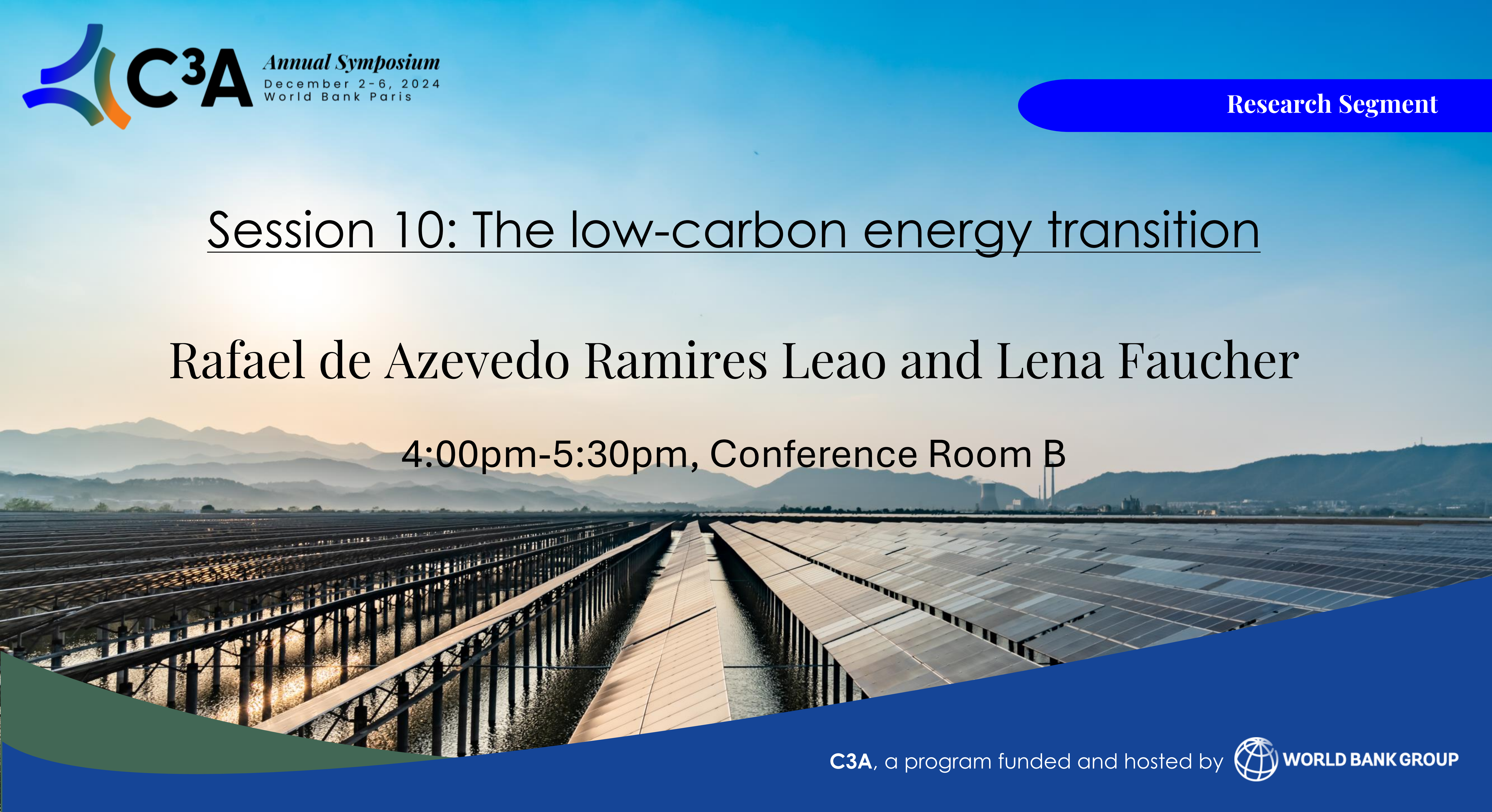
C3A Annual Symposium
December 2-6, 2024
World Bank Paris

Research Segment

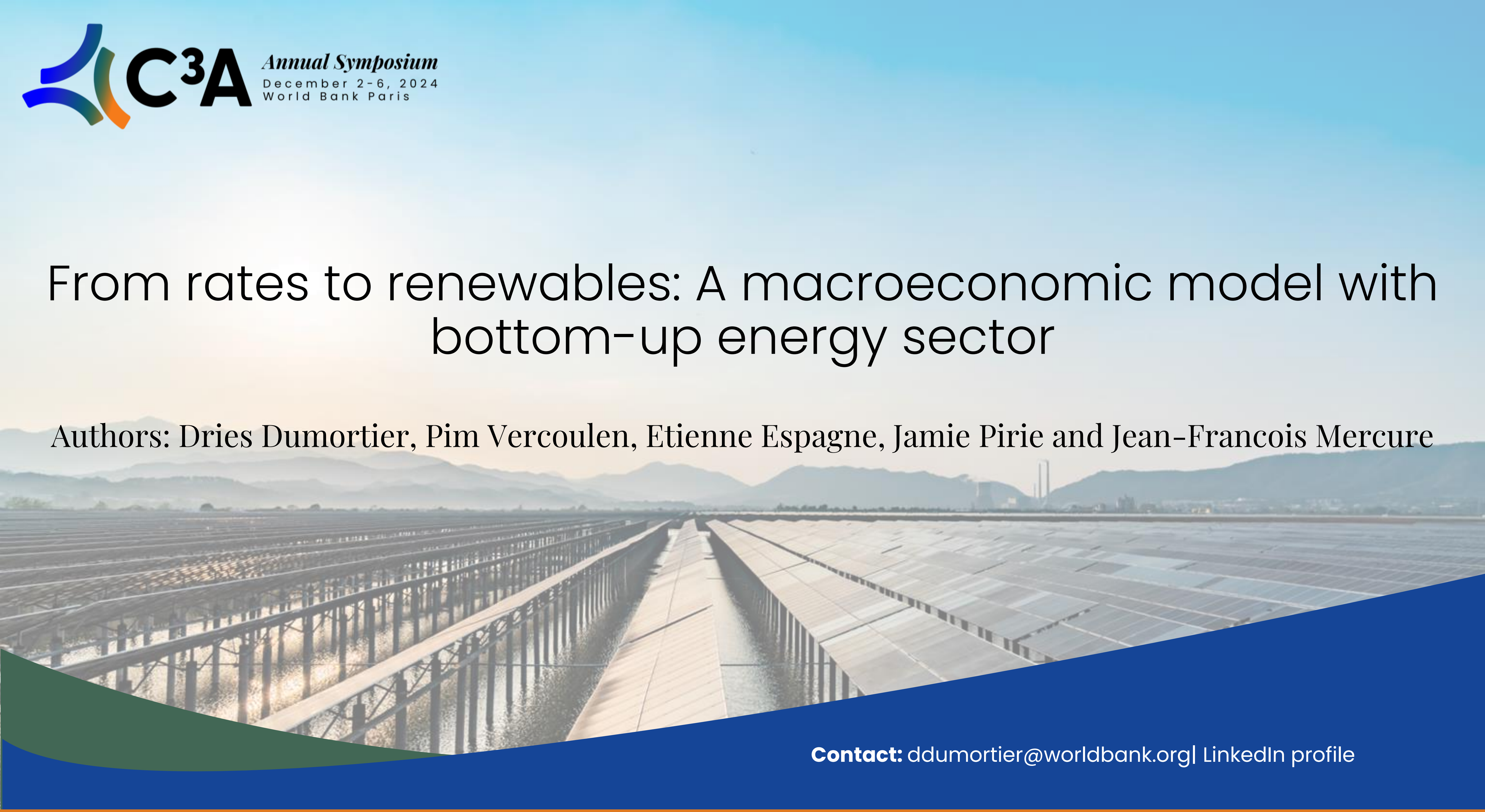


Session 10: The low-carbon energy transition

Rafael de Azevedo Ramires Leao and Lena Faucher

4:00pm-5:30pm, Conference Room B

C3A, a program funded and hosted by WORLD BANK GROUP



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From rates to renewables: A macroeconomic model with bottom-up energy sector

Authors: Dries Dumortier, Pim Vercoulen, Etienne Espagne, Jamie Pirie and Jean-Francois Mercure

Contact: ddumortier@worldbank.org| LinkedIn profile

From rates to renewables

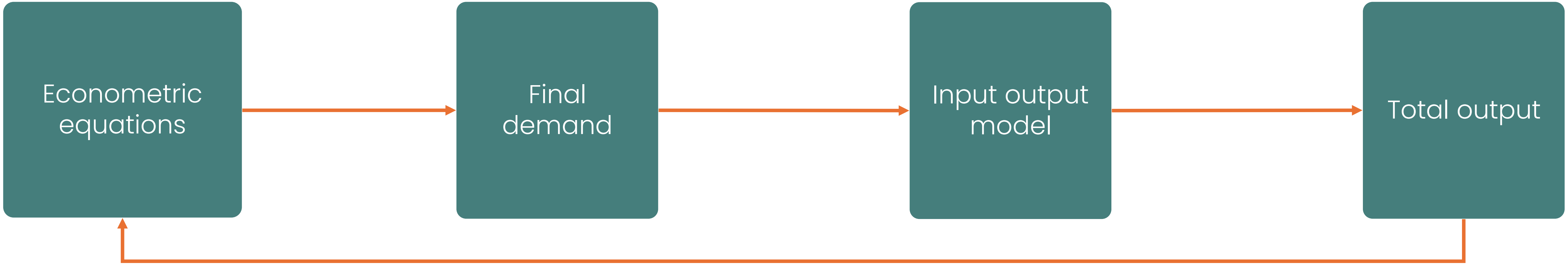
First macroeconomic model with bottom-up electricity sector allowing to represent interest rate impacts

E3ME-FTT model

- E3ME
  - Macro model
  - Impact interest rates on demand
- FTT
  - Technology diffusion model
  - Interest rates impact on technology preference

