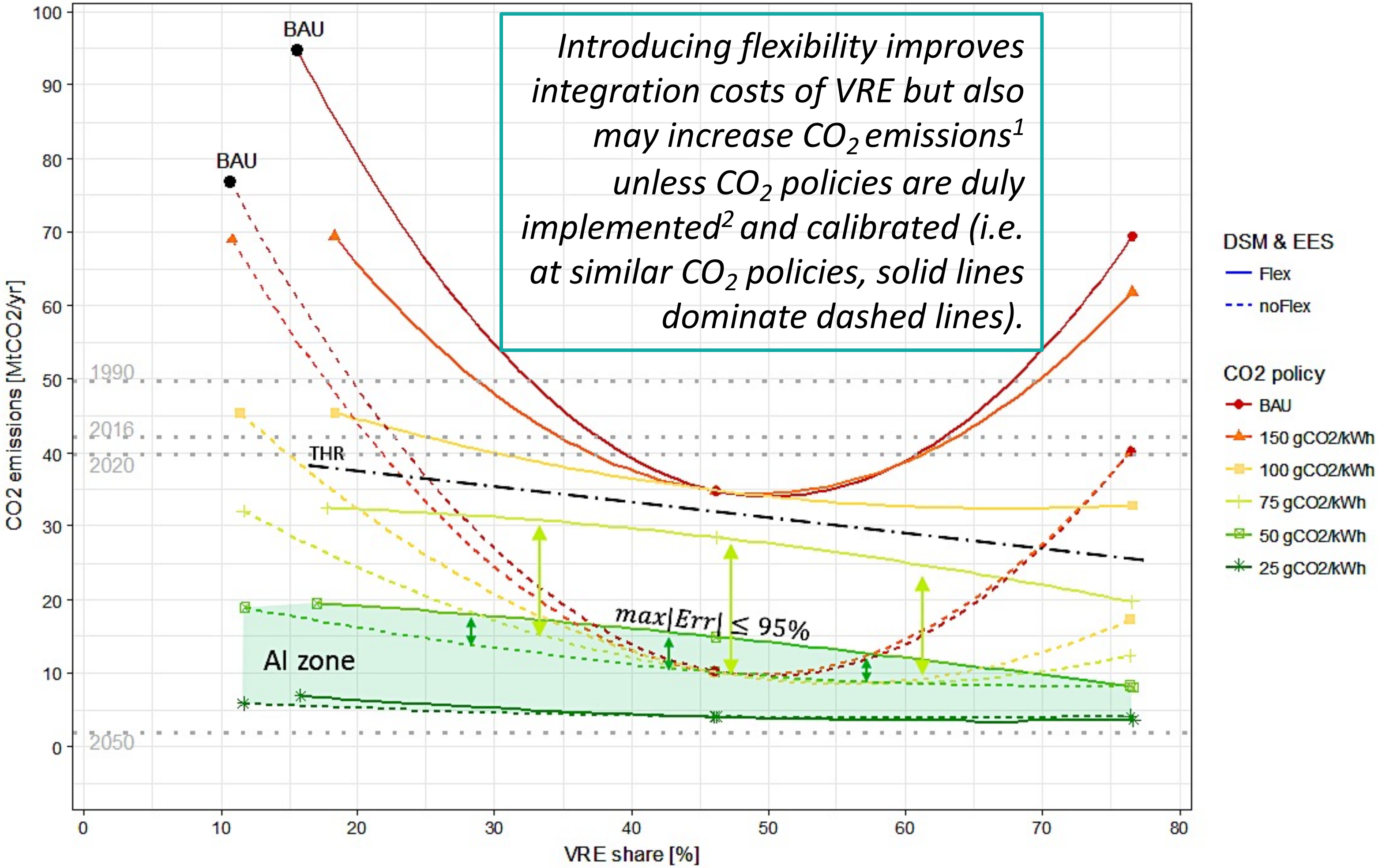
Policy highlight: Flexibility technologies may induce higher CO_2 emissions



[1] CO_2 policies may be volume based (e.g. carbon caps & trade) or price based (e.g. Tax, carbon floor, etc).

[2] *In a market framework flexibility takes advantage of price arbitrage (i.e. peak/off-peak) regardless CO_2 emissions.*

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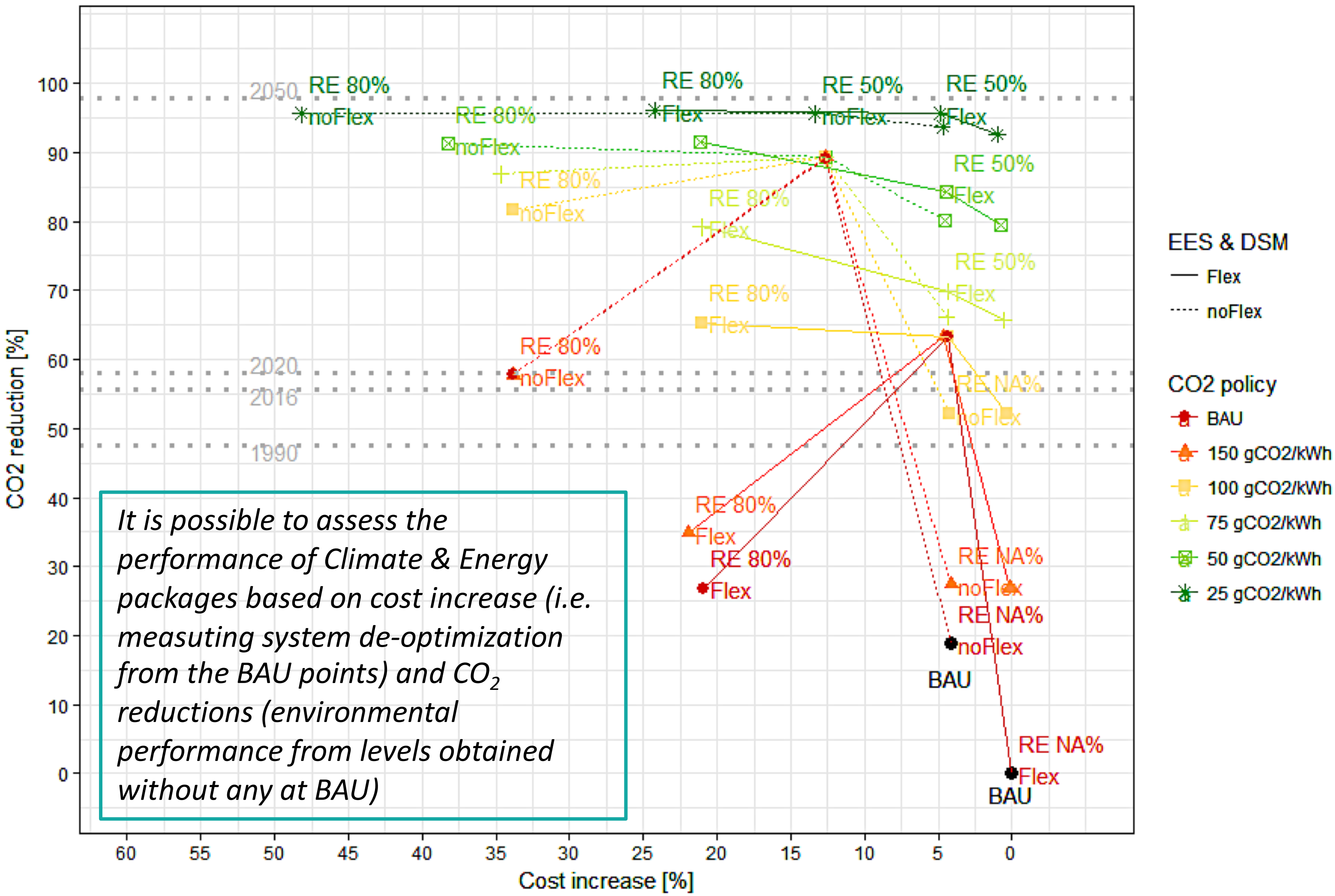
Performances and coherence of combined climate & energy instruments , and the role of flexibility technologies:



It is possible to assess the performance of Climate & Energy packages based on cost increase (i.e. measuting system de-optimization from the BAU points) and CO_2 reductions (environmental performance from levels obtained without any at BAU)

