

Endogenizing Industrial Demand in Energy System Optimization Models

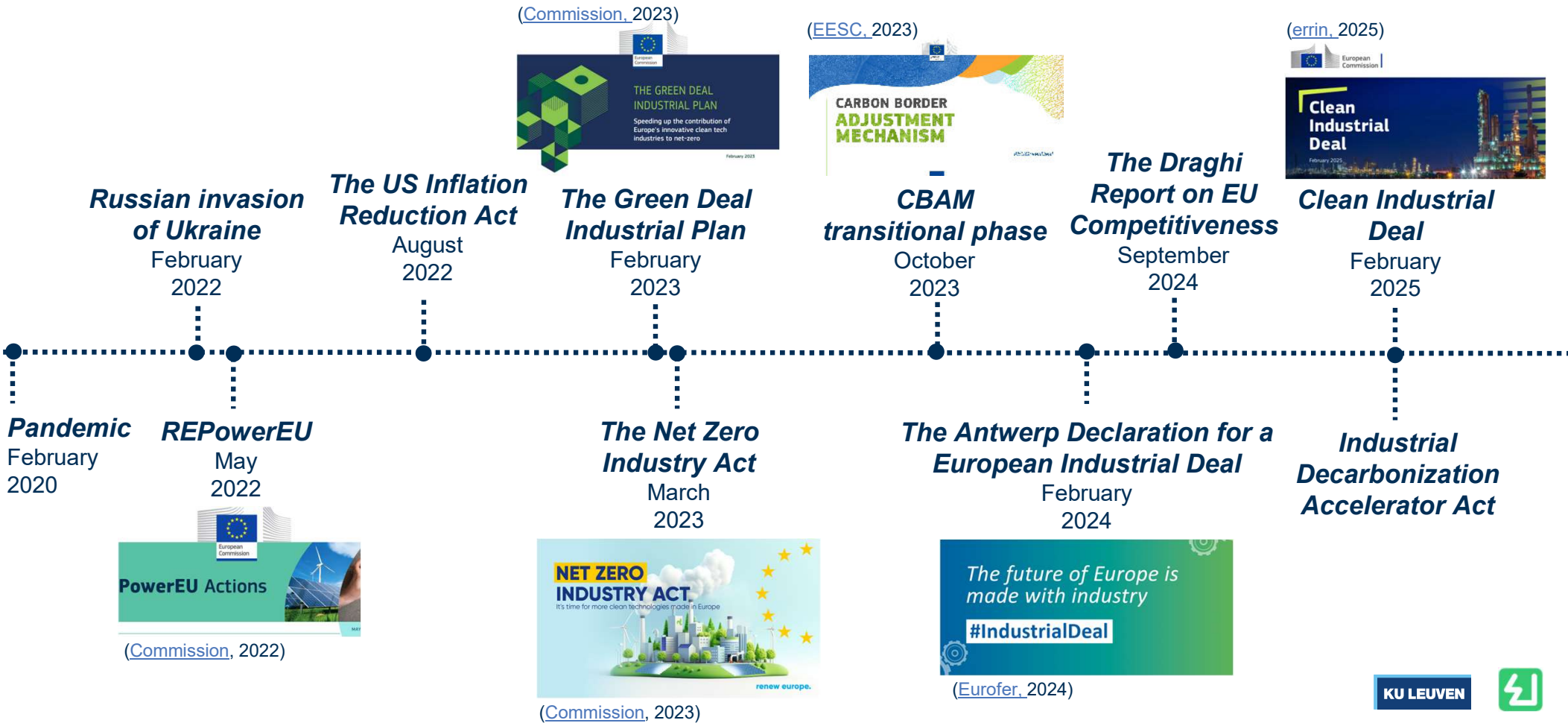
A Novel Classification and Case Studies

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Introduction & Research Question

The European Industrial Transformation



Contents

- Classification of macroeconomic interventions in ESOMs
- Stylized experiments
- Real model experiments
- Conclusion & next steps