The E3ME model

- Econometric model
- Based on Post-keynesian theory



Econometric equations

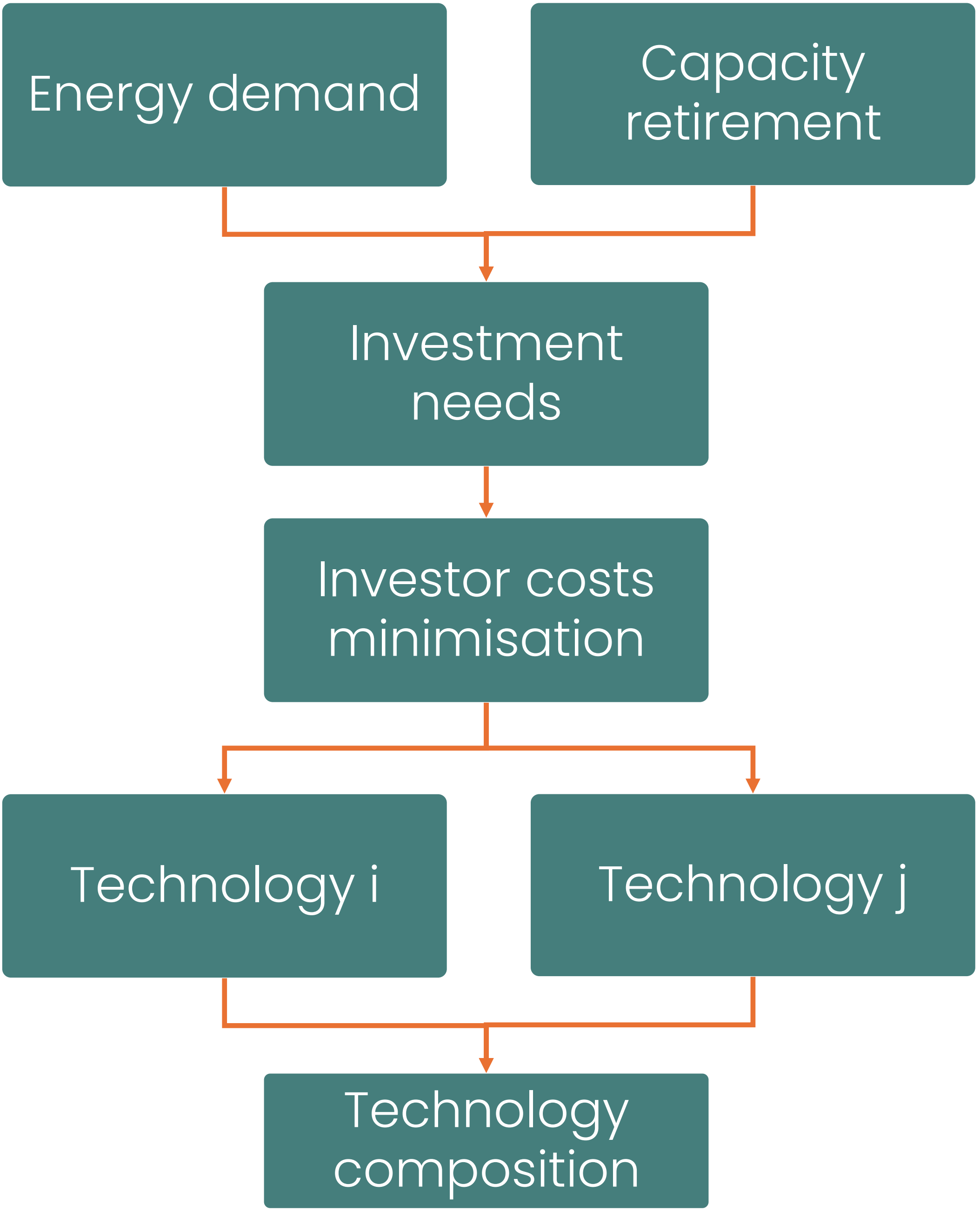
Final demand

Input output model

Total output

The FTT:Power model

- Bottom-up technology model
- Allowing for price and quantity-based policies
- Investment in technologies based on
  - Discrete choice theory
  - Diffusion dynamics



Energy demand

Capacity retirement

Investment needs

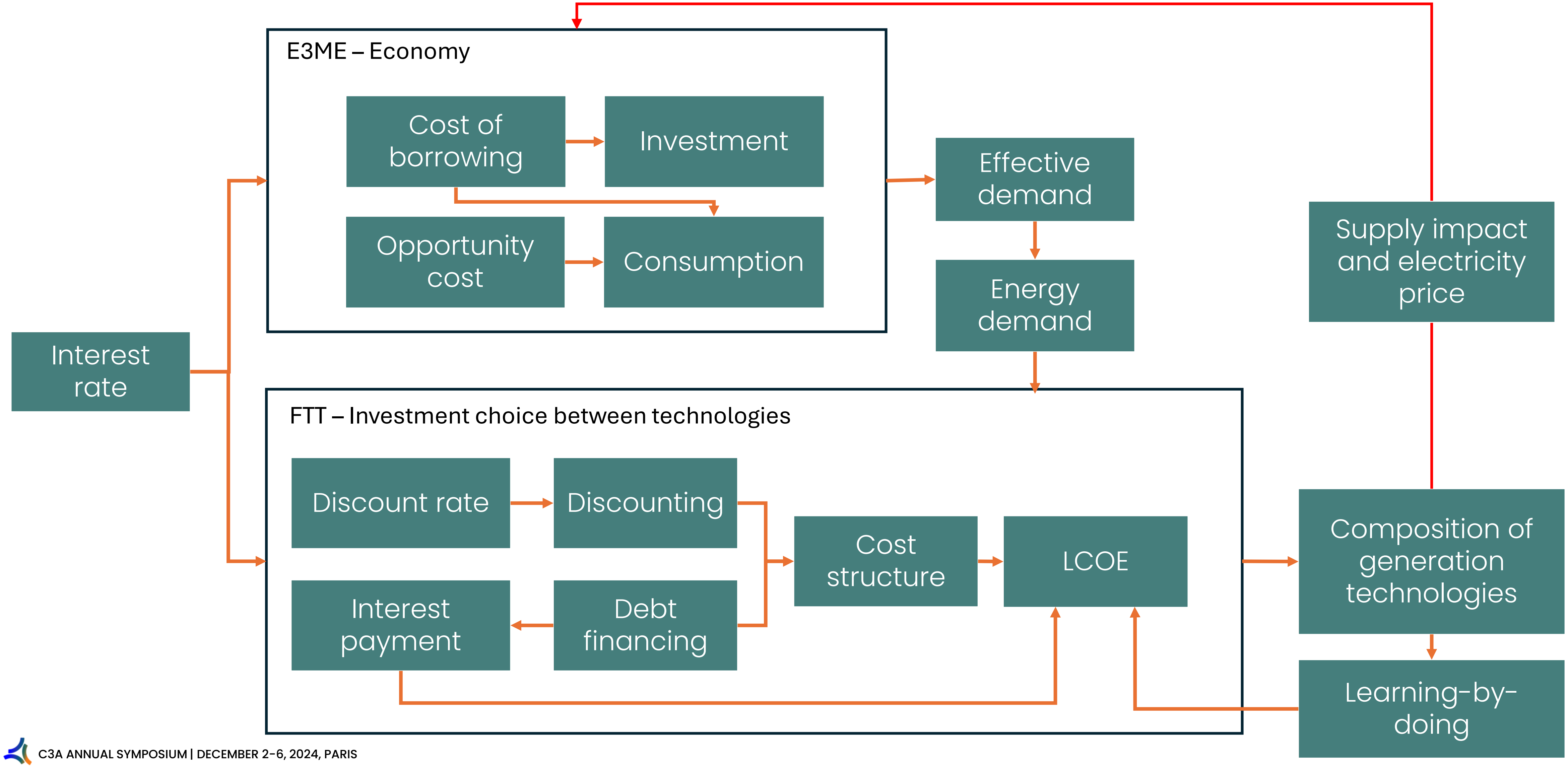
Investor costs minimisation

Technology i

Technology j

Technology composition

The interest rates effect in E3ME-FTT



E3ME – Economy

Cost of borrowing

Investment

Opportunity cost

Consumption

Effective demand

Energy demand

Supply impact and electricity price

Interest rate

FTT – Investment choice between technologies

Discount rate

Discounting

Cost structure

LCOE

Interest payment

Debt financing

Composition of generation technologies

Learning-by-doing

The cost equation in FTT:Power

Break-even

$$\frac{\mathit{Price} \cdot \mathit{Lifetime\ Electricity\ Production}}{\mathit{Discount\ Rate}} = \frac{\mathit{Lifetime\ Costs}}{\mathit{Discount\ Rate}}$$

Isolating the price (LCOE)

$$\mathit{Price} = \frac{\frac{\mathit{Lifetime\ Cost}}{\mathit{Discount\ Rate}}}{\frac{\mathit{Lifetime\ Electricity\ Production}}{\mathit{Discount\ Rate}}} = \frac{\frac{\mathit{Cost\ per\ unit}}{\mathit{Discount\ Rate}}}{\frac{1}{\mathit{Discount\ Rate}}}$$

With

$$\mathit{Cost\ per\ Unit} = \sum_{t=0}^{BT} (IT) + \sum_{BT}^{BT+LT} (OM + FC + CO2C)$$

and

$$IT = \left(\frac{IC}{BT \cdot CF \cdot 8766} \right)$$

Build time (BT)
Lifetime (LT)
Fuel costs (FC)
Capacity factor (CF)
Emission costs (CO2C)
CAPEX factor ($/kW) (IC)
Upfront investment component (IT)
Overhead and maintenance costs (OM)
Number of hours in a year (8766)

The impact of interests on costs

- Discounting
  - Δ interest rate → Δ discount rate
  - Dependent timing of costs
- Debt
  - Changes occurrence of cost
  - Δ interest rate → Δ debt cost

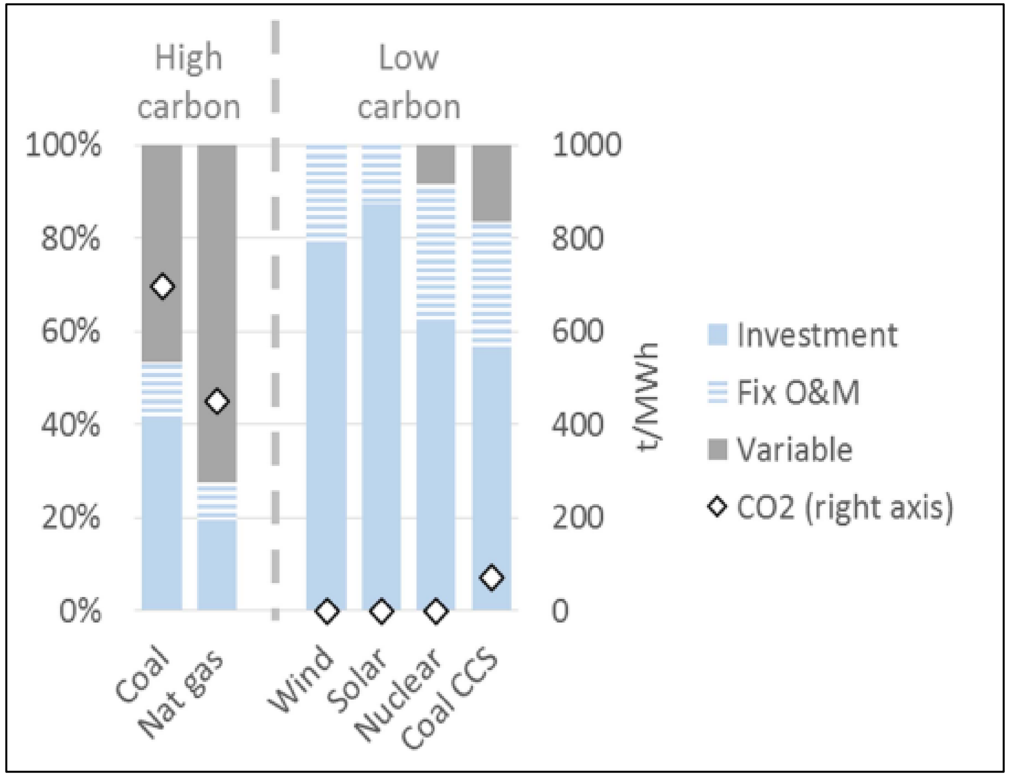


Figure 1: cost profile of energy technology projects (Hirth & Steckel, 2016)

Adjusted cost equation

LCOE with debt financing and interest rate changes adjusting discount rate and debt cost

$$LCOE = \frac{\dfrac{\sum_{t=0}^{BT}\left(IT \cdot (1-DR)\right) + \sum_{BT}^{BT+LT}(OM + FC + CO2C) + \sum_{t=0}^{n} DRP}{\sum_{t=0}^{BT+LT}(1+WACC)^{t}}}{\dfrac{1}{\sum_{t=0}^{BT+LT}(1+WACC)^{t}}}$$

Interest rate (i)
Loan period (n)
Cost of debt (CoD)
Debt repayment (DRP)