4. The cost-effectiveness of combined policy instruments

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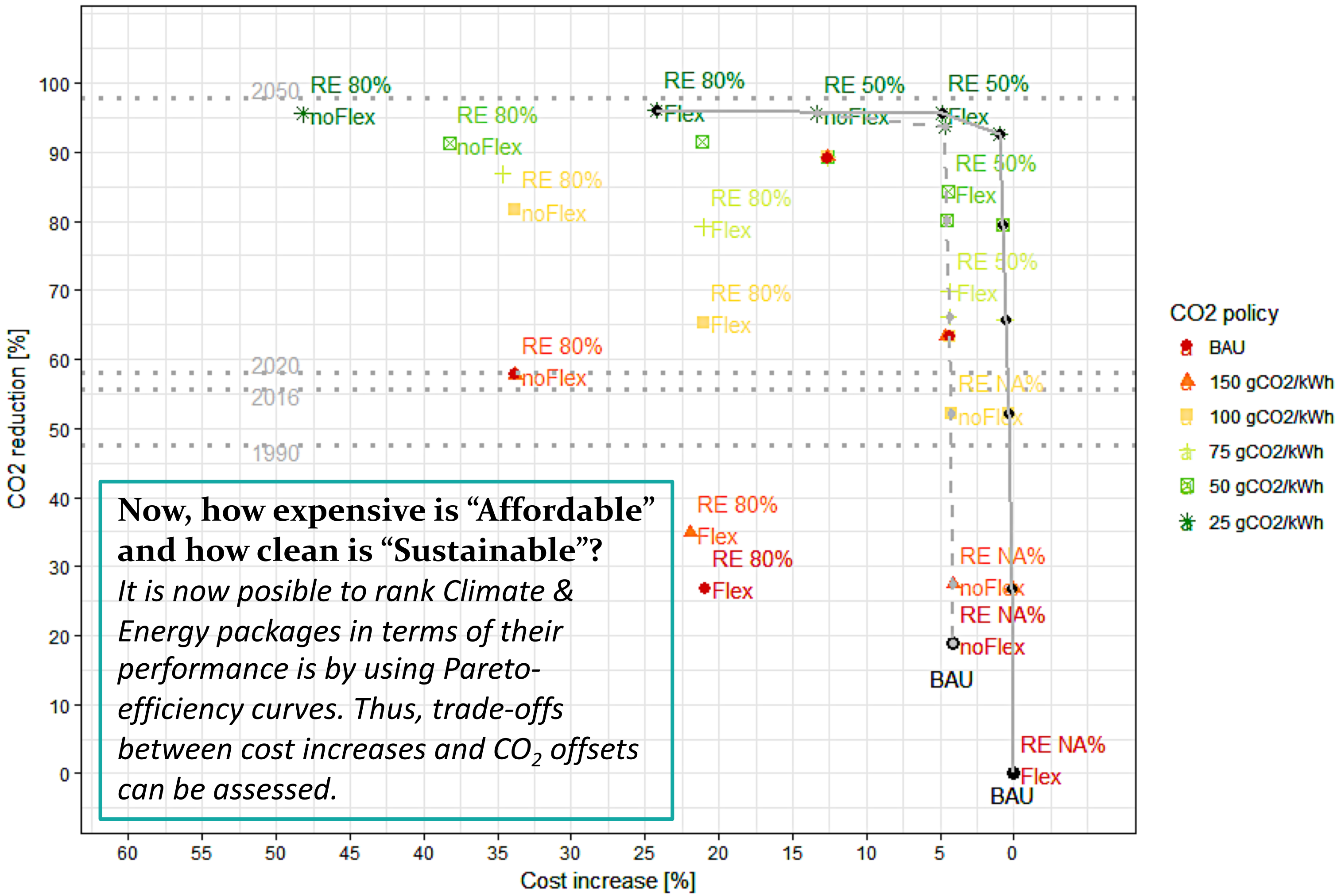
Pareto-efficient curves of combined policy instruments: Ranking (first, second and further best optimums)



Now, how expensive is "Affordable" and how clean is "Sustainable"?

It is now posible to rank Climate & Energy packages in terms of their performance is by using Pareto-efficiency curves. Thus, trade-offs between cost increases and CO_2 offsets can be assessed.

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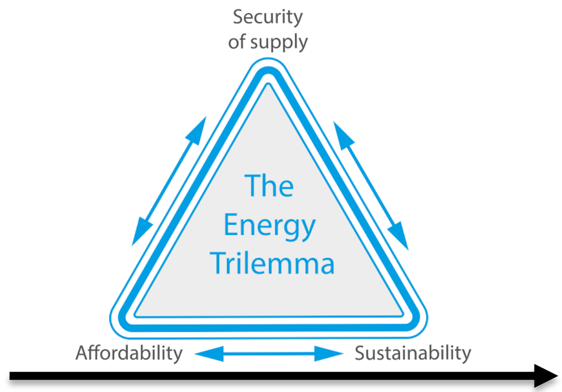
Designing Climate & Energy packages in“Proper Planning”:



The technical rationale
Technical progress and cost decrease are inputs of the method

The economical rationale
Policy design and trade-offs are the outcomes.

- It is a comprehensive framework” for assessing “Climate & Energy” targets and designing cost-efficient and environmental effective policies, avoiding any conflicts of coherence between policies due to technological externalities non captured by simpler approaches (e.g. LCOE, LCOS, among others).
- The methodology proposed allows to capture the interplays between variability, flexibility, system costs and CO_2 emissions. It can be implemented parsimoniously as a tool for supporting policy making (e.g. The French PPE).

Summing-up the main results:

- *In the different second-best optimums, the optimal share of VRE in the electricity mix remains low while that of nuclear remains high, without influence from the carbon constraint level.*
- *Setting a RE target beyond this optimal level implies a higher system cost than that resulting from a CO_2 policy directly capping total emissions.*
- *Very high RE obligations may have lower environmental performance.*
- *New sources of flexibility (storage, demand-response) improve the economic efficiency of policies based mainly on RE obligations, but not forcibly those based on environmental performance.*
- *For policies targeting VRE at the 80% level, it should be sought out the best combination of measures including a carbon constraint and development of flexibility to attain CO2 emissions offsets with limited additional cost.*

Thank you for your attention.

Any questions?

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Chaire European Electricity Markets (CEEM)
Université Paris-Dauphine

			investment costs (€/KW)	quasi-fix costs (€/KW*a)	variable costs (€/MWh$_e$)	fuel costs (€/MWht)	CO_2 intensity (t/MWht)	efficiency (1)
Dispatchable		Nuclear*	4000	40	2	3	-	0.33
Dispatchable	CHP Technologies	Lignite*	2200	30	1	3	0.45	0.38
Dispatchable	CHP Technologies	Lignite CCS*	3500	140	2	3	0.05	0.35
Dispatchable	CHP Technologies	Hard Coal*	1500	25	1	12	0.32	0.39
Dispatchable	CHP Technologies	CCGT	1000	12	2	25	0.27	0.48
Dispatchable	CHP Technologies	OCGT**	600	7	2	50	0.27	0.30
Dispatchable		Load shedding	-	-	-	***1000	-	1
vRES		Wind	1300	25	-	-	-	1
vRES		Solar	2000	15	-	-	-	1
		Pump Hydro**	1500	15	-	-	-	0.70

Nuclear plants are assumed to have a life-time of 50 years, all other plants of 25 years. OCGT fuel costs are higher due to structuring costs. Lignite costs include mining.
* Base-load plants run even if the electricity price is below their variable costs (run-through premium).
**Flexible technologies are assumed to earn 30% of their investment cost from other markets (e.g. regulating power).
***This can be interpreted as the value of lost load (VOLL).

Reference:

Hirth, Lion. 2015. “The Optimal Share of Variable Renewables.” *The Energy Journal* 36 (1): 127–62. doi:10.5547/01956574.36.1.6.