Classification of macro-economic interventions in ESOMs

Classification of macro-interventions in ESOMs

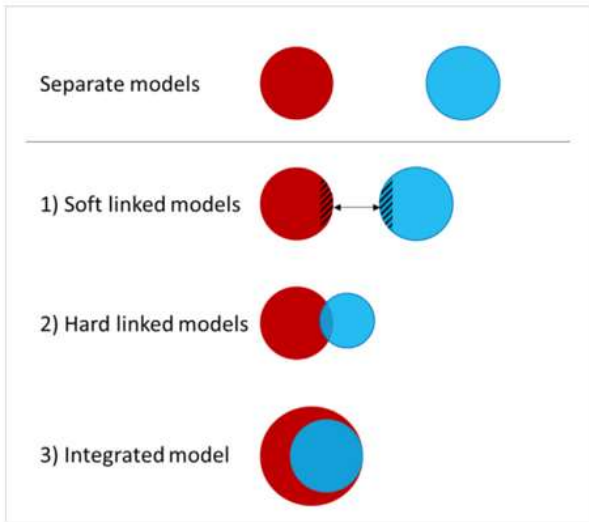
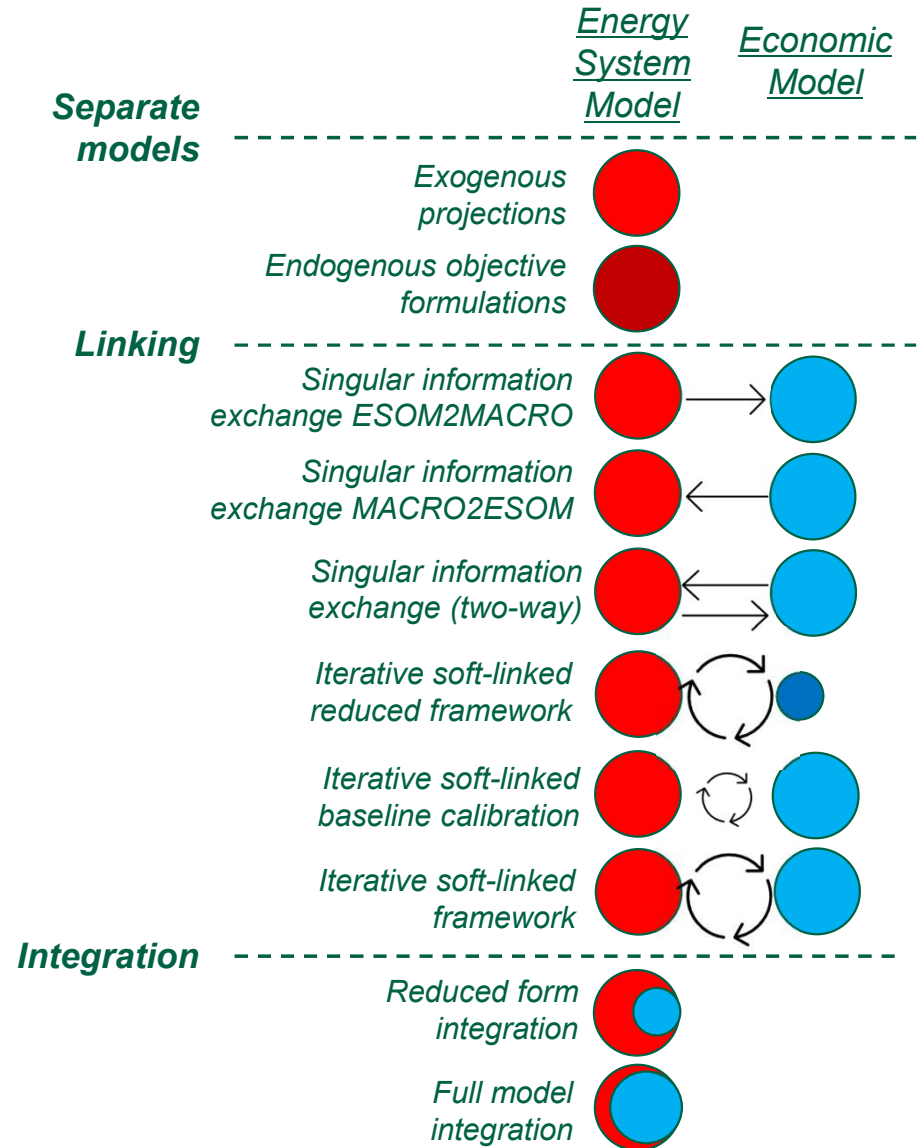


Figure 1 Hybrid model variants as defined by Helgesen et al. [13]



Classification of macro-interventions in ESOMs

Classifying existing frameworks

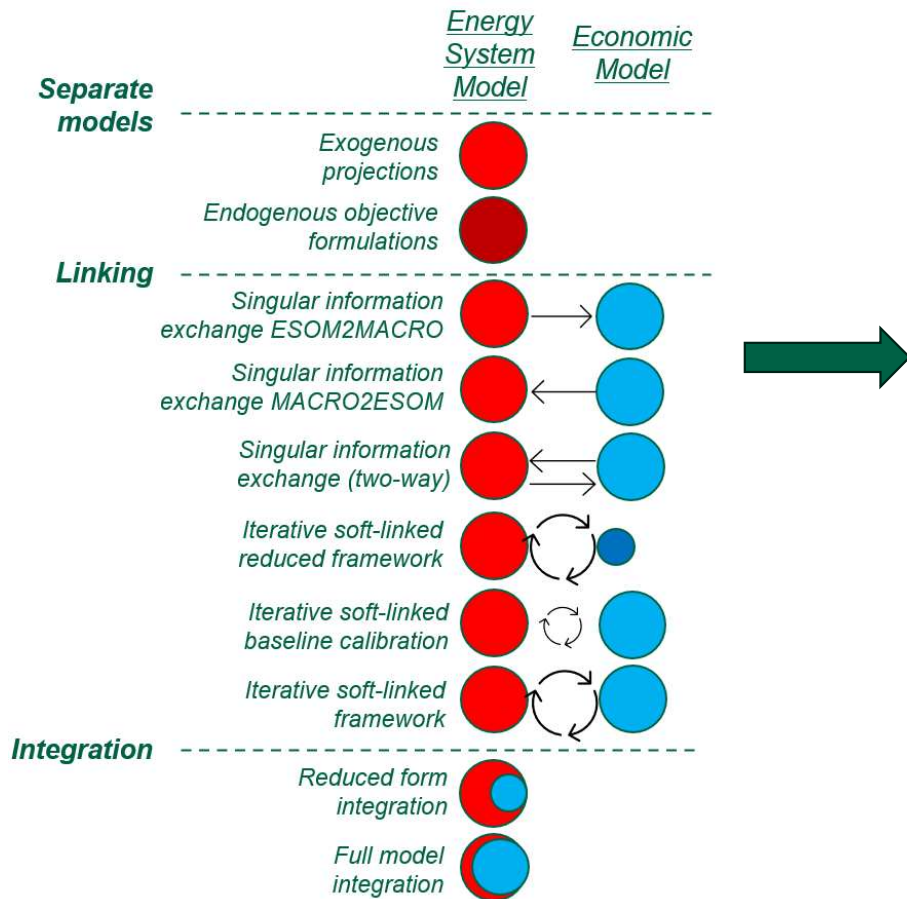


Table 3 Classification of existing energy-economy frameworks.