With

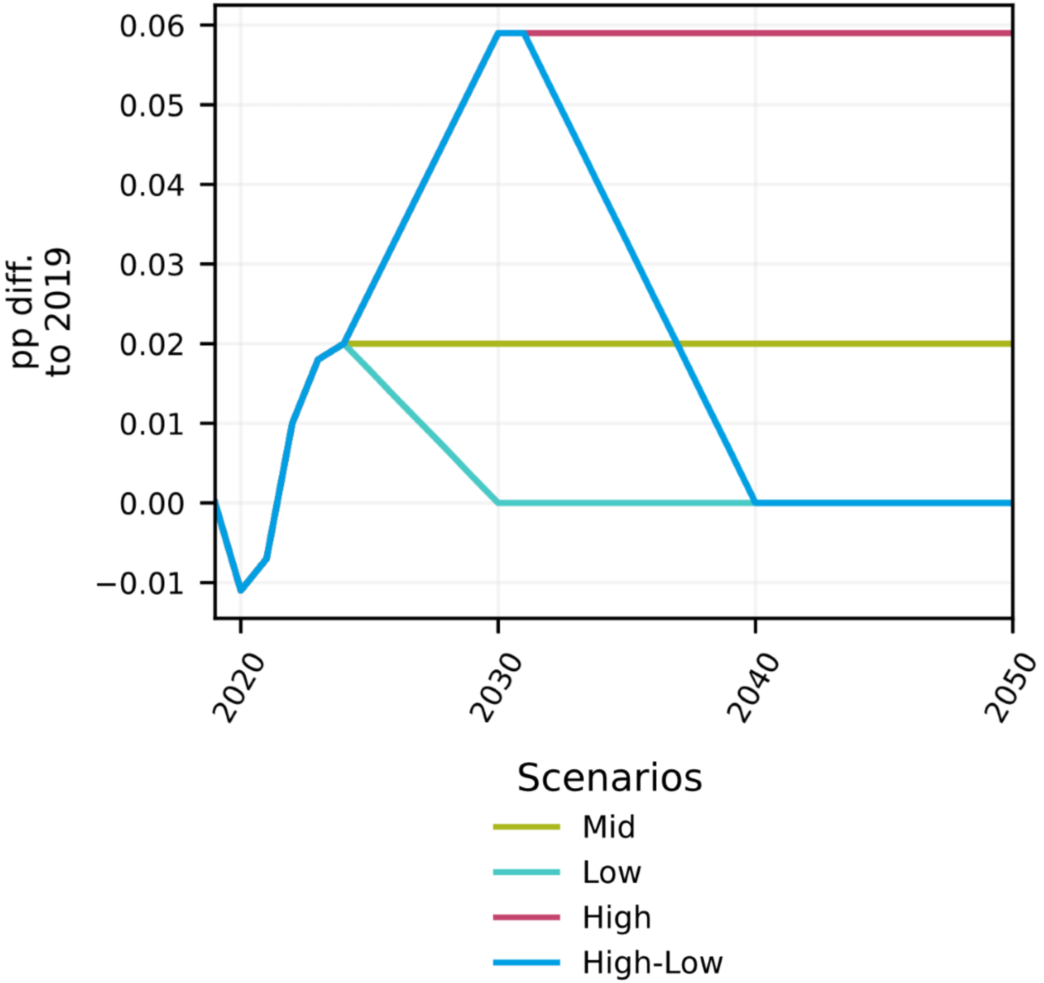
$$DRP = \left(\frac{IC}{CF \cdot 8766}\right) \cdot DR \cdot \left(\frac{(1+CoD)^{t}}{(1+CoD)^{t}-1}\right)$$ and $$WACC_t = i_t + Fixed\ Risk\ Premium$$

Assuming time independent risk premium

$$WACC_t = WACC_t + (i_t - i_0)$$

Interest rate scenarios

- **Mid:** Follow recent US trend up to 2024; static thereafter (reference scenario)
- **Low:** Follow recent US trend up to 2024 and after 2024 a return to 2019 values
- **High:** Follow recent US trend up to 2024 and after 2024 interest rates continue to increase until 2030; static thereafter
- **High-low:** Follow recent US trend up to 2024 and after 2024 interest rates continue to increase until 2030; followed by a decline to 2019 values by 2040; static thereafter



LCOE components

- **WACC**

  CAPEX/OPEX ratio; Response to interest rates
- **Debt repayment**

  Debt rate (CAPEX factor and load factor);

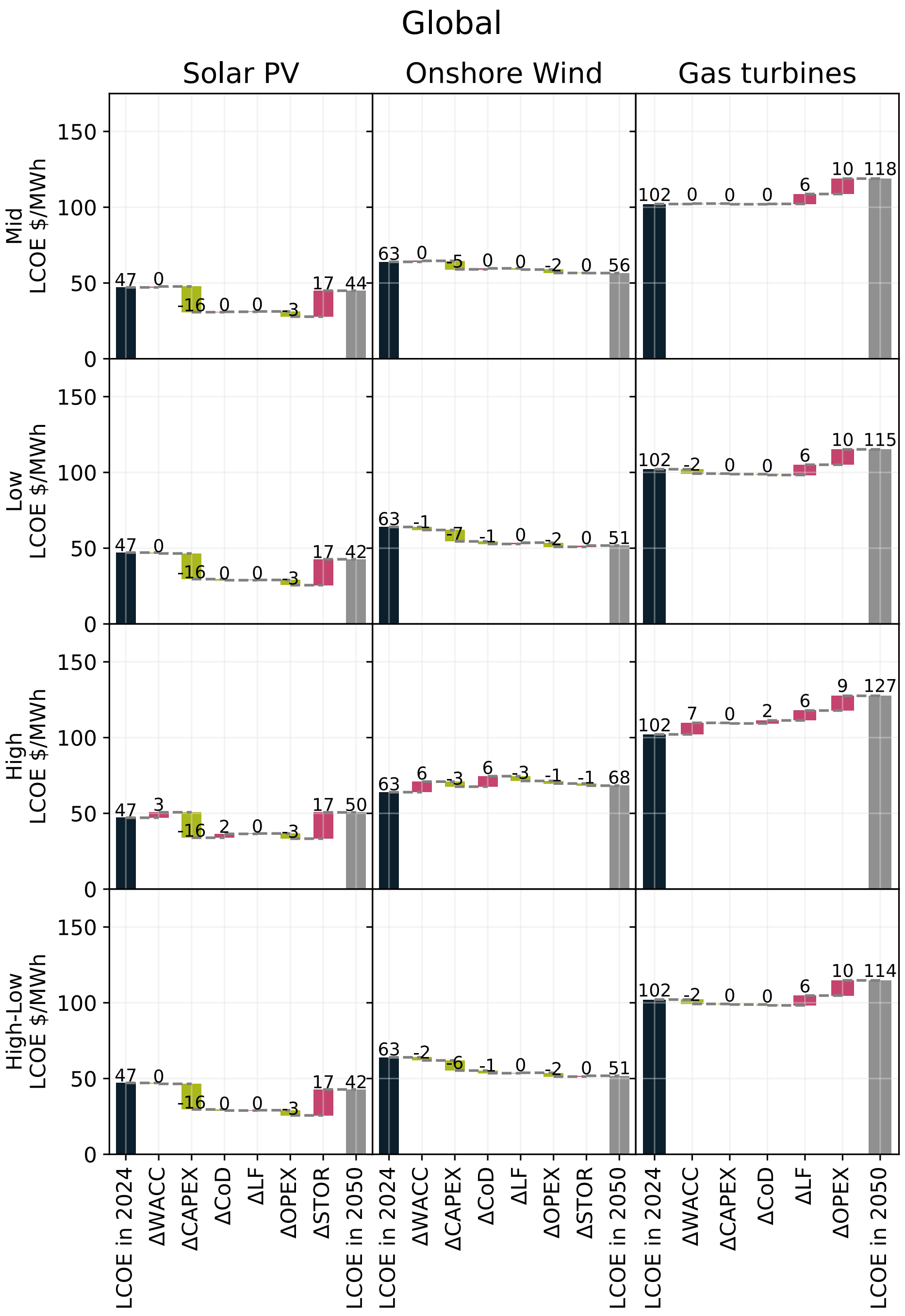
  Response to interest rates
- **CAPEX**

  LBD dependent on maturity of technology
- **Storage**

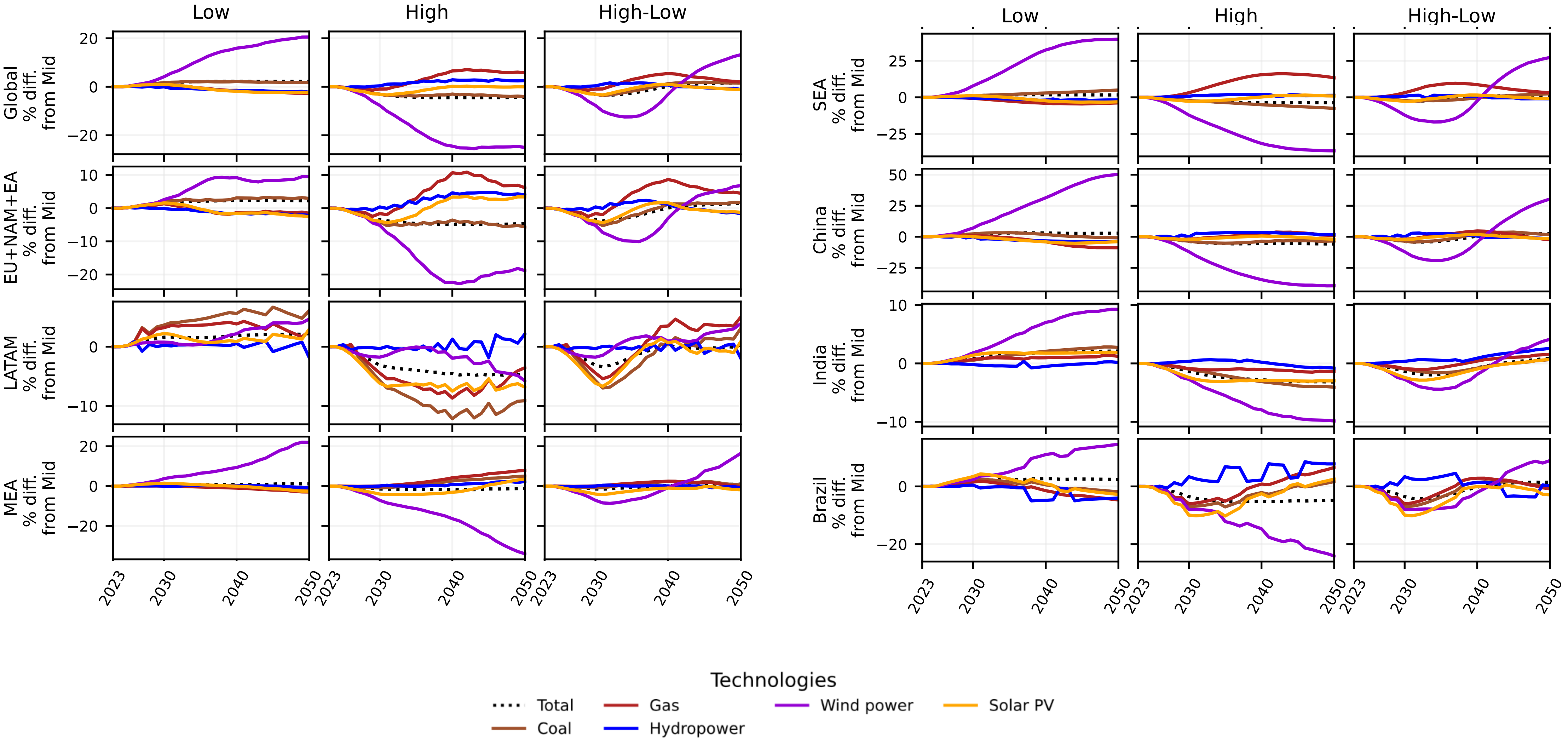
  Share VRE but complementarity effects for Wind