Technologies	Cost sec of inv. [€/kW]	Expected Life [yr]	O&M[V] [€/MWh]	Fuel costs [€/MWh]	Unitary emissions rate [t CO_2/MWh]
Nuclear	3750	60	2,5	7,0	0,015
Coal	1264	40	6,9	19,8	0,96
Coal FBLwith CCS	3500	40	10,0	11,2	0,13
Coal PSC with CCS	2550	40	3,0	19,8	0 ,10
CCGT	785	30	4,7	51,7	0,34
CCGT with CCS	1500	30	4,0	51,7	0,07
OCOT	490	30	7,3	67,3	0,67
OCGT-flexible	400	25	6,1	51,7	0,64
Reservoirs	2686	80	0,0	0,0	0,01

Technologies	Investment cost (overnight) [€/kW]	Expected life [yr]	Annualised fixed cost [€/kW-yr]
Wind	1100	25	96,0
Solar PV	710	25	61,8

Expected cost of power production technologies in 2050.
Sources: IEA/NEA (2010, 2015), SETIS (2014)

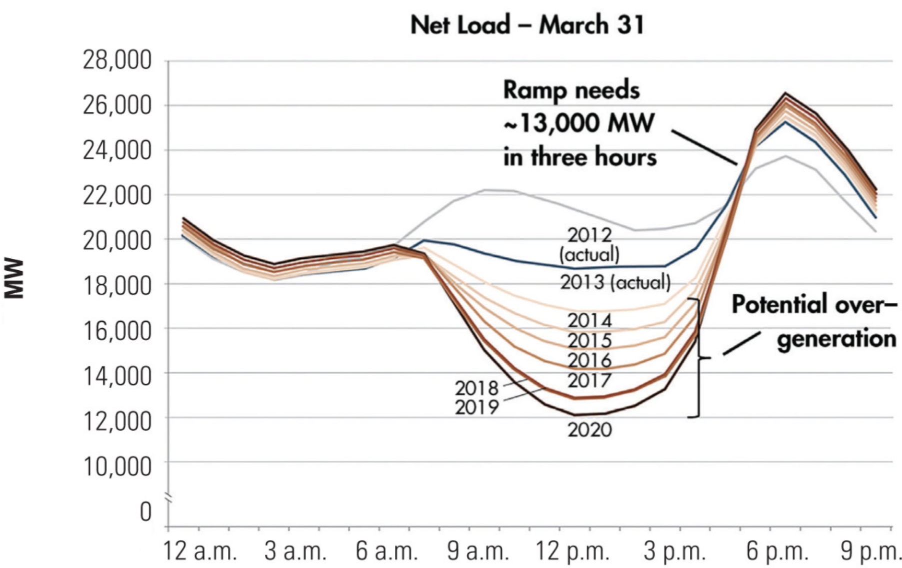
Technologies	Acronyms	CAPEX			OPEX	
		Power conversion system [€/kW]	Energy reservoir [€/kWh]	Expected Life [yrs]	$O\&M^F$ [€/kW]	$O\&M^V$ [€/kWh]
Lithium ion batteries	Li-Ion	140	245,5	10	2,0	2,6
New pumped storage	PHS-New	1500	68	60	6,0	0
Renovated pumped storage	PHS-retro	400	-	-	22,5	0
Interseasonal H_2 Electrolyser with fuel cell	H_2-FC	2465	130	8	25,0	-
Diabatic compressed air storage	CAES	450	26,3	55	5,9	1,2
Adiabatic compressed air storage	ACAES	679	78,8	60	9,5	2,0

Costs for storage technologies in 2050. Source: SETIS (2014), Zerrahn and Schill (2015).

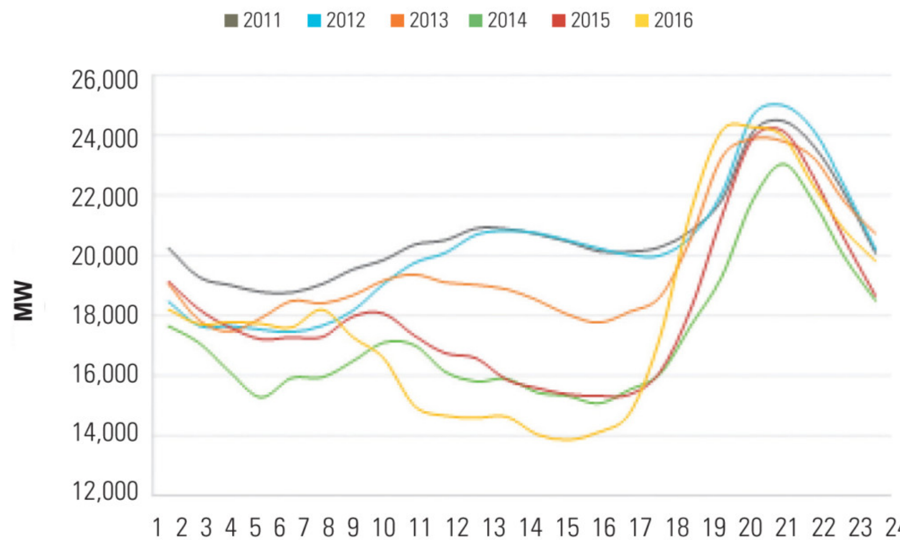
Type	Acronym	Resource availability [GW]	Investment cost [k€/MW/an]	O&M^{V} [€/MWh]	Continuous duration [h]	Max hours per day (L_{hpd}) [h]	Type of service
ToU tariff	HC_HP	23,4	0	0	0	N/A	shape
Household time arbitrage	LS_hh1	10,3	16,8	0	3	4	shift
Household dynamic control	LS_hh2	0,8	46,2	0	3	4	
Industry long-term dynamic control	LS_ind_L1	1,2	15	300	108	N/A	shift & shimmy
	LS_ind_L2	0,8	30	300	108	N/A	
	LS_ind_L3	0,8	60	300	108	N/A	
	LS_ind_L4	1,0	100	300	108	N/A	
Industry short-term dynamic control	LS_ind_C1	0,6	20	0	1	2	
	LS_ind_C2	0,4	50	0	1	2	
	LS_ind_C3	1,0	100	0	1	2	
	LS_ind_C4	0,3	150	0	1	2	
	LS_ind_C5	0,1	200	0	1	2	

Hypothesis related to DR categories. Source: ADEME (2017) and RTE (2017).

Technological externalities of VRE (Keppler and Cometto (2012) following Scitovsky (1954)):

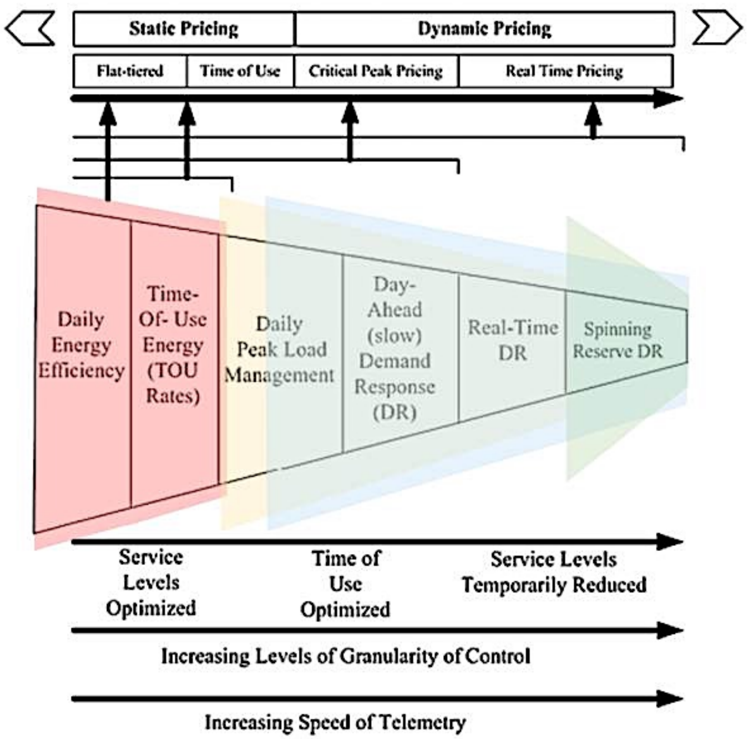


Expected duck curves. Source: CAISO 2013



Actual duck curves. Source: ScottMadden (October 2016)

Handling flexibility/stability issues:
b) DSM capabilities



Schematic representation of different DSM programs. Source: Siano. 2014, modified for integrating the DR categories

Service type	DSM program	Balancing block concerned	Unit
Shape	• TOU rate program	On-peak/off-peak arbitrage on the EOM on a daily basis	MWh
Shed	• LC program	Hourly load shedding for balancing the EOM with financial compensation upon activation	MWh
Shift	• RT rate program • Short-term and Long-term industrial load management • Dynamic management of sanitary usages	Hourly arbitrage on the EOM specified by the length of the modulation given by the type of DR program	MWh
Shimmy	• LC program • Dynamic management of sanitary usages • Short-term and Long-term industrial load management	All the suppliers participate on the supply of upward FRR. All the suppliers participate on the downward FRR balance but load curtailment.	MW