Level	Type	Model [ESOM x MACRO]	Economic theory	Scope	Source
Dynamic exogenous projections	Dynamic exogenous projections	TIMES-BE – SHIFT (ESOM)	Normative/ optimization	Belgium	2024, EnergyVille [22]
		Endogenous formulations	JRC-EU-TIMES (ESOM)	Normative/ optimization	Europe
TIAM-Elastic (ESOM)	Normative/ optimization		Global	2008, R. Loulou & M. Labriet [43]	
TIMES-Canada (ESOM)	Normative/ optimization		Canada	2014, K. Vaillancourt et al. [44]	
Linking	Cross-price elasticities	GTAP-E (CGE)	Positive/ simulation	Global	2007, T. Truong & J. M. Burniaux [45]
		Singular information exchange	REMES-EU x EXIOMOD (OpenEntrance)	Positive/ simulation	Europe
	Microsimulation x CGE		Positive/ simulation	Belgium	2014, T. Vandyck & D. Van Regemorter [27]
	Iterative information exchange for soft-linked framework	TIMES-Sweden x EMEC	Mix	Sweden	2017, A. Krook-Riekkola et al. [28]
		IEASA-Opt x ThreeME-	Mix	The Netherlands	2023, A. Fattahi et al. [29]
		TIMES-DK x CGE (IntERACT)	Mix	Denmark	2019, K. S. Andersen [14]
	Iterative information exchange for baseline calibration	TIMES-PT x GEM-E3-PT	Mix	Portugal	2013, P. Fortes et al. [15]
		PRIMES x JRC-GEM-E3	Positive/ simulation	Europe	2017, P. Fragkos [47]
		POLES-JRC x JRC-GEM-E3	Positive/ simulation	Global	2020, Z. Vrontisi [48]
	Integration	Reduced model integration	TIAM-MACRO	Mix	Global
TIMES-MACRO-UK			Normative/ optimization	United Kingdom	2014, H. E. Daly et al. [50]
MESSAGE(-GLOBIOM)-MACRO			Normative/ optimization	Global	2000, S. Messner & L. Schrattenholzer [51]
Full model integration		GreenREFORM (Integration of TIMES-DK in DREAM)	Positive/ simulation	Denmark	2025, B. Sørensen et al. [52]

Stylized Experiments

Stylized Cases

 *Exogenous demand projections*

 *Endogenous formulations with constant own price elasticity*

 *Singular information exchange with MACRO*

 *Reduced form integration with MACRO*

 *Soft linked ESOM-MACRO framework*

How well do these different approaches capture deeper levels of energy-economy interaction such as the impacts of ‘green relocation’ effect?

Exogenous Demand Projections



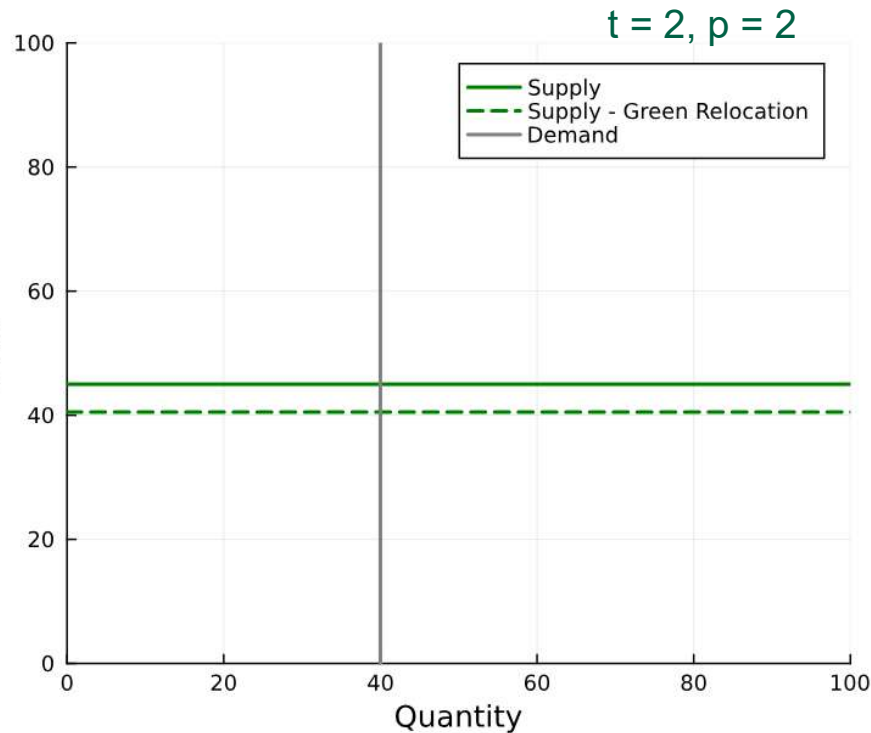
$$\text{Min } [c \cdot X]$$

Model Setup

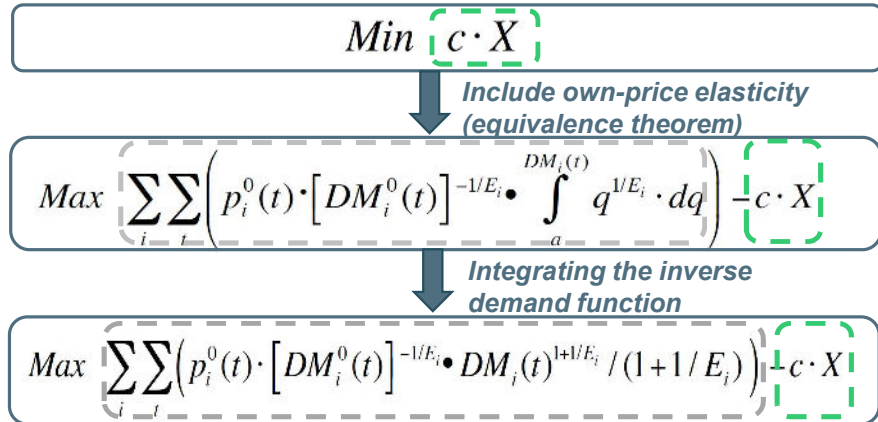
- Demand = 40 → **Energy intensive products**
- Investment cost = 25
- Variable cost = 20
- Three periods of 10 years
- Initial stock to satisfy demand
- Lifetime of processes = 1 period, AF = 1

Perfectly Inelastic Demand Function

- Maximizing net total surplus OR Minimize total cost
→ $\text{Max } q^* - c X = \text{Max } - c X = \text{Min } c X$
→ Maximizing Producer Surplus only (or simply minimizing total cost)
- Variables are CAP and GEN of each technology
- Linear objective function