  power
- **OPEX**

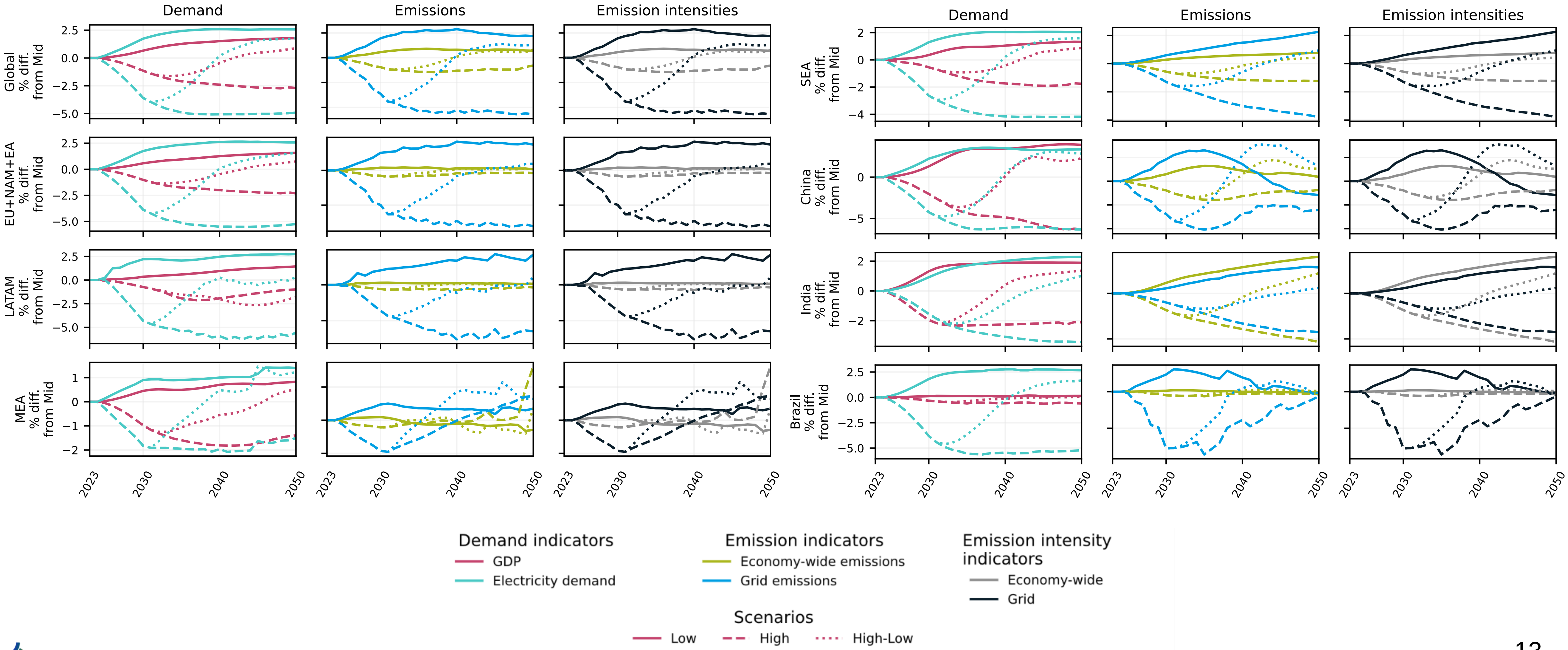
  LBD; fuel prices; ETS prices



Technology composition



Demand and emissions



Limitations

- Interest rates don't affect electrification process
- Cost-based investor decisions
- No exchange rate effect
- WACC data assumed to represent a reproducible financing condition
- Missing dynamics in discount rate
- Grid costs not included
- Missing new policies

Thank you

Discussion by Frédéric Ghersi

Paper outline

- Section 1 introduces to the research question: how do interest rates impact on the transition/on the deployment of transition capital in the power generation sector

- Section 2 presents the modelling implemented to address the question
  - The E3ME model and the FTT-Power technology-rich model coupled to it, in broad terms
  - The investment decision in FTT-Power based on the LCOE of competing technologies and how the interest rate influences the LCOE (is this original modelling development?)

- Section 3 presents modelling results for 4 scenarios of investment rate fluctuations
  - LCOEs, generation mix, electricity prices, ‘price level’ (CPI?), GDP and components, emissions (?)
- Section 4 concludes on 5 main findings and 4 limitations

Comments and questions

1. The research question may need clarifications: seems to be changes of interest rates of power generation investments only but then the introduction comes in potentially misleading too-broad terms

2. Or could the analysis be extended to adjustments of all (?) interest rates in E3ME?

3. Results appear descriptive, any normative conclusion from them that could find its way into the paper?

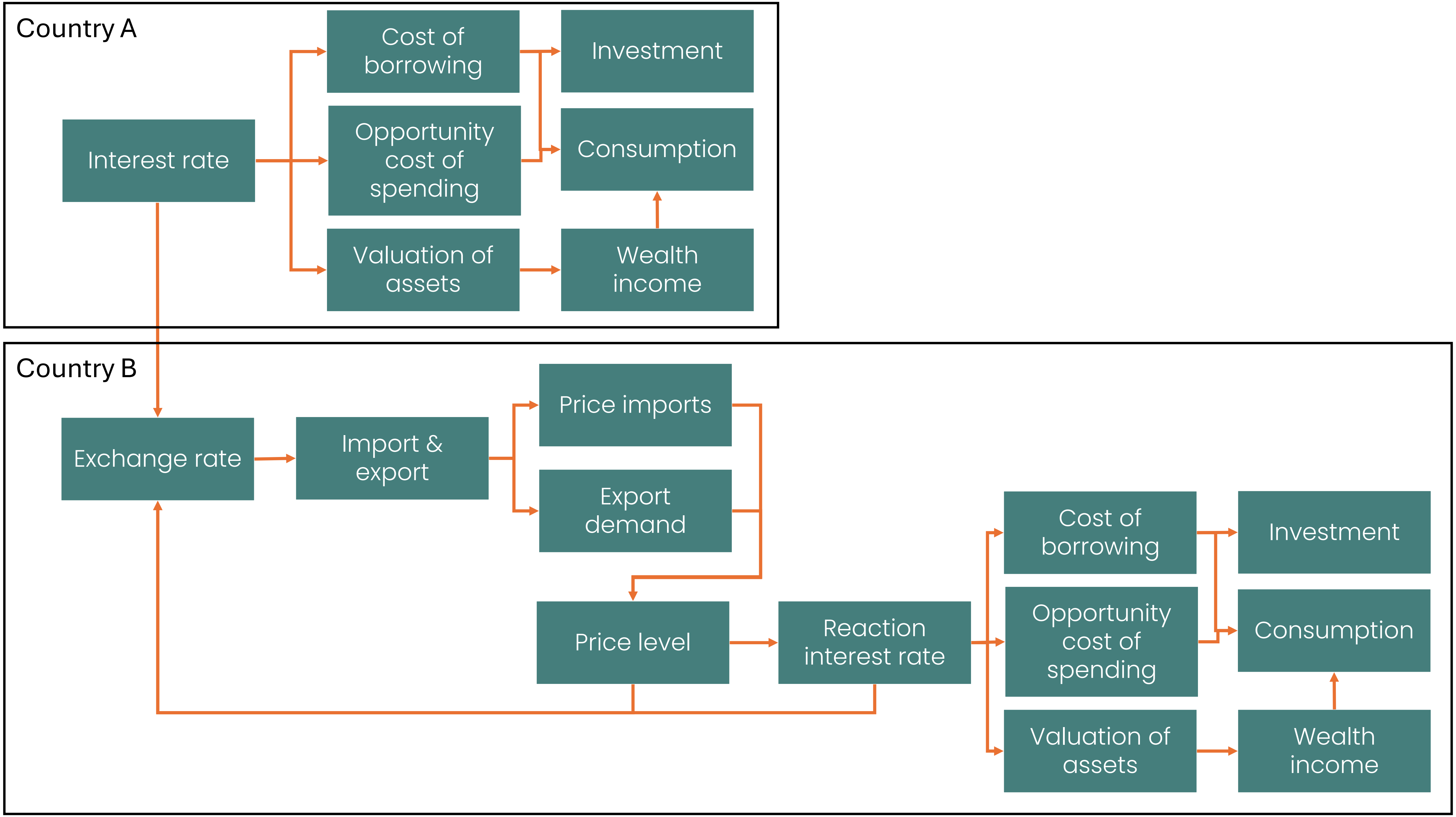
4. Fig. 6 reports impressive dominance of solar PV across global regions! Any insight on the supply chains backing that? Localisation? Required resources?

5. Finding 1 on how LBD dominates interest rate increase surely conditional to LBD, what are the rates? Those on solar PV based on past trends i.e. more cost reductions to come?

6. Limit 1 on the absence of feedback on exchange rates, how are these settled in E3ME? Would they not be impacted by changes of E3ME interest rates (link to question 2)?

7. One technical comment on Fig. 9: GDP disaggregation probably rest on valuation at calibration year prices, i.e. unchained Laspeyres price indexes; would be interesting to compare some variations with those obtained with chained Laspeyres or Fisher indexes

Appendix



Country A
Interest rate
Cost of borrowing
Opportunity cost of spending
Valuation of assets
Investment
Consumption
Wealth income
Country B
Exchange rate
Import & export
Price imports
Export demand
Price level
Reaction interest rate
Cost of borrowing
Opportunity cost of spending
Valuation of assets
Investment
Consumption
Wealth income

Background FTT

1. The share equations
2. LCOE
3. Learning-by-doing
4. Cost-Supply curve
5. Residual load duration curve
6. Capacity factor change

- 1.

1. The share equations

Lotka-Volterra equations

= which share of technology i goes to technology j, given the original shares (S), build time (BT), lifetime (LT) and comparison of the costs (F)

$$\Delta S_{j\to i} \propto \frac{S_i}{BT_i} \cdot \frac{S_j}{LT_j} \cdot F_{ij} \cdot \Delta t \qquad \Delta S_{i\to j} \propto \frac{S_j}{BT_j} \cdot \frac{S_i}{LT_i} \cdot F_{ji} \cdot \Delta t$$

Replicator function

= the change in the share of each technology derived from Lotka-Volterra equations

$$\Delta S_i = \sum_{j=1}^{N} S_i S_j \left[A_{ij}F_{ij} - A_{ji}F_{ji}\right]\Delta t \qquad \text{with} \qquad A_{ij} = \frac{K}{LT_j BT_i}$$

Preference matrix

= comparison of cost (LCOE) distributions in binary logit

$$F_{ij} = \frac{1}{1 + exp\left(\frac{C_j - C_i}{\sigma_{ji}}\right)} \qquad \sigma_{ji} = \sqrt{\sigma_i^2 + \sigma_j^2} \qquad F_{ij} + F_{ji} = 1$$

2. LCOE (1/2)

- 1. $Cost\ per\ Unit = IT + OM + FC + CO2C$ where $IT = \left(\frac{IC}{BT \cdot CF \cdot 8766}\right)$

Investment cost (IT)
Overhead and maintenance costs (OM)
Fuel costs (FC)
Emission costs (CO2C)
Number of hours in a year (8766)
Capacity factor: actual electrical energy output over a given period of time to the theoretical maximum electrical energy

3. Learning-by-doing

Experience curve

$$C_i(t) = C_{0,i}\left(\frac{W_i(t)}{W_{0,i}}\right)^{-b_i}$$

implicit $C_{0,i}$ and $W_{0,i}$

$$\Delta C_i = -b_i \frac{C_i}{W_i}\Delta W_i$$

Learning spillover

$$W_i(t) = \sum_j B_{ij} \begin{cases} \int_0^t \left(\frac{dU_j(t)}{dt} + \delta_j U_j(t)\right) dt & \frac{dU_j(t)}{dt} > 0 \\ \int_0^t \delta_j U_j(t) dt & \frac{dU_j(t)}{dt} \leq 0 \end{cases}$$

W_i number of units sold since first one came out of factory
U capacity in GW

4. Cost-Supply curves (1/2)

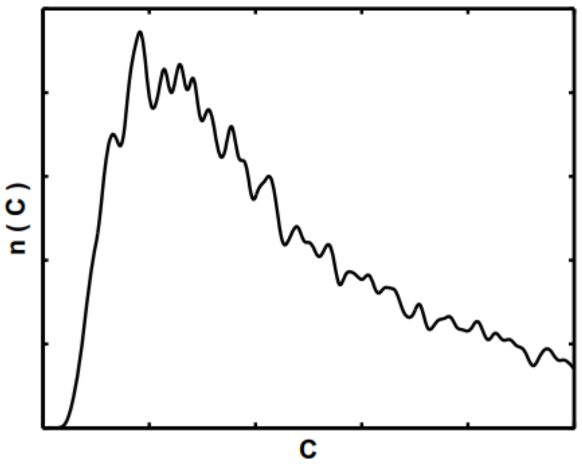
= Cost of extraction as function of cumulative amount of that have been extracted