=> to some extent, EES and DSM are complementary

The role of electric energy storage

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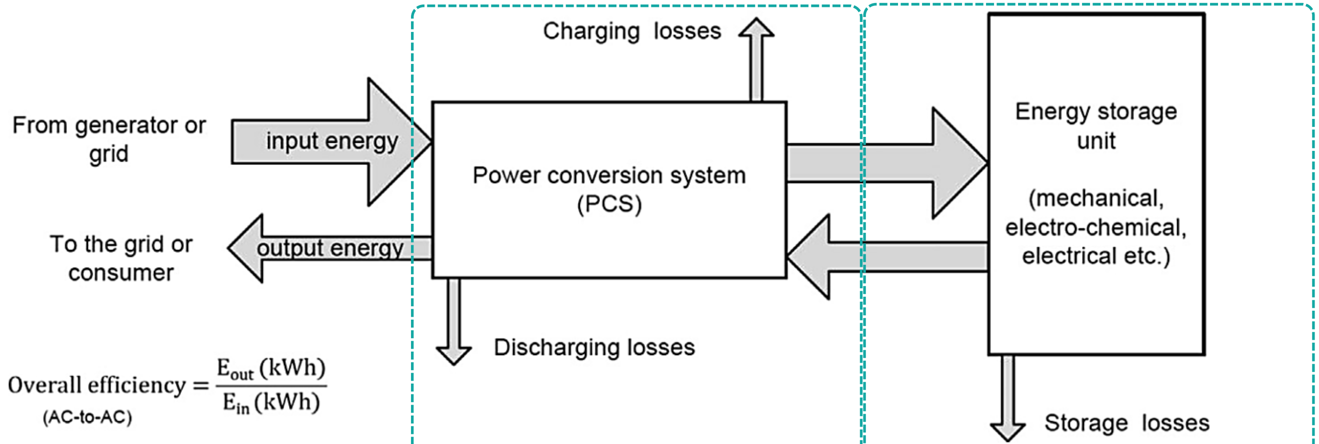
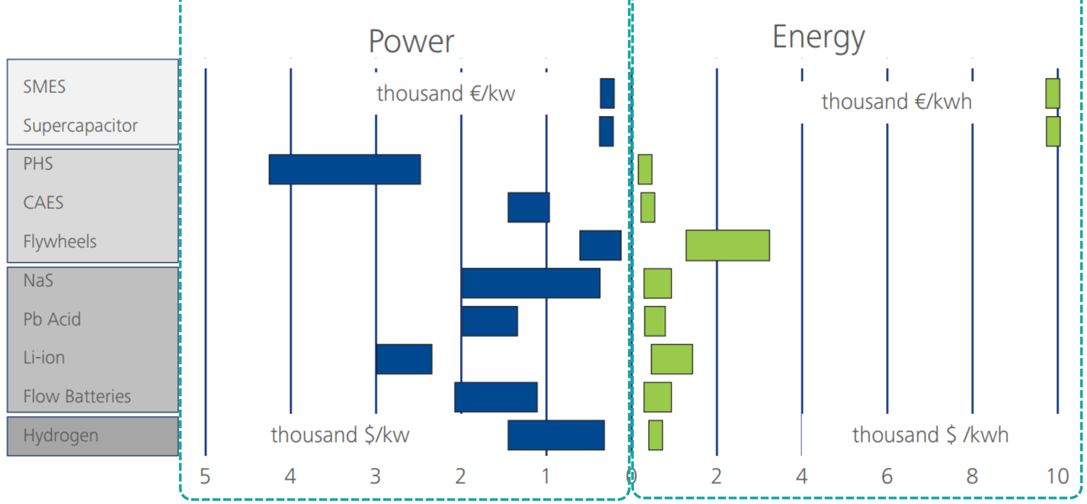


Components and energy flows of EES technologies. Source: Zakeri and Syri (2015)



Cost ranges of energy storage technologies. Source: EPRI (2010) and SANDIA Labs (2011)

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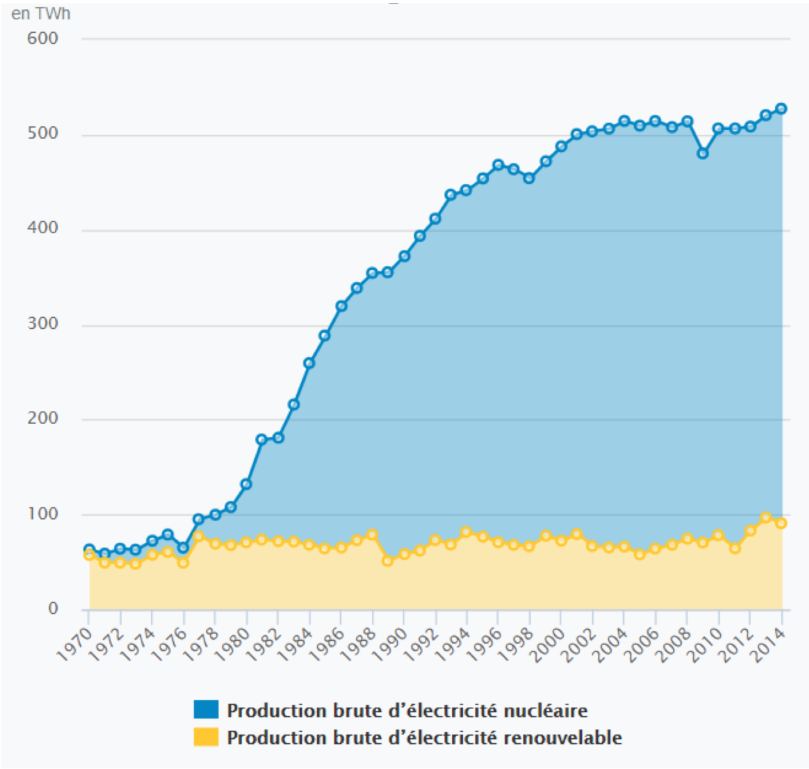
The energy transition of the French power sector by 2050: What implications?



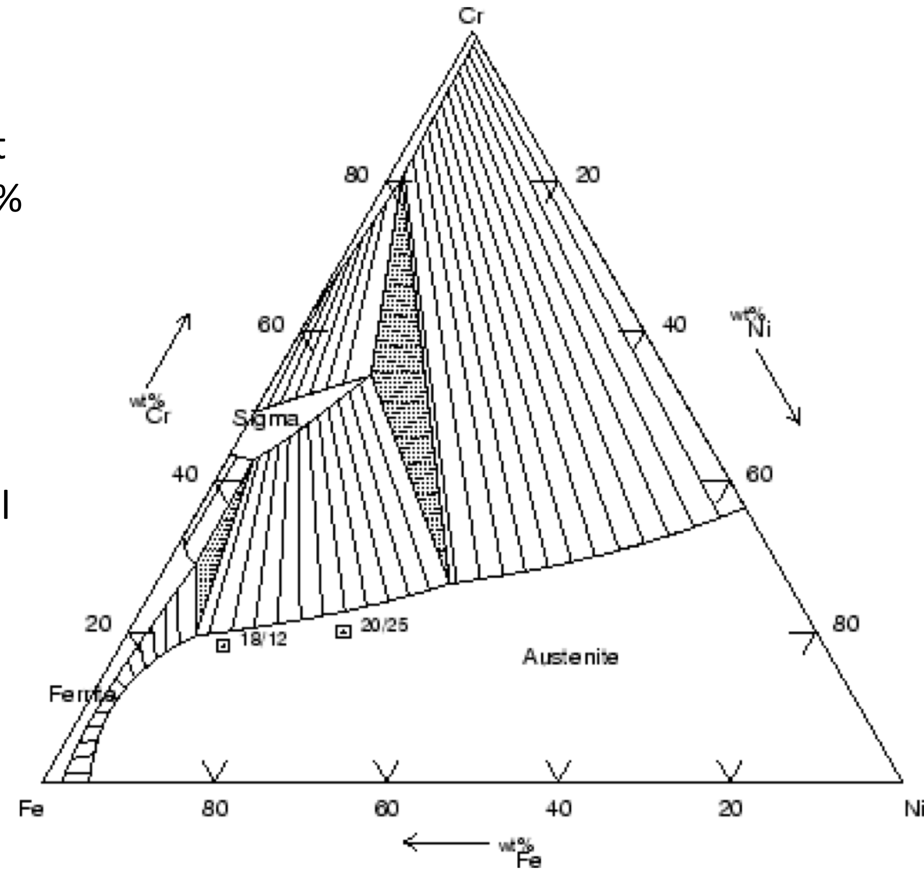
Development of nuclear power in France. Source: MEEDDM, CGDD, SOES

Stainless steel equilibrium phases :

Austenitic stainless steels are, by far, the most widely used stainless steels comprising 70-80% of stainless production. The are essentially alloys of Fe-Cr-Ni, which owe their name to their room temperature austenitic structure.