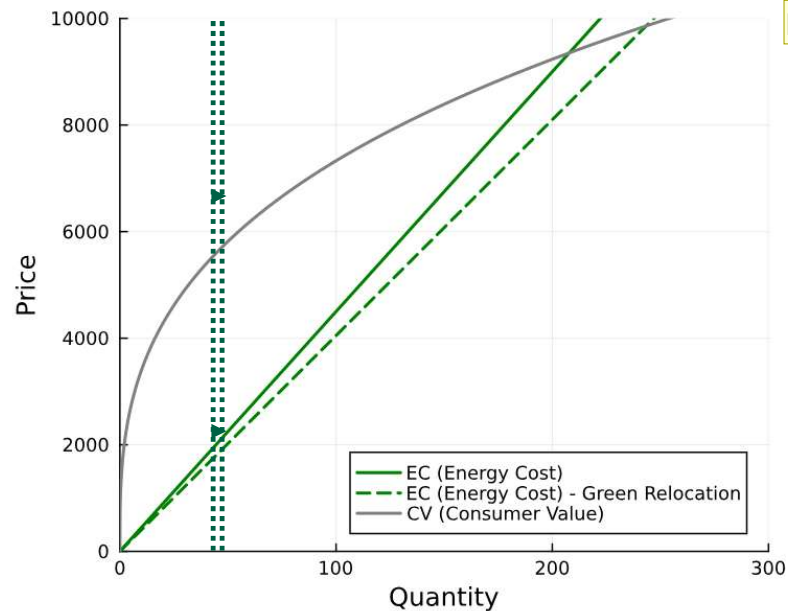
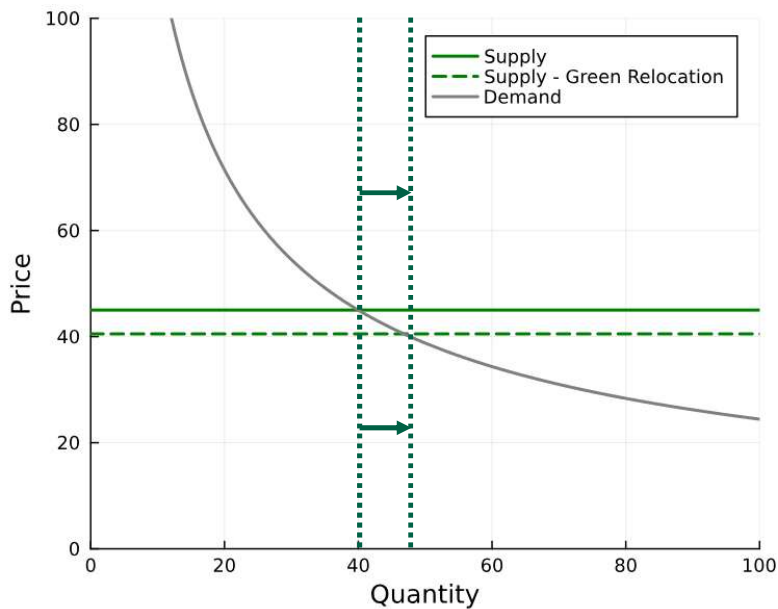
Endogenous Formulation Constant Elasticity



Elastic Demand Function

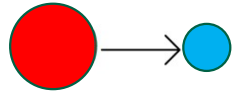
- Maximizing net total surplus
- Constant own price elasticity function
- Now demand becomes a variable as well
- Non-linear objective function to be linearized

$$E = \frac{\frac{\Delta Q}{Q1}}{\frac{\Delta P}{P1}} = -1.5$$



EL1 Change units to demand and €
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Singular Information Exchange



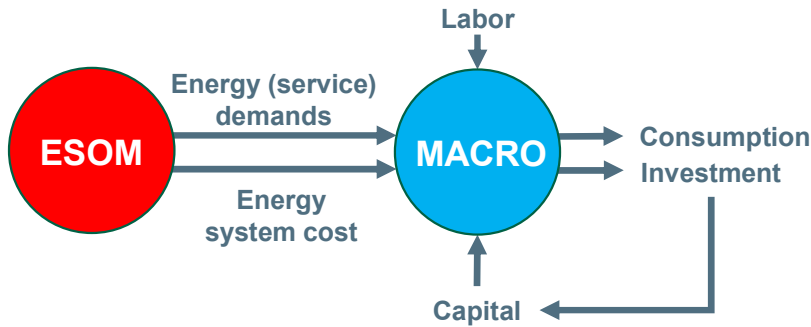
Singular Information Exchange

- ESOM output becomes MACRO input: EC & DEM
- MACRO on its own cannot provide useful input to ESOM