Different impacts on different types of generation

- Non-renewable → fuel prices
- Wind and solar → capacity factor
- Hydro and geothermal → investment factors

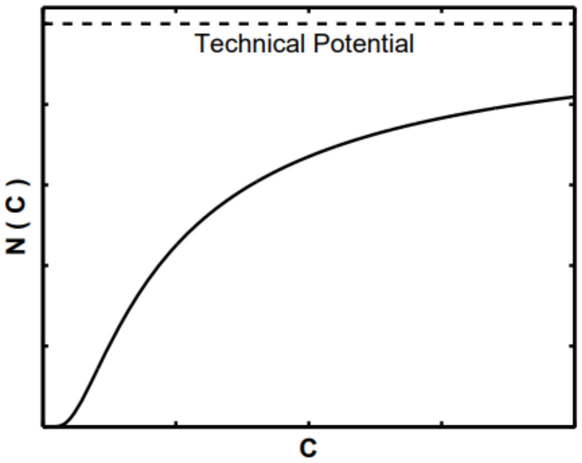
4. Cost-Supply curves (2/2)

Histogram of energy units as function of cost of extraction



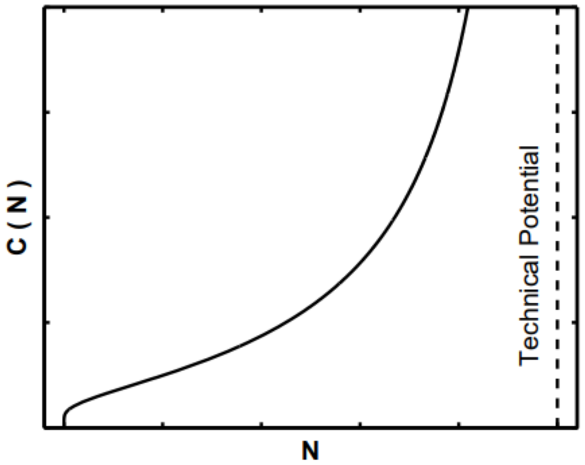
$$n(C) = \frac{AB}{C^2} e^{-\frac{B}{C-C_0}}$$

Cumulative distribution of energy units



$$N(C) = Ae^{-\frac{B}{C-C_0}}$$

Cost of extraction as function cumulative amount of units extracted



$$C(N) = \frac{B}{ln\left(\frac{N}{A}\right)} + C_0$$

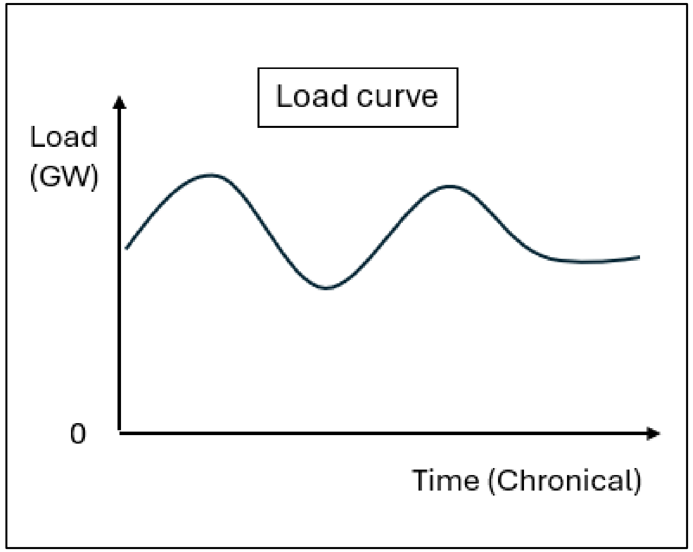
A: technical potential, the point where additional supply of energy leas cost to go hyperbolic
B: scales the cost supply curve
C_0: the initial cost

Assumption: perfect ordering in natural resource use and depletion

5. Capacity to generation (1/4)

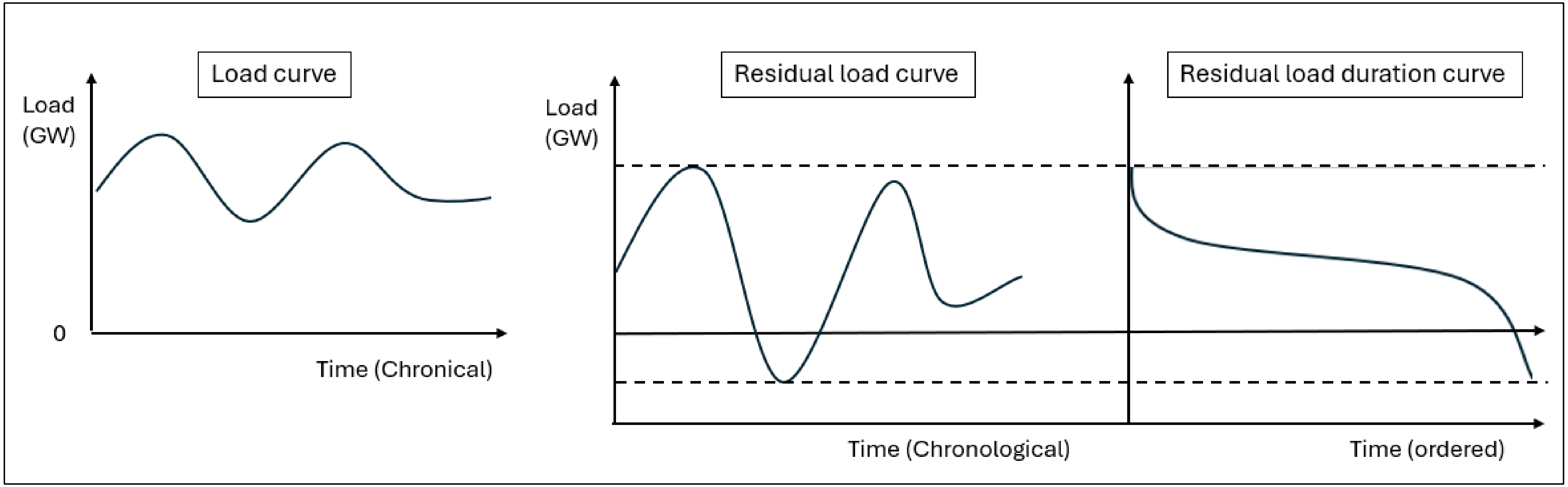
- When does capacity needs to be utilised to meet load demand?
- Answered by using Residual Load Duration Curve (RLDC)

- RLDC is constructed starting from load curve:



5. Capacity to generation (2/4)

Constructing RLDC

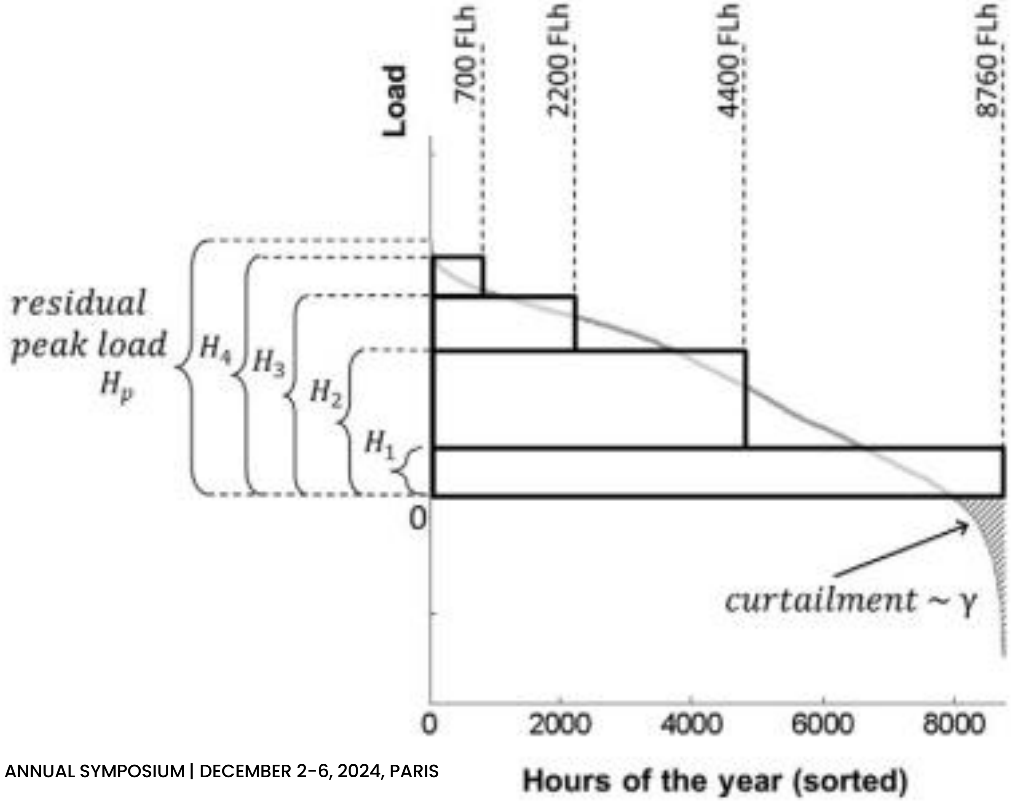


- Residual load curve = load curve – solar and wind generation
- Residual load duration curve: order load from high to low

5. Capacity to generation (3/4)

- From RLDC a third-degree polynomial is constructed
- Inputs: share of wind and solar in gross generation

$$f(\alpha, \beta) = a_{00} + a_{10}\alpha + a_{01}\beta + a_{20}\alpha^2 + a_{02}\beta^2 + a_{11}\alpha\beta + a_{21}\alpha^2\beta + +a_{12}\alpha\beta^2 + a_{30}\alpha^3 + a_{03}\beta^3$$



Returns: 1) curtailment rates, 2) short-term storage capacity, 3) short-term storage costs, 4) peak load band, 5) lower-mid load band, 6) mid load band, 7) upper-mid load band, and 8) base load band

5. Capacity to generation (4/4)

Gale-Shapley algorithm:

Mimic dispatching routine of grid operators who match supply and demand

Load bands from RLDC are matched to capacity market shares based on technology's suitability for load band and marginal cost

Long term storage: non-variable capacity – residual peak demand

6. Capacity factor change

For non-renewables

- Matching capacity to load demand leads to capacity factor
- Technical: RLDC and Gale-Shapley algorithm

For variable renewables

- Next unit probably build in less sunny or windy place
- Inverse cost-supply curve gives capacity of new plant

For base load

- More fixed but like non-renewables
- Technical: RLDC and Gale-Shapley algorithm