The addition of chromium has long been known to improve corrosion resistance. Nickel is the basic substitutional element used for austenite stabilisation.

The equilibrium phases depend on the proportion of the three elements, as well illustrated in an isothermal section of the ternary diagram for Fe-Cr-Ni



Isothermal section of the Fe-Cr-Ni diagram at 750 C: a typical 18Cr-12Ni wt% lies in the austenitic field. Calculated using MT-DATA and the SGTE database.

T. Sourmail. Department of Materials Science and Metallurgy. Pembroke Street, CB2 3QZ Cambridge, U.K. Mat.Sci.Tech. 2001: 17-1 p1-14. Source: http://www.thomas-sourmail.net/papers_html/precipitation_review/

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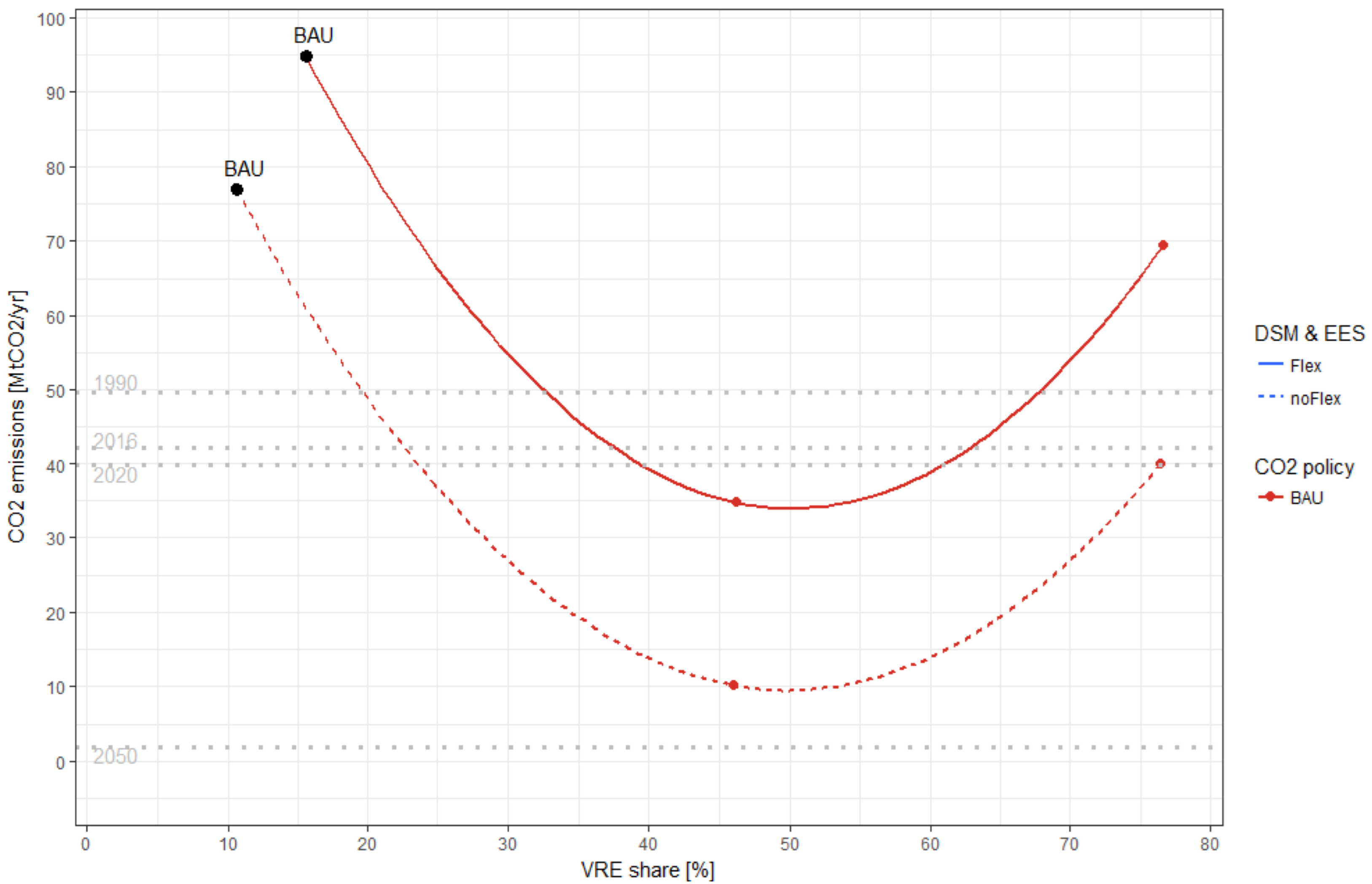

Results

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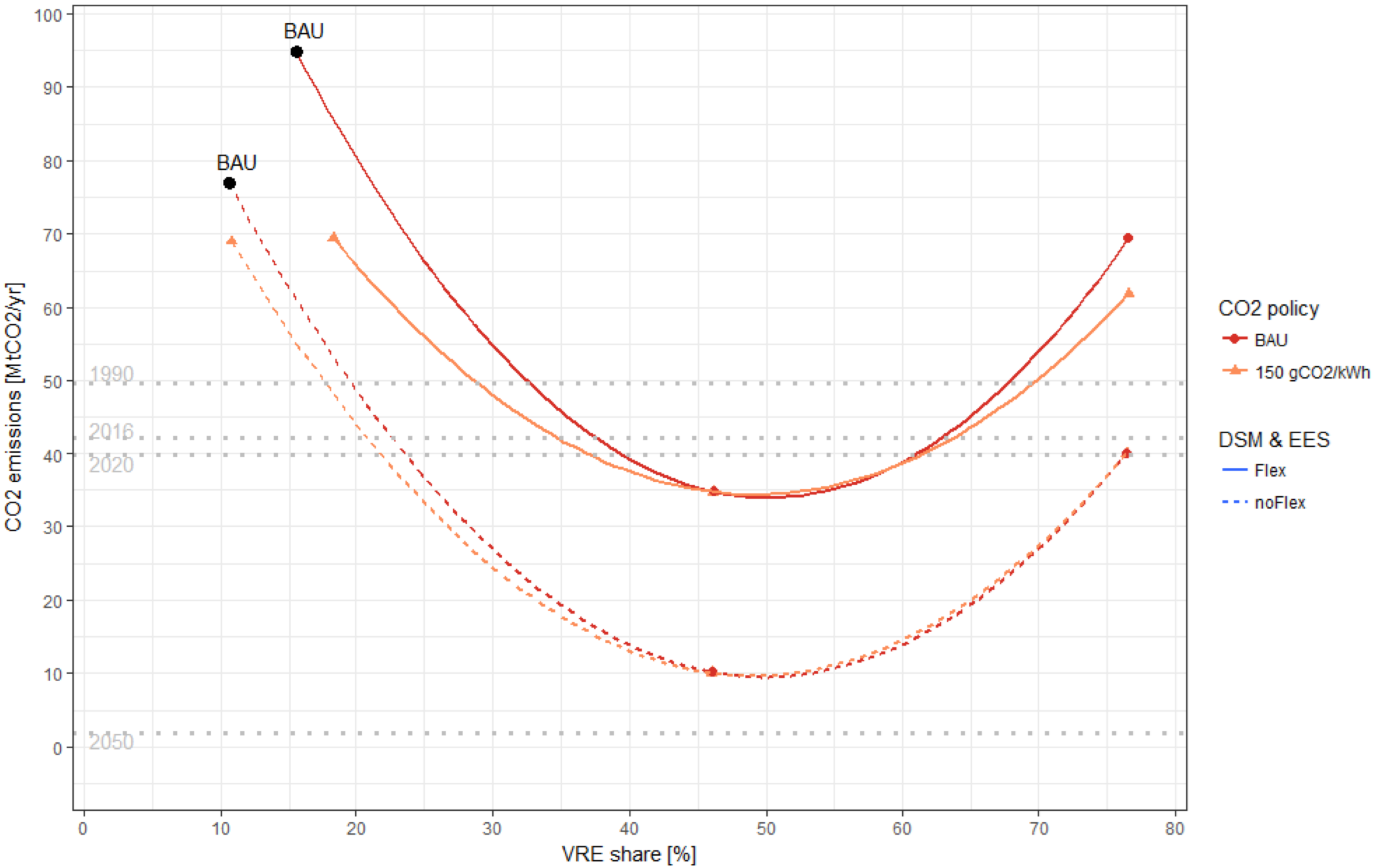