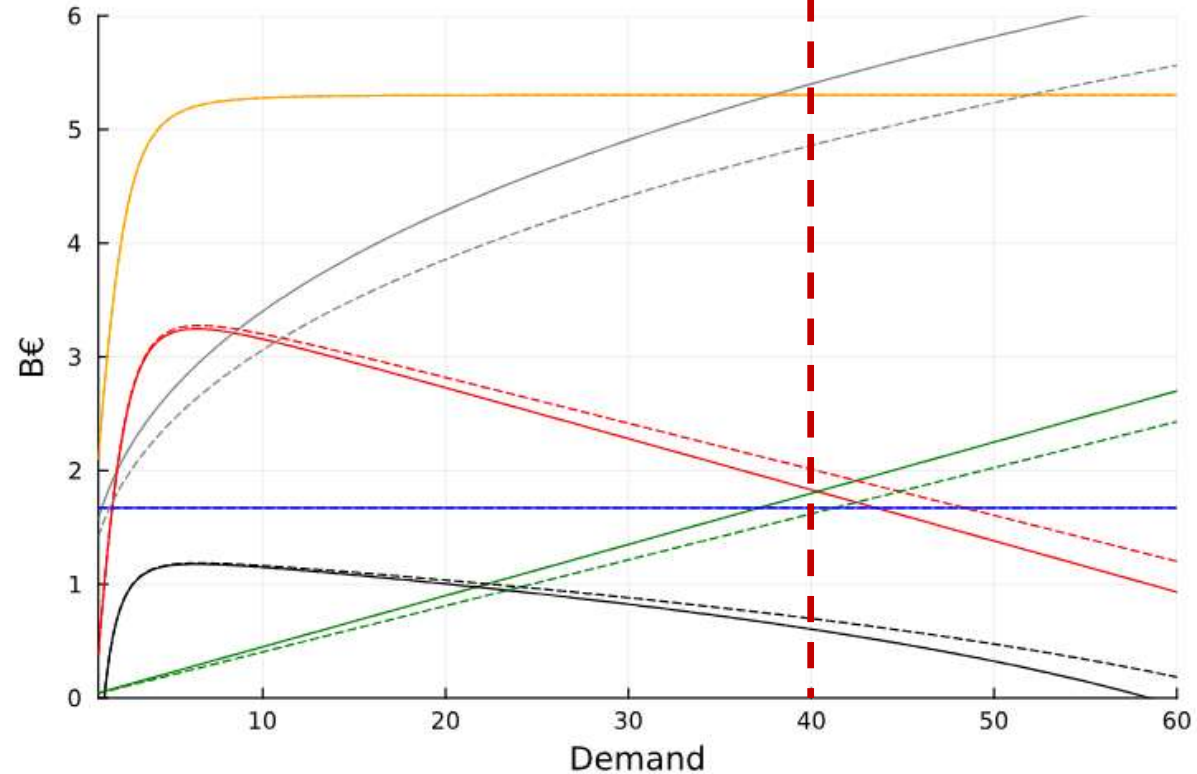
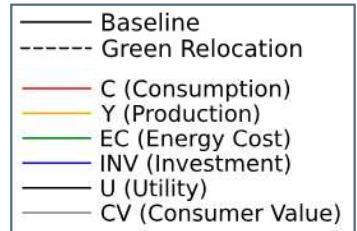
$$Y = INV + C + EC$$

$$U = \log(C)$$

$$\text{Max} \sum_{t=1}^{T-1} dfact_t \cdot \ln(C_t)$$



Singular information exchange



Reduced Form Integration with MACRO



Singular Information Exchange

- ESOM output becomes MACRO input: EC & DEM
- MACRO on its own cannot provide useful input to ESOM

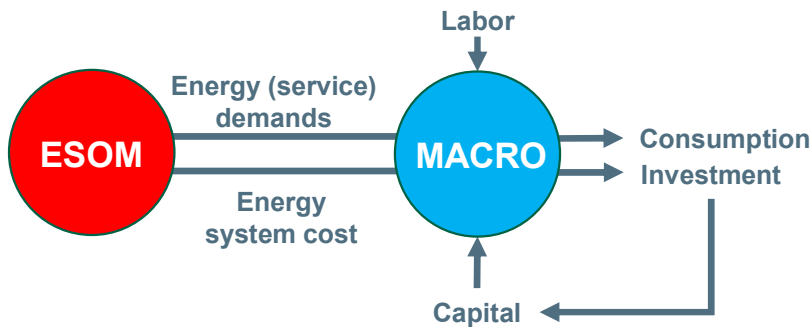
Reduced From Integration

- Energy (service) demands are endogenous again
- Energy system cost defined by ESOM equations