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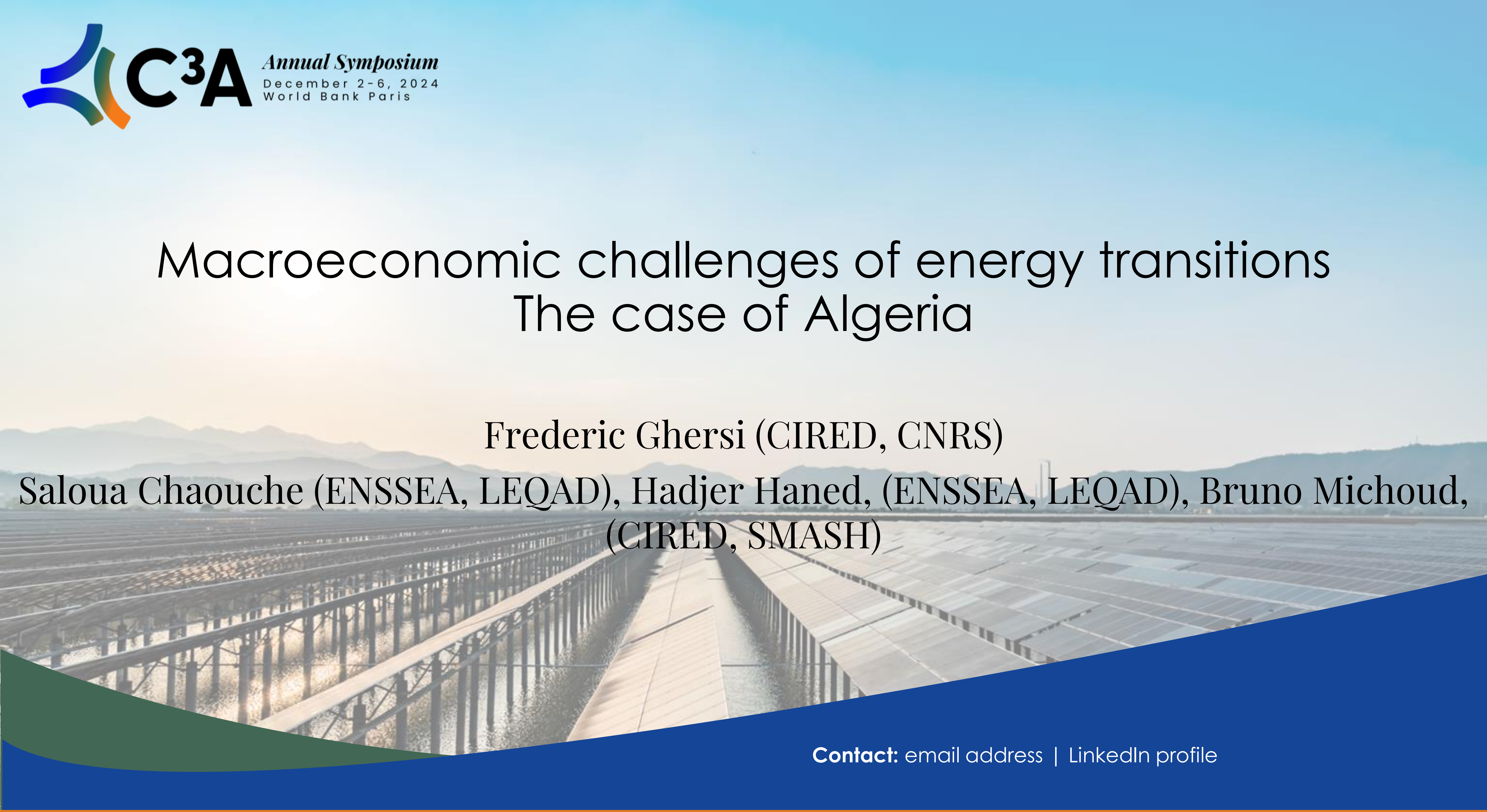


Macroeconomic challenges of energy transitions
The case of Algeria

Frederic Ghersi (CIRED, CNRS)
Saloua Chaouche (ENSSEA, LEQAD), Hadjer Haned, (ENSSEA, LEQAD), Bruno Michoud, (CIRED, SMASH)

Contact: email address | LinkedIn profile

Table of contents

1

Algeria on a fossil-based development path

Algeria on a fossil-based development path

Dependency on fossil fuels

Oil and gas sector 21% of GDP over 2018-2021

Oil and gas 96% of exports over 2018-2021

Oil and gas 99% of domestic primary energy consumption in 2021

An economic model at risk

Depletion of conventional resources, mature wells

Increasing domestic energy demand, low energy efficiency

Short-term benefit from unstable geopolitics, but climate risk

Macroeconomic context

Growing at 3.6% with trade surplus at 11.3% GDP but

Unemployment 11.6% in 2022 (among youth at around 60%)

Without oil and gas trade deficit of 12.4% GDP

Yet, with strong potential for an energy transition

Renewable energy sources (RES) and energy efficiency (EE)

Solar, wind, biomass, geothermal resources abundant and economically viable

Significant energy efficiency opportunities in the energy, building, industry and waste management sectors

Reinforced legislation and regulation, national energy plan

Market and non-market mechanisms: financial support, tax incentives, FIT, auctions, etc.

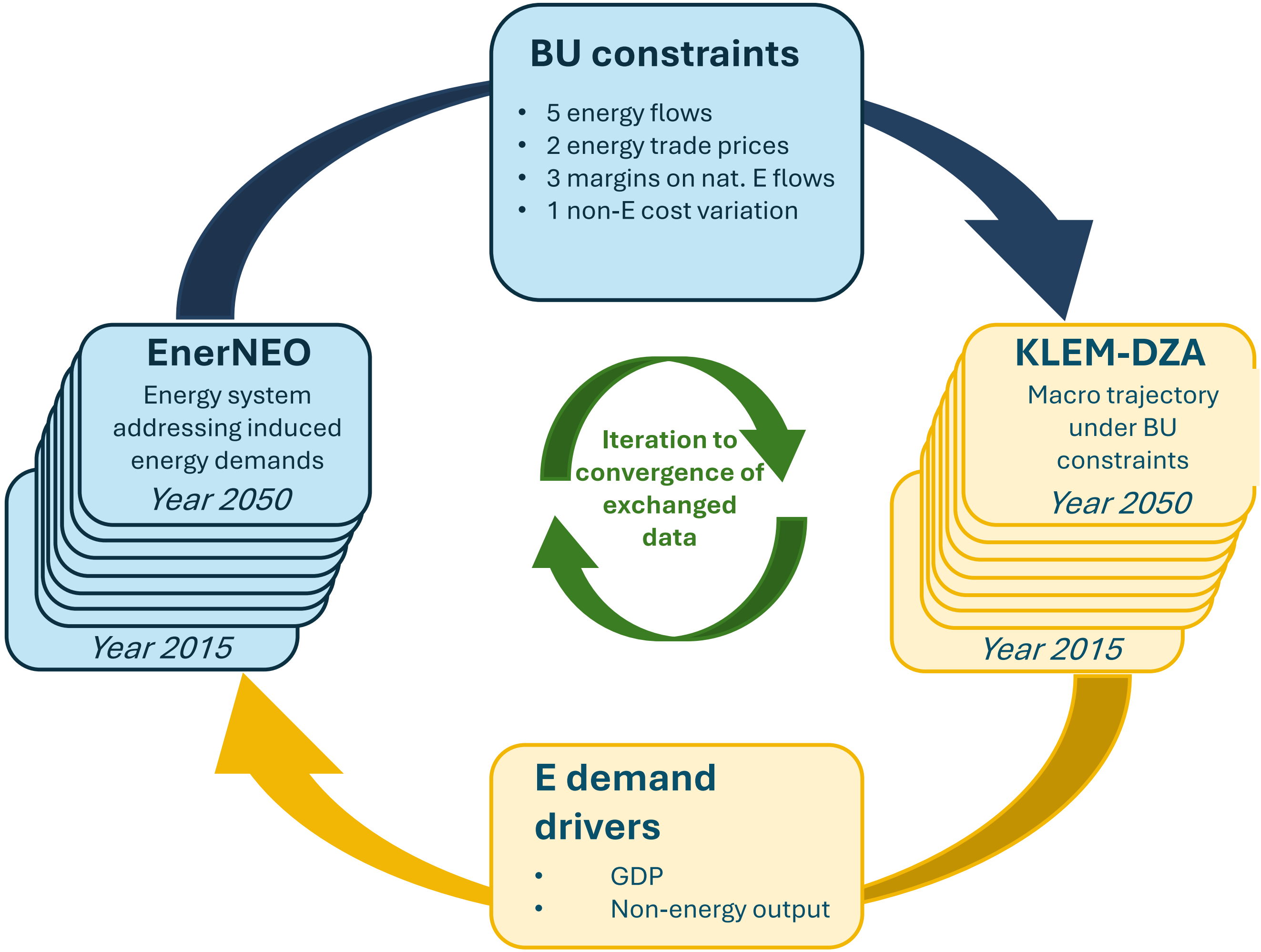
Energy Transition Plan: 30% RES in power generation by 2030; 10% annual energy efficiency improvements (industry, housing); 25 GWh of power from blue and green hydrogen by 2050

ective: assess macroeconomic implications of energy systems evoluti

2

Methods

Method: Hard-coupling bottom-up & top-down modelling



BU constraints

- 5 energy flows
- 2 energy trade prices
- 3 margins on nat. E flows
- 1 non-E cost variation

EnerNEO

Energy system addressing induced energy demands

Year 2050

Year 2015

Iteration to convergence of exchanged data

KLEM-DZA

Macro trajectory under BU constraints

Year 2050

Year 2015

E demand drivers

- GDP
- Non-energy output

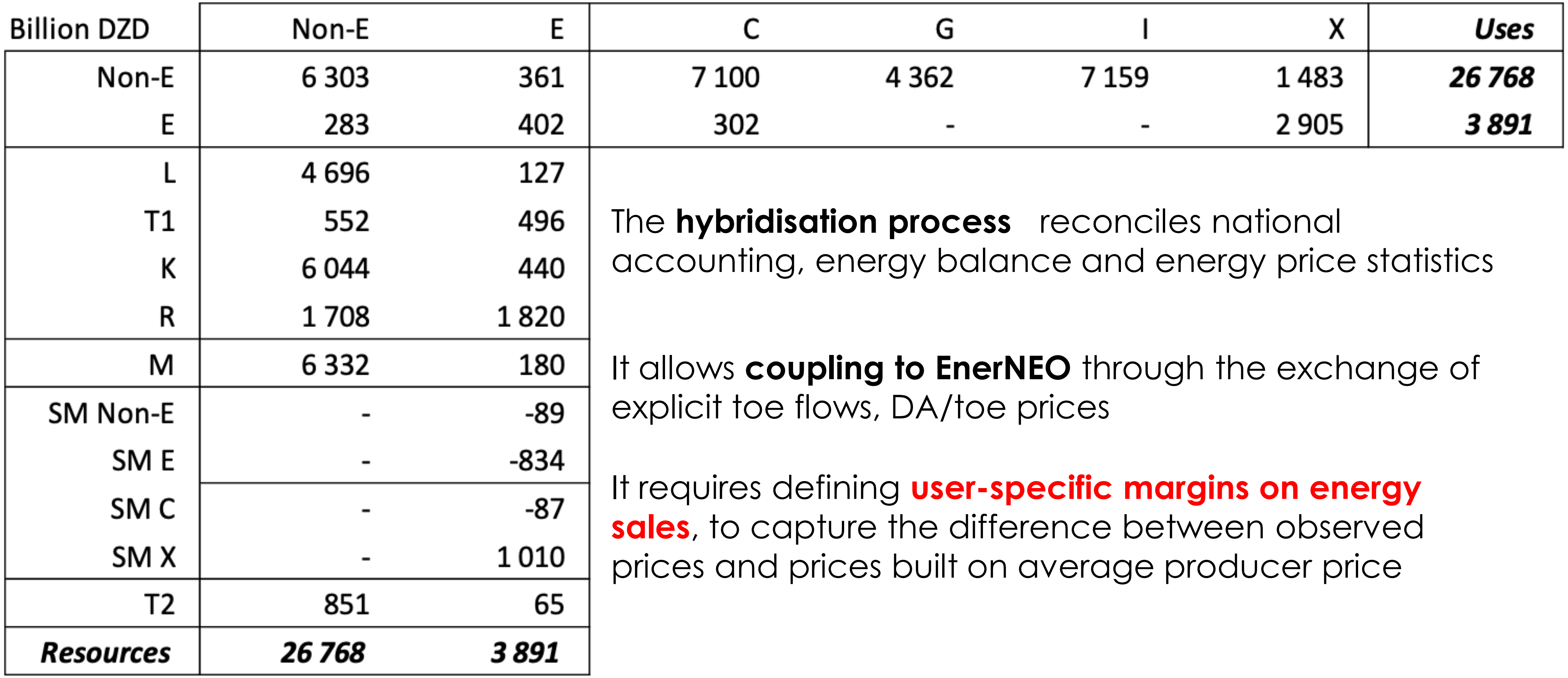
EnerNEO

- Dynamic recursive BU energy model
- 15 end-use demands for 9 energy vectors
- Exogenous fossil production
- Detailed description of power generation and hydrogen production