Results

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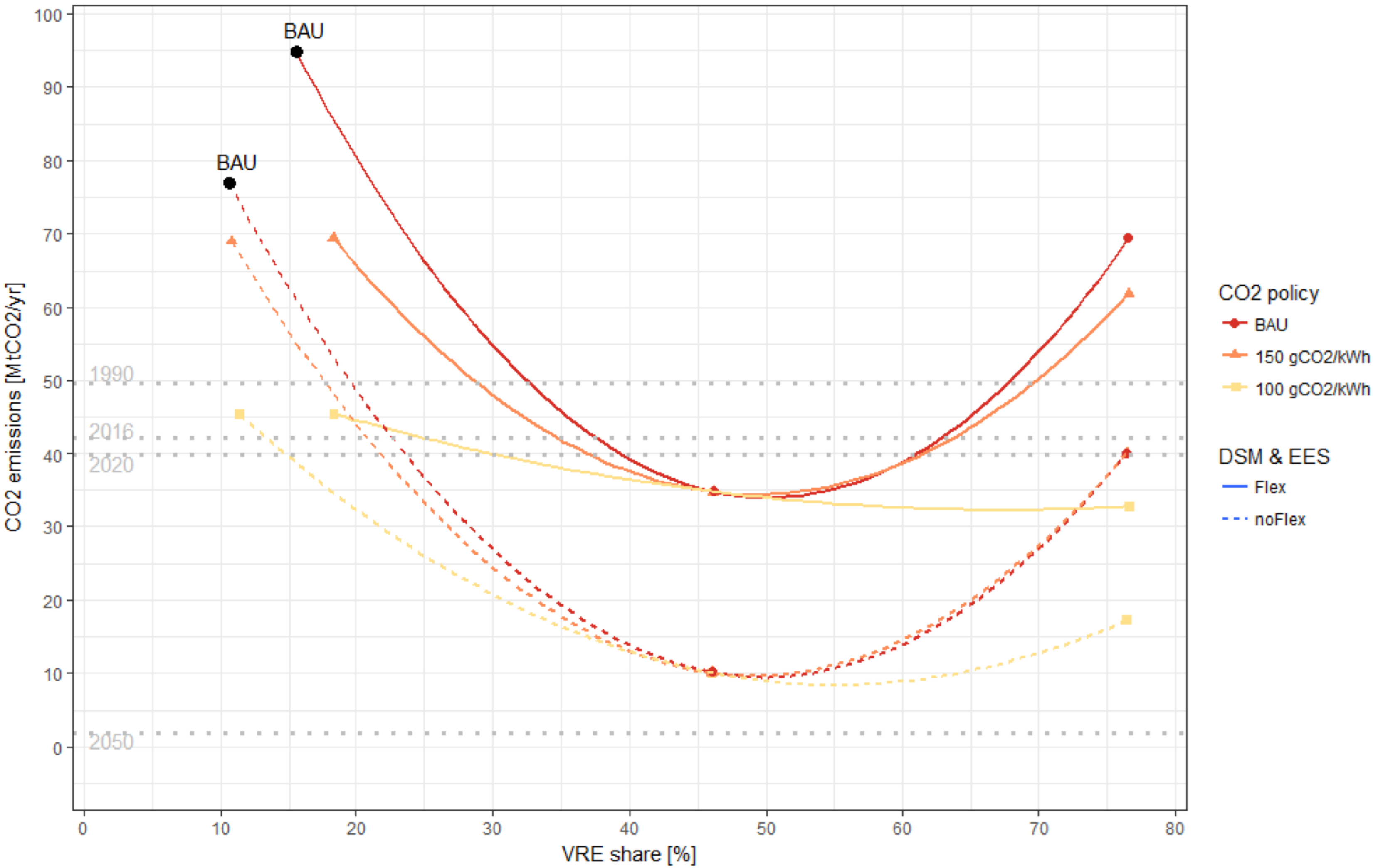