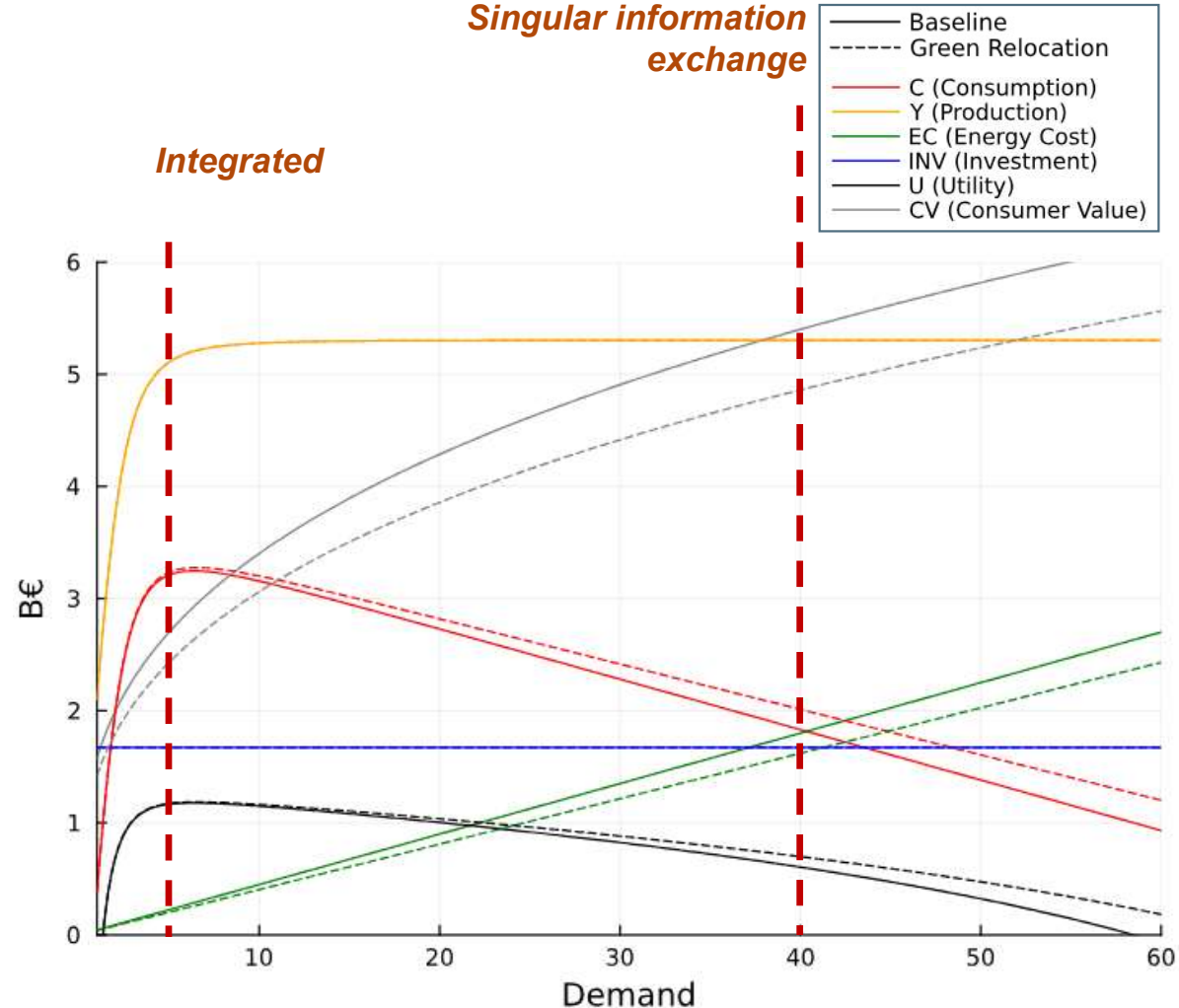
$$Y = INV + C + EC$$

$$U = \log(C)$$

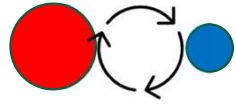
$$\text{Max} \sum_{t=1}^{T-1} dfact_t \cdot \ln(C_t)$$



Singular information exchange



Soft Linked ESOM-MACRO



Singular Information Exchange

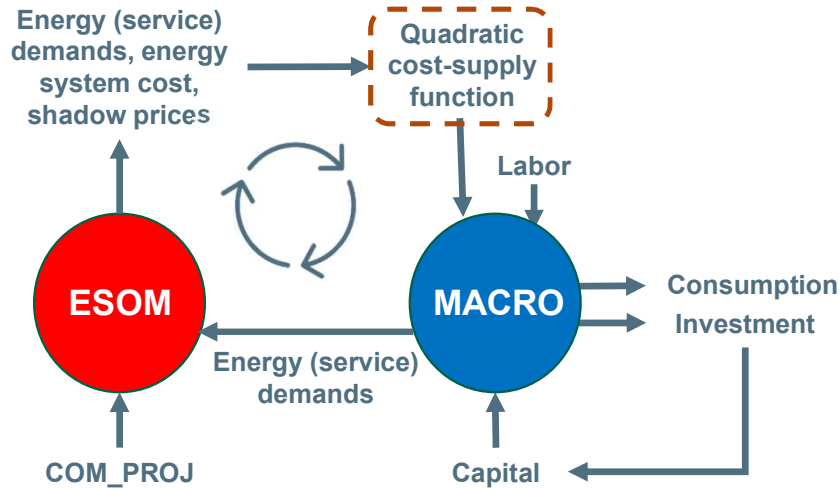
- ESOM output becomes MACRO input: EC & DEM
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Reduced From Integration

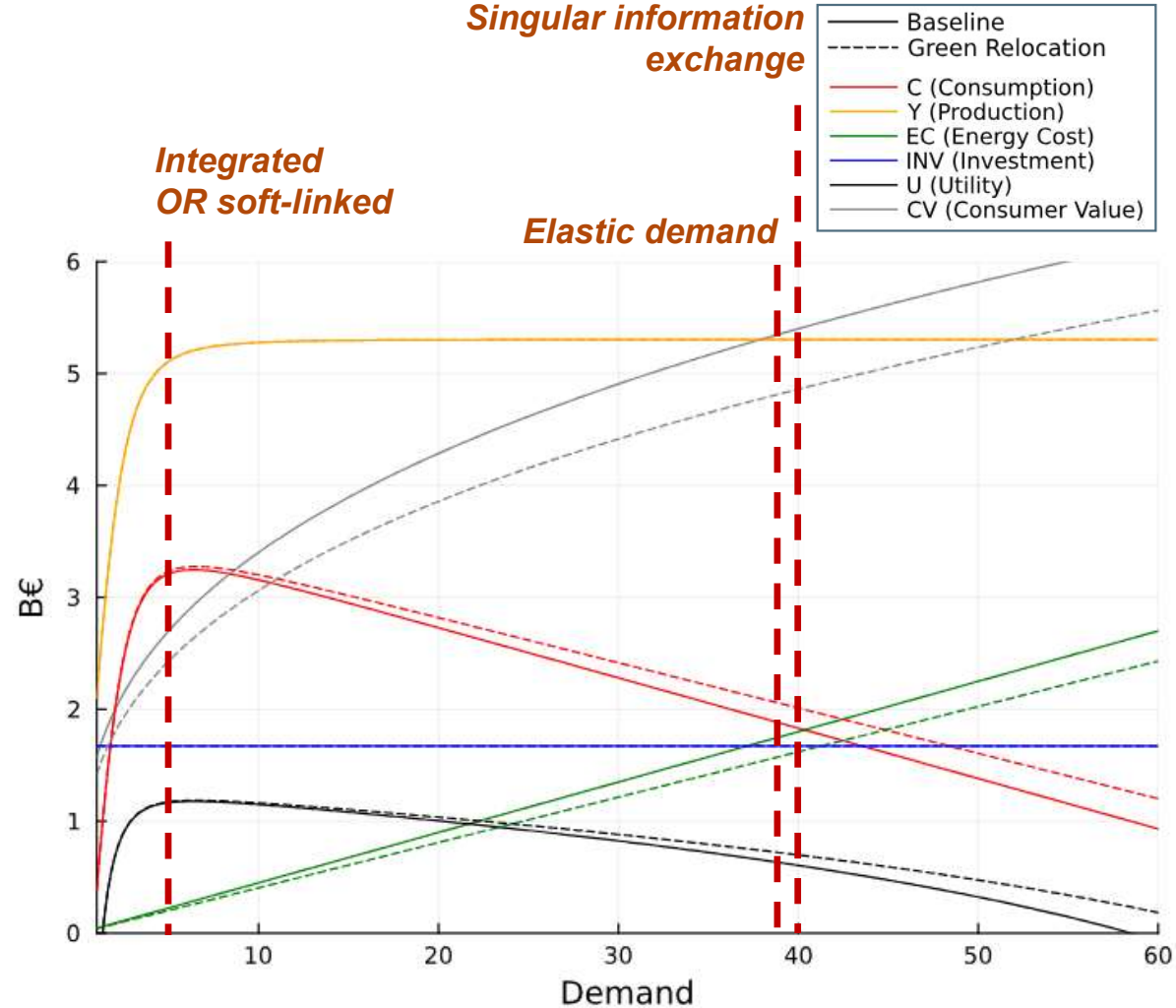
- Energy (service) demands are endogenous again
- Energy system cost defined by ESOM equations