KLEM-DZA

- Dynamic recursive TD macroeconomic model, 2 factors K & L, 2 sectors E & 'M'
- Exogenous E supply and demand
- Neo-Keynesian version with rigid wages, exogenous investment and trade balance (endogenous domestic savings)
- 'Dynamic calibration' to observed GDP, unemployment and REER 2016-2022

Prerequisite: hybrid IOT at calibration year 2015



Billion DZD	Non-E	E	C	G	I	X	*Uses*
Non-E	6 303	361	7 100	4 362	7 159	1 483	***26 768***
E	283	402	302	-	-	2 905	***3 891***
L	4 696	127					
T1	552	496					
K	6 044	440					
R	1 708	1 820					
M	6 332	180					
SM Non-E	-	-89					
SM E	-	-834					
SM C	-	-87					
SM X	-	1 010					
T2	851	65					
Resources	***26 768***	***3 891***					

The **hybridisation process** reconciles national accounting, energy balance and energy price statistics

It allows **coupling to EnerNEO** through the exchange of explicit toe flows, DA/toe prices

It requires defining **user-specific margins on energy sales**, to capture the difference between observed prices and prices built on average producer price

3

Scenario description

Main assumptions and scenario description

Common to 4 scenarios

Potential growth from IPCC SSP2 GDP (REMIND) and active (20-69) population growth

Investment effort 31.1% of GDP (2022-2050)

Trade balance soft landing from +11.3% in 2022 to equilibrium from 2030 on

Successful diversification modelled as stabilisation of the unemployment rate from 11.6% in 2020 to 5% from 2030 through **positive non-price**


Four evolutions of the energy sector

REFERENCE

No unconventional resources, limited RES

Past demand trends extended

BROWN

Unconventional gas and oil

Past demand trends extended

BLUE

1/2 unconventional gas and oil, increased RES

Decreased energy demand

GREEN

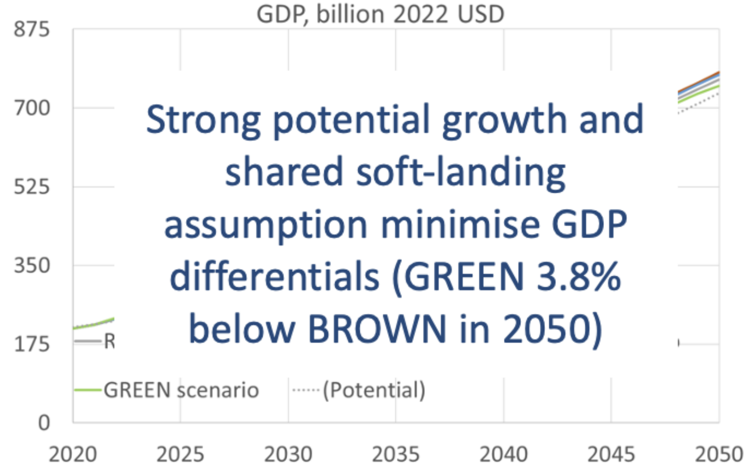
Accentuated BLUE w/o unconventional

Paris Agreement compatible?

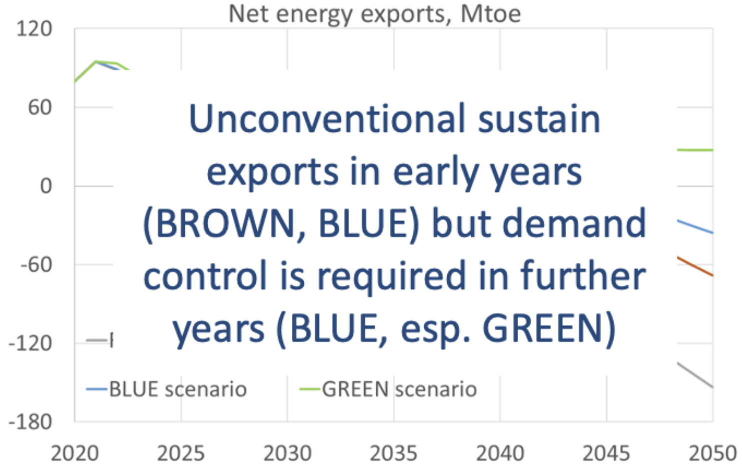
4

Results

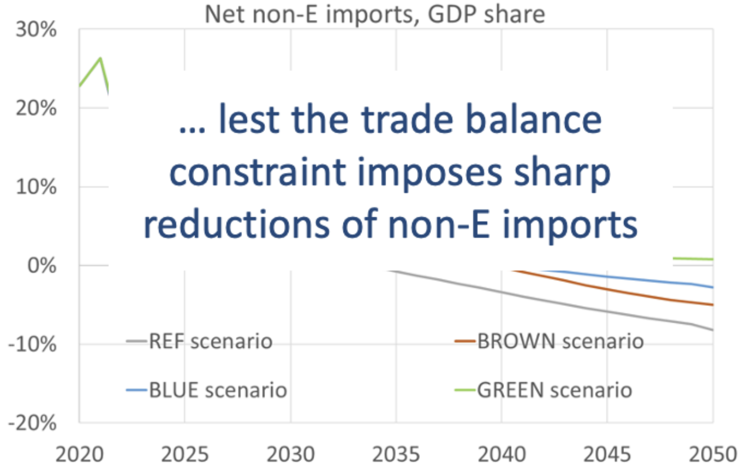
Results under successful economic transformation



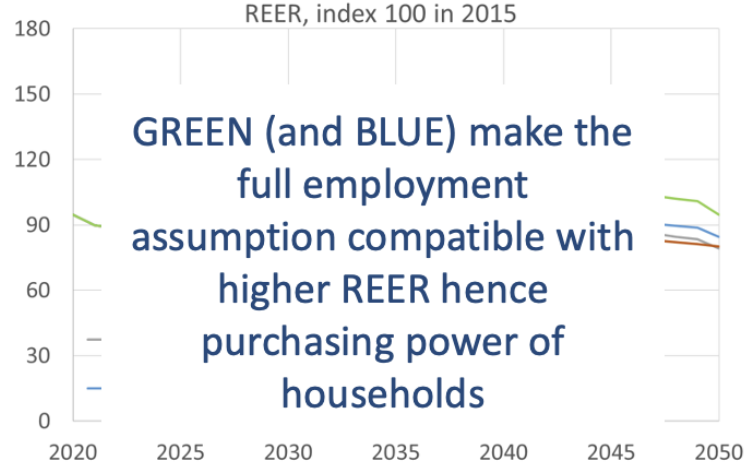
Strong potential growth and shared soft-landing assumption minimise GDP differentials (GREEN 3.8% below BROWN in 2050)



Unconventional sustain exports in early years (BROWN, BLUE) but demand control is required in further years (BLUE, esp. GREEN)

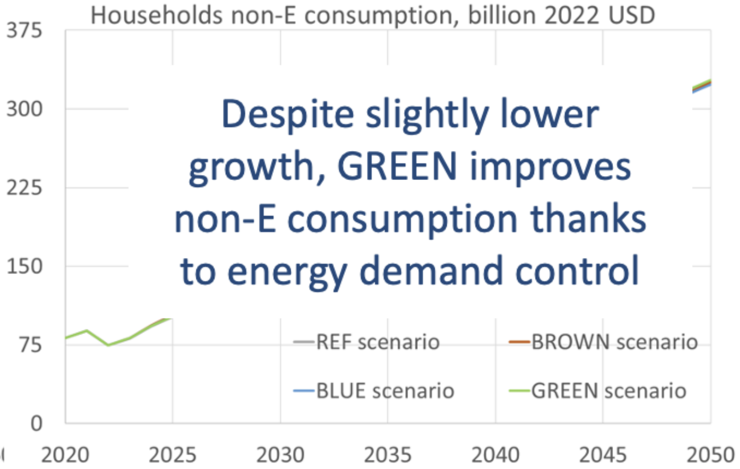


… lest the trade balance constraint imposes sharp reductions of non-E imports



GREEN (and BLUE) make the full employment assumption compatible with higher REER hence purchasing power of households

GREEN requires slightly stronger diversification effort in the medium term, but manages to cap it after 2040 when BROWN accelerates it



Despite slightly lower growth, GREEN improves non-E consumption thanks to energy demand control

5

Conclusion

Conclusion

Inability to shape scenarios that would leave the oil & gas rent in the ground!

- With successful economic transformation, the macroeconomic benefits of the energy transition (weaker BLUE or stronger GREEN forms) are clear compared to the extension of past trends (REFERENCE)
    - Energy demand control allows reaping more rent on international markets rather than losing it on domestic markets with administered prices close to costs
    - Delayed pressure on the current account buys time for the unescapable diversification (import substitution) policies: 9 to 12 years under current assumptions, probably more in updated runs with differentiation of rent from hydrogen exports

- Less clear benefits when compared with BROWN unconventional hydrocarbon exploitation scenario
    - Short-term import substitution more demanding in BLUE and esp. GREEN than in BROWN
    - Tipping point in 2045 when BROWN exports run down, BLUE and esp. GREEN start dominating
    - Environmental performance! 2050 CO_2 emissions 33%/66% below BROWN scenario in BLUE/GREEN scenario

Thank you for your attention

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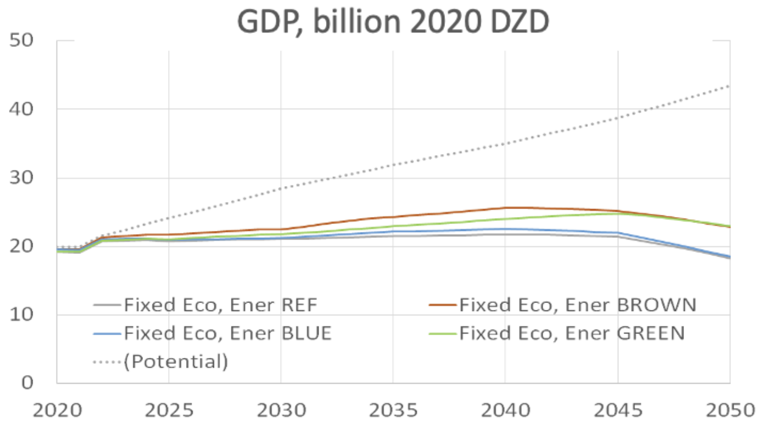
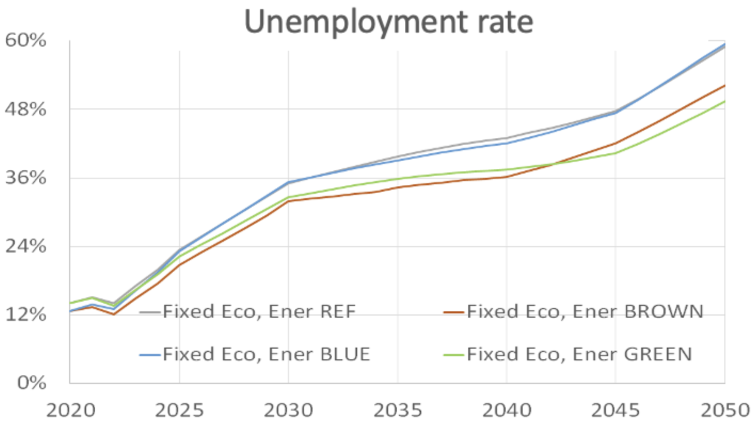
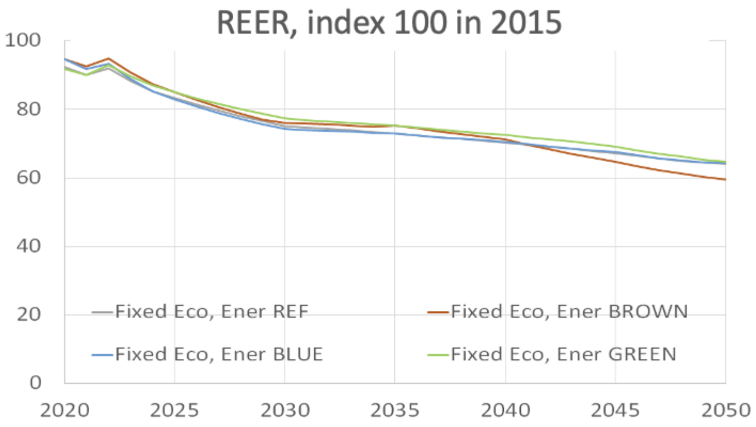
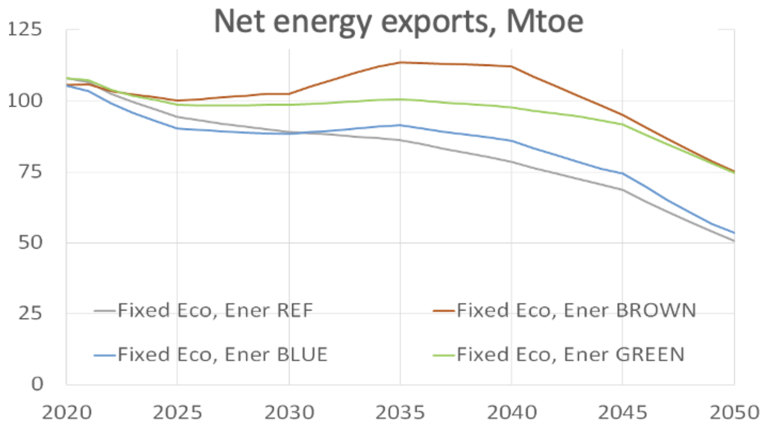
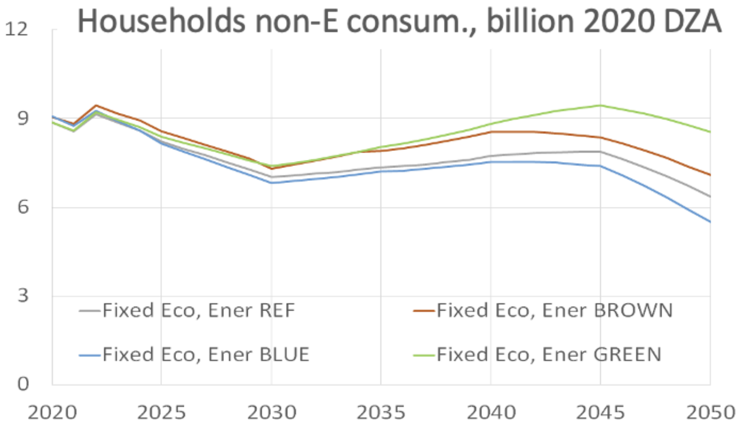
Results under inertia of the economic system

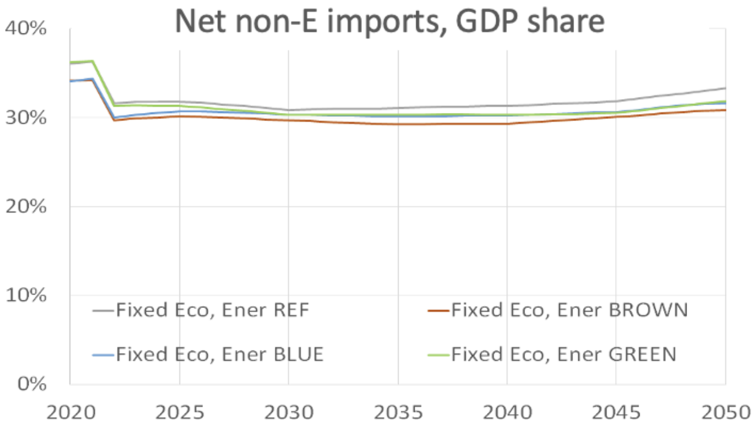

GDP, billion 2020 DZD


Unemployment rate


REER, index 100 in 2015


Net energy exports, Mtoe


Households non-E consum., billion 2020 DZA


Net non-E imports, GDP share

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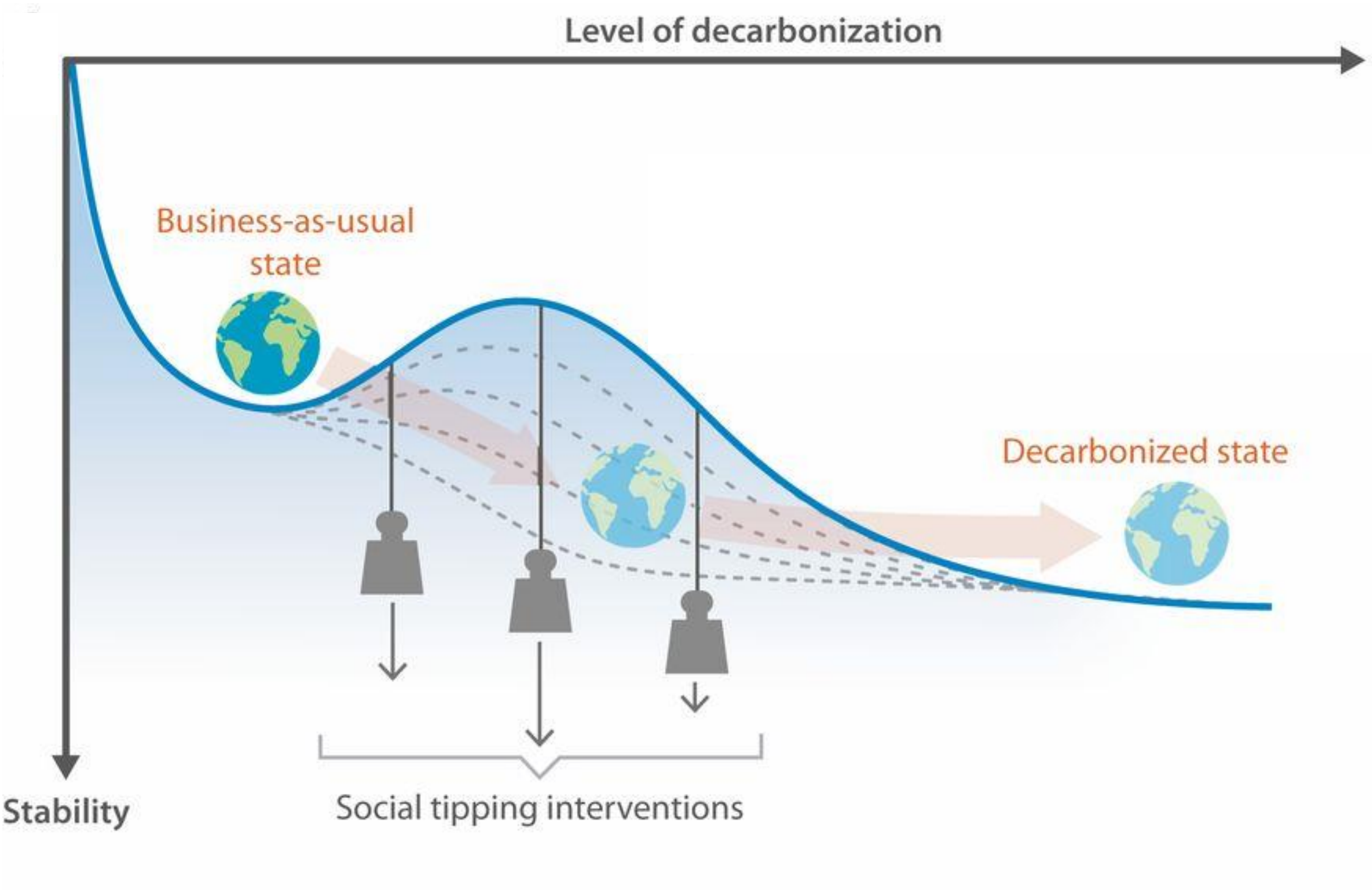
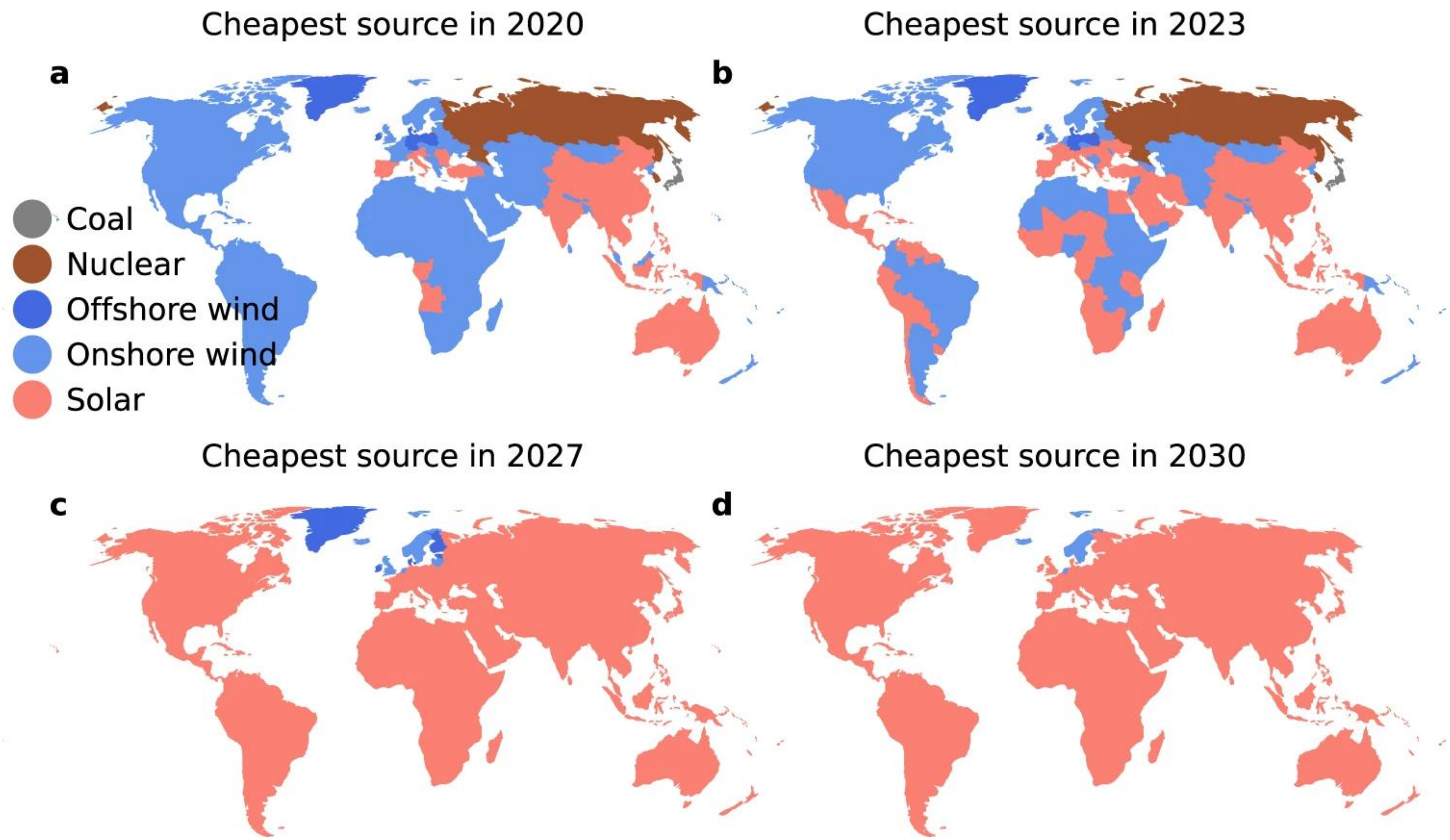
A positive tipping cascade in power, transport and heating

Femke Nijsse, Simon Sharpe, Rishi Sahastrabuddhe, Tim Lenton

Contact: t.m.lenton@exeter.ac.uk