Results

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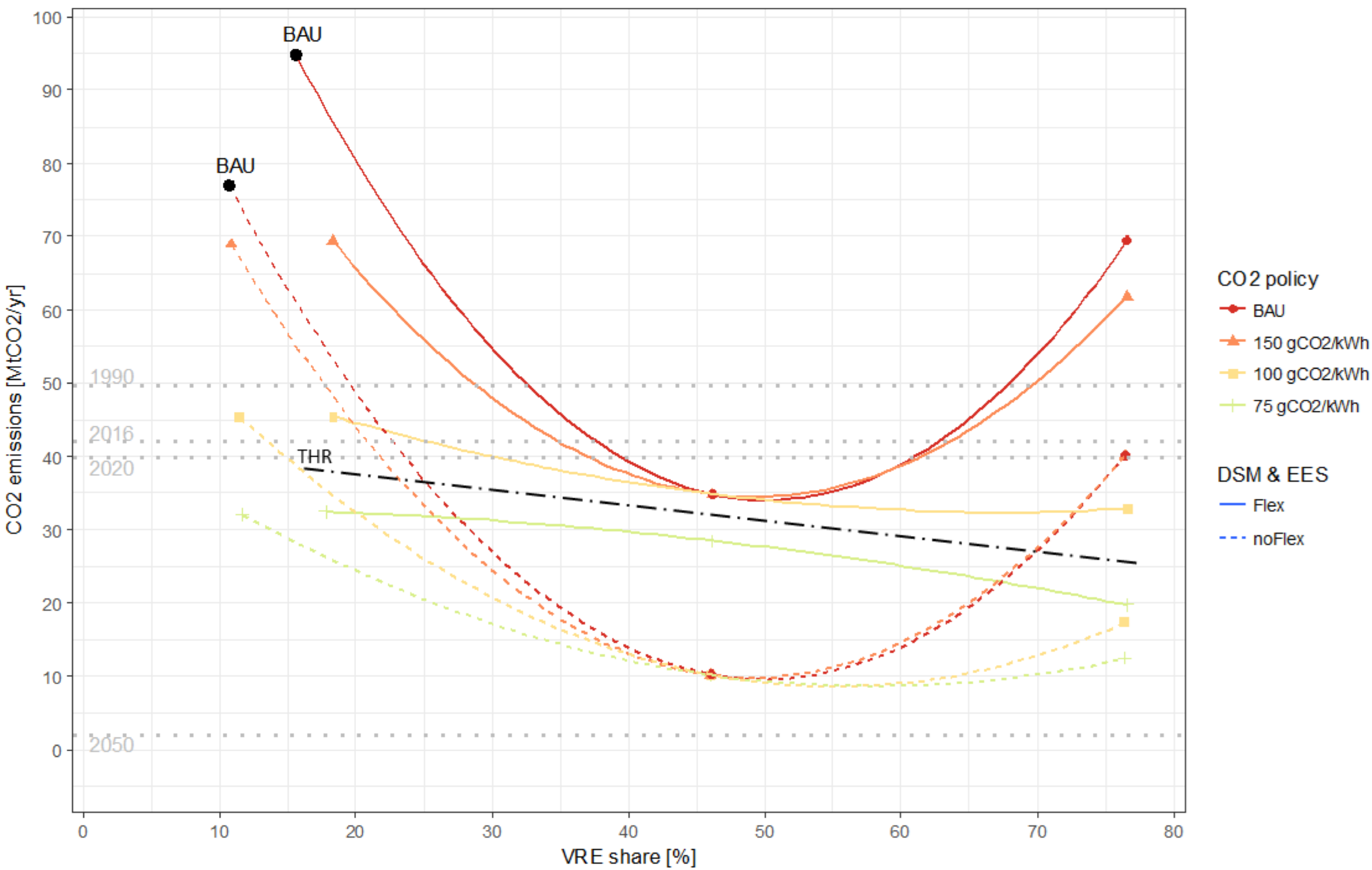
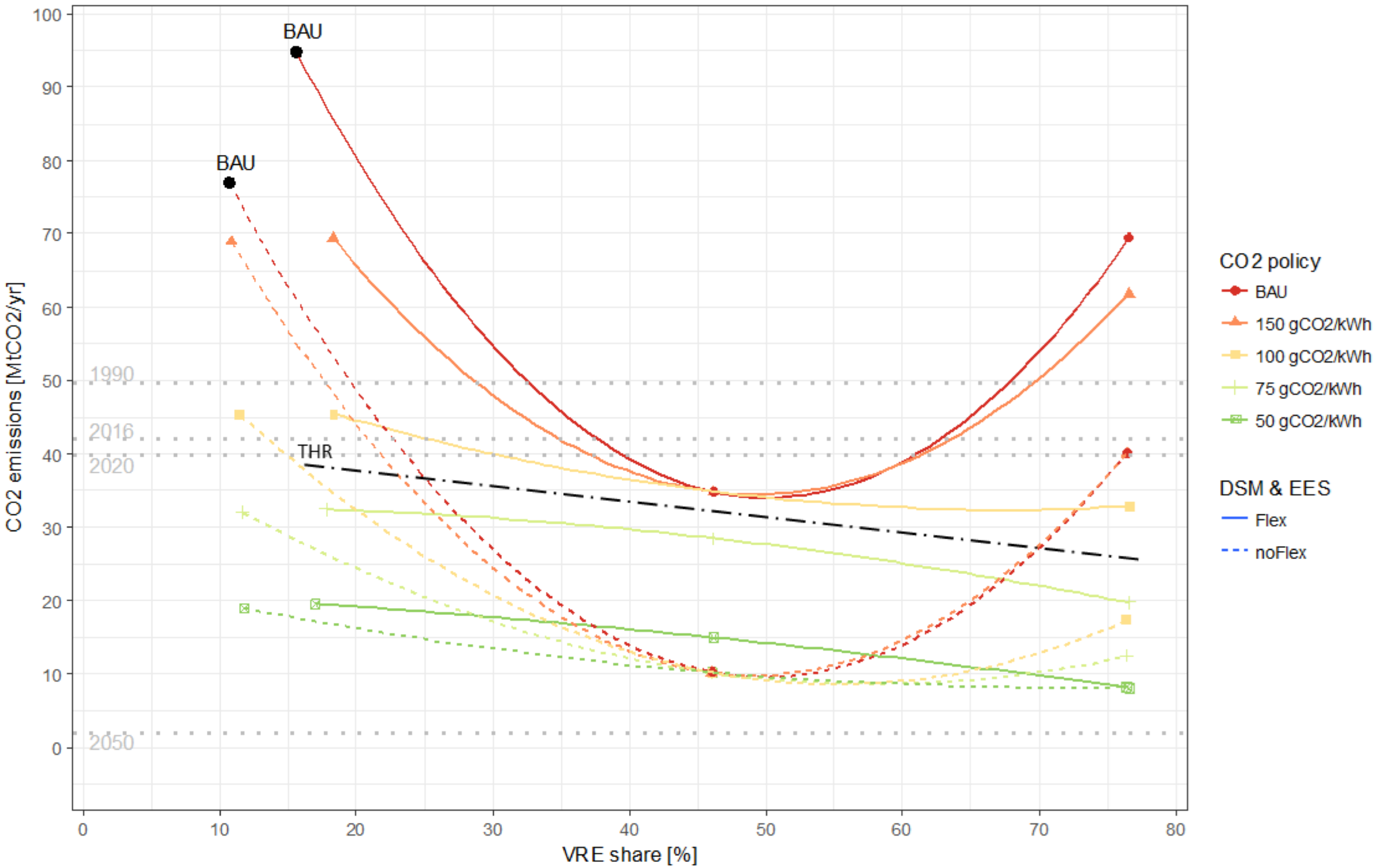


Results



BAU
BAU
THR
1990
2016
2020
2050
CO2 emissions [MtCO2/yr]
VRE share [%]
0
10
20
30
40
50
60
70
80
90
100
CO2 policy
BAU
150 gCO2/kWh
100 gCO2/kWh
75 gCO2/kWh
50 gCO2/kWh
DSM & EES
Flex
noFlex