Soft Linked ESOM-MACRO



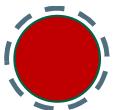


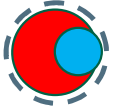
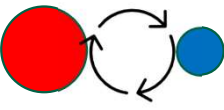
- The ESOM energy system cost is approximated by a quadratic cost-supply function
- Fully reproduces the integrated solution



Singular information exchange



Overview

	Solver	Runtime (s)	Resulting demand t = 2	Demand levels	Objective formulation
	Gurobi (LP)	~5.67	40	Fixed	$Min \quad c \cdot X$
	Juniper (MINLP)	~23.50	~40	Variable	$Max \sum_i \sum_i PVF(t) \cdot dc_i(t) \cdot DM_i(t)^{1+1/E_i} - c \cdot X$
	Gurobi (LP)	~1.00	~40	Variable	$Max \sum_i \sum_i PVF(t) \cdot dc_i(t) \cdot DM_i(t)^{1+1/E_i} - c \cdot X$
	Gurobi – IPOPT (LP - NLP)	~10.88	~40	Variable	$Max \sum_{t=1}^{T-1} dfact_t \cdot \ln(C_t) \quad \& \quad Min \quad c \cdot X$
	IPOPT (NLP)	~15.00	4.73	Variable	$Max \sum_{t=1}^{T-1} dfact_t \cdot \ln(C_t)$
	Gurobi (LP)	~1.00 EL1	4.73	Variable	$Max \sum_{t=1}^{T-1} dfact_t \cdot \ln(C_t)$
	Gurobi – IPOPT (LP-NLP)	~18.93	4.73	Variable	$Max \sum_{t=1}^{T-1} dfact_t \cdot \ln(C_t) \quad \& \quad Min \quad c \cdot X$

EL1

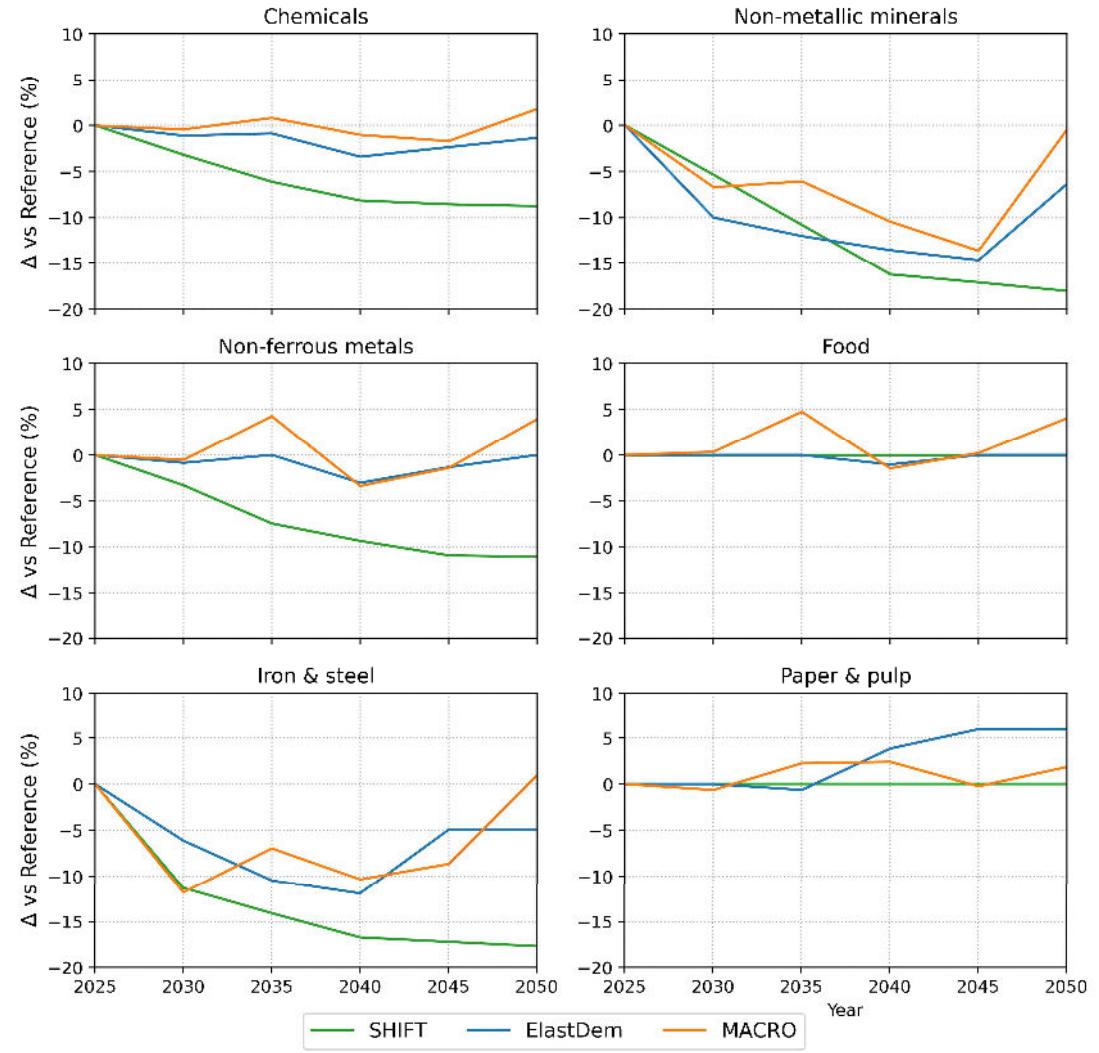
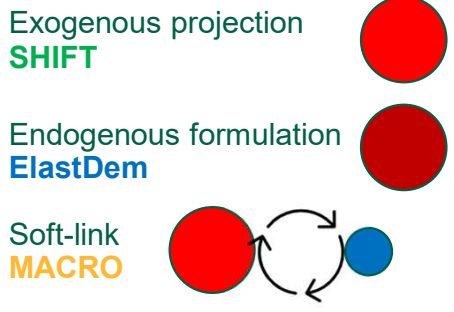
TO DO