Results

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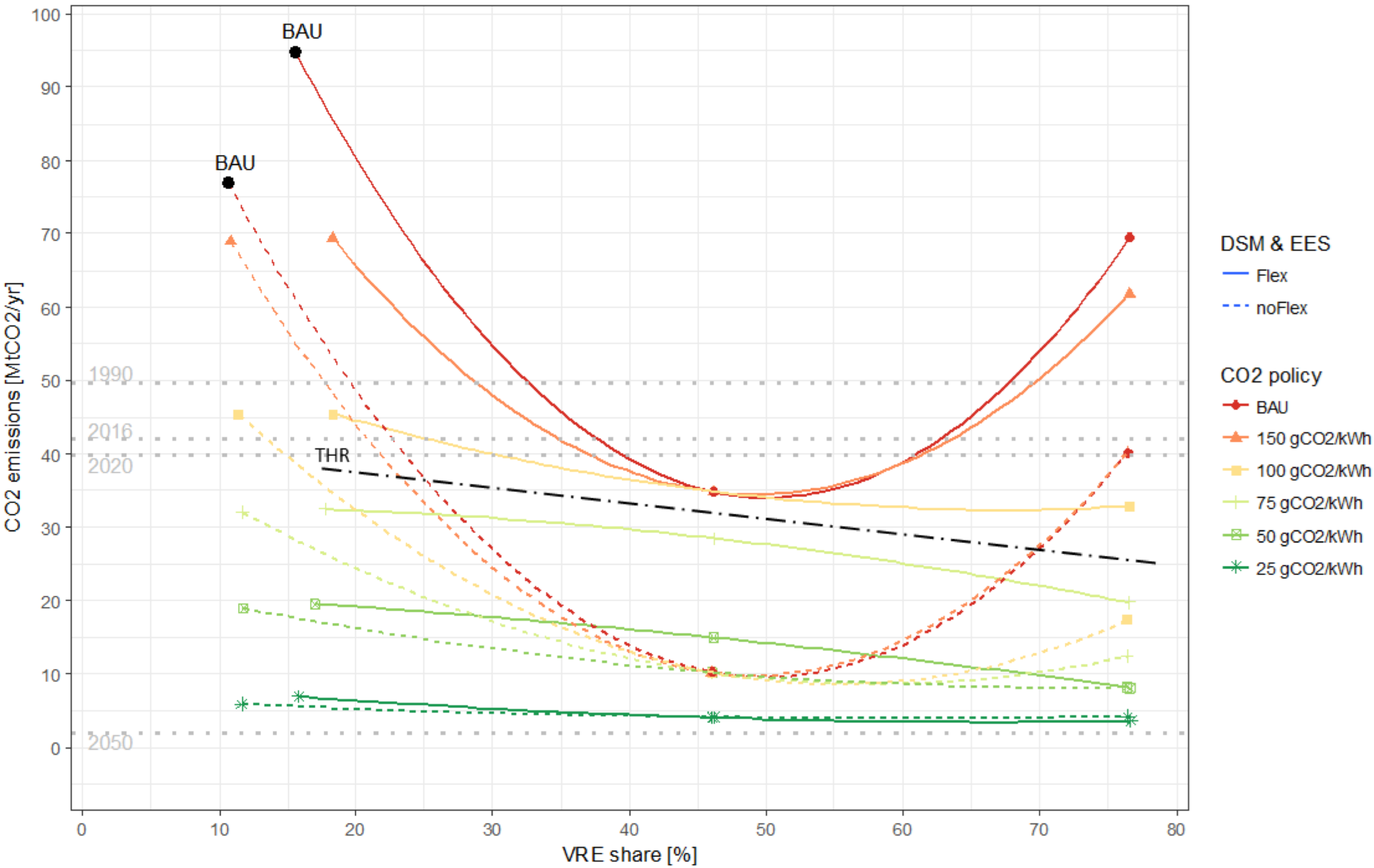
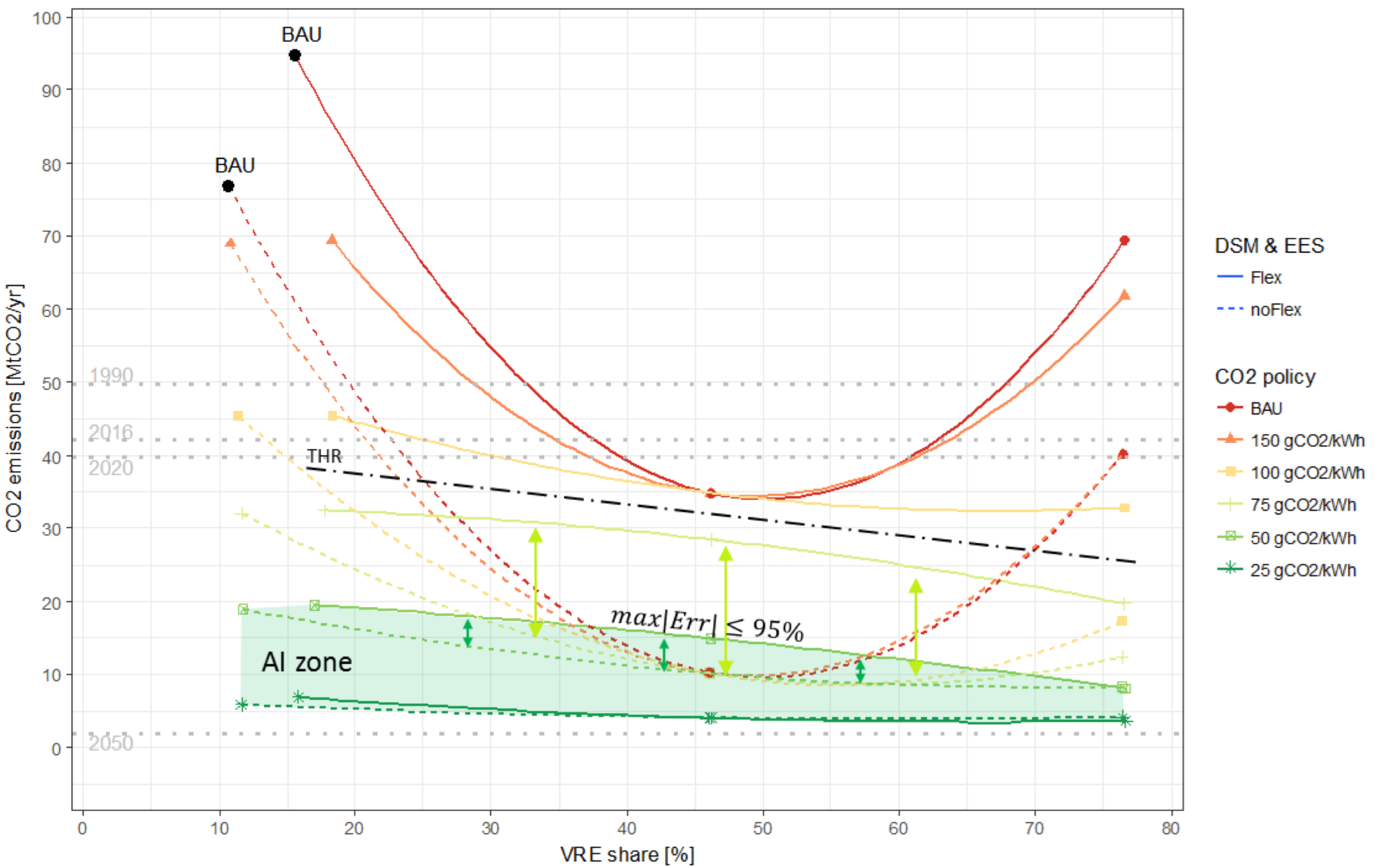


Results


BAU
BAU
THR
1990
2016
2020
2050
max|Err| ≤ 95%
AI zone
CO2 emissions [MtCO2/yr]
VRE share [%]
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
DSM & EES
Flex
noFlex
CO2 policy
BAU
150 gCO2/kWh
100 gCO2/kWh
75 gCO2/kWh
50 gCO2/kWh
25 gCO2/kWh

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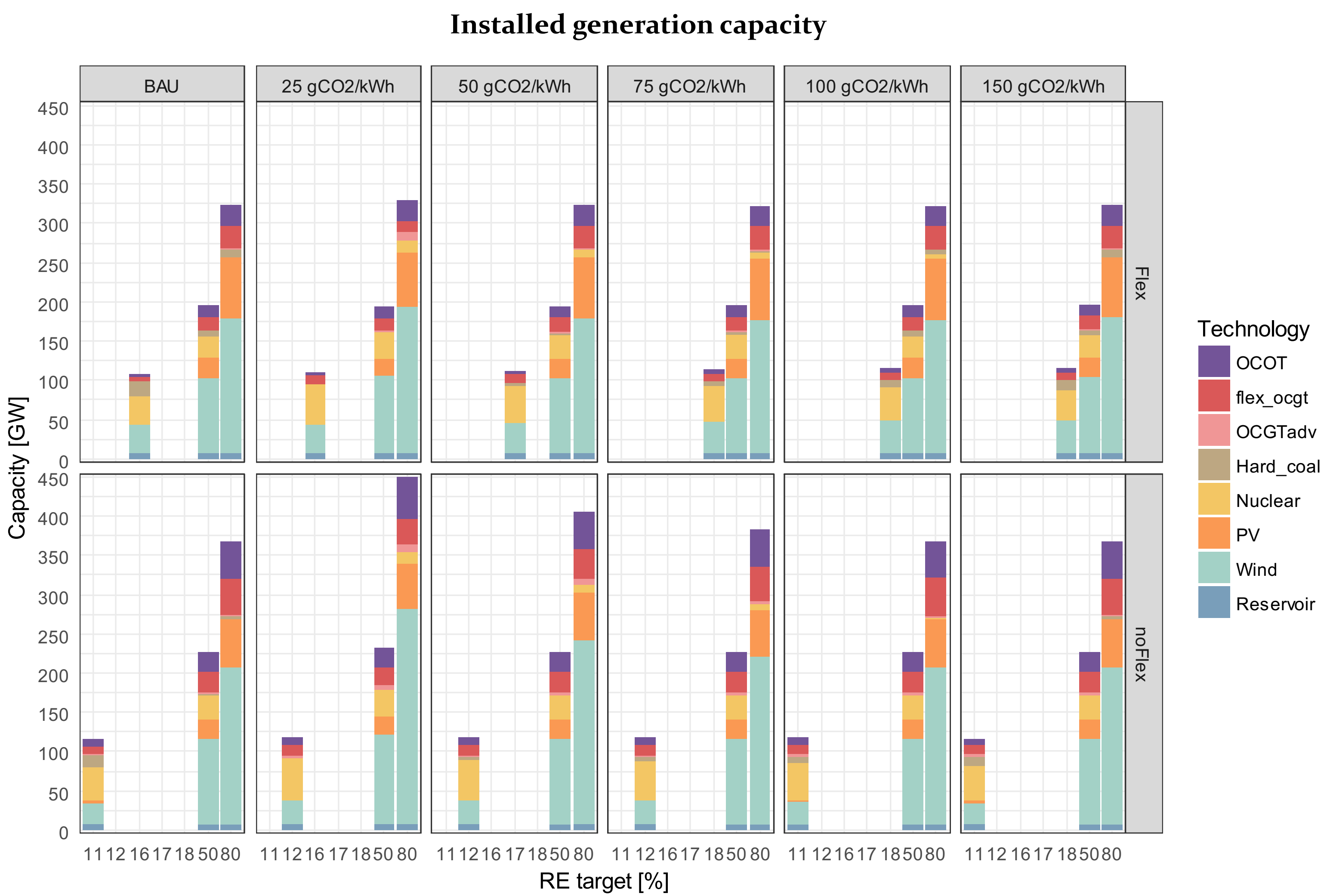
Cost-optimal pathways for attaining the RE and decarbonization objectives:



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Cost-optimal pathways for attaining the RE and decarbonization objectives:

Installed flexibility technologies