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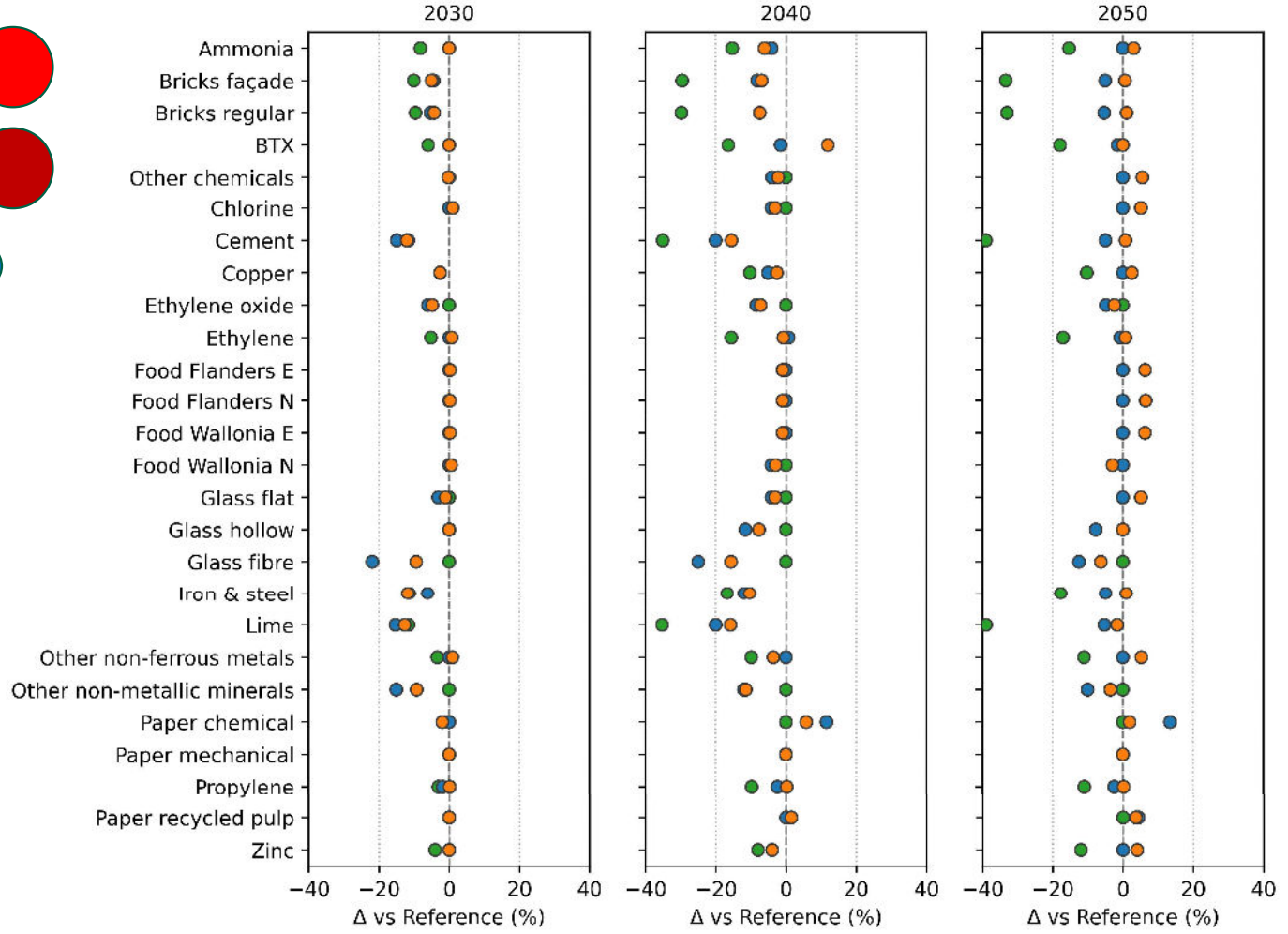
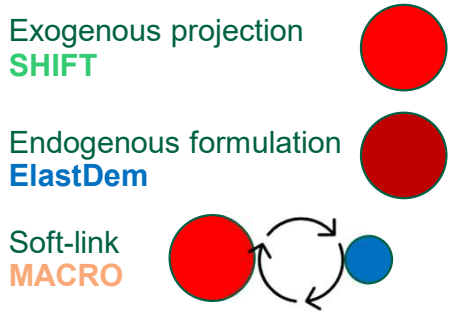
Applied Model Experiments

Work in progress

A Spectrum of Industrial Demands



A Spectrum of Industrial Demands



● SHIFT ● ElastDem ● MACRO



Conclusion & Next Steps

Conclusion & Next Steps

Conclusion

- *Standalone Energy System Optimization Models (ESOMs) can identify cost-effective net-zero pathways to support national decarbonization strategies.*
- *Linking to a MACRO module provides macroeconomic information and insights in the optimal economic state of the system.*
- *However, the integration of macroeconomic interactions into these pathways remains limited. When such integration does occur, it often **lacks critical feedback mechanisms**, such as:*
 - 1) *The effect of job losses or income effects.*
 - 2) *The influence of rising capital costs or resource constraints on investment capacity needed to realize the energy transition pathway.*

Next steps

- *To address these gaps, a more **detailed mapping of the value chains and capital intensity** in the energy system model to the macroeconomic model is needed.*
- *Further applied experiments for larger model interactions: identify strengths and weaknesses of different levels of macroeconomic interventions.*
- *Comparing the soft-linking approach to a fully integrated one for applied models.*



Questions?

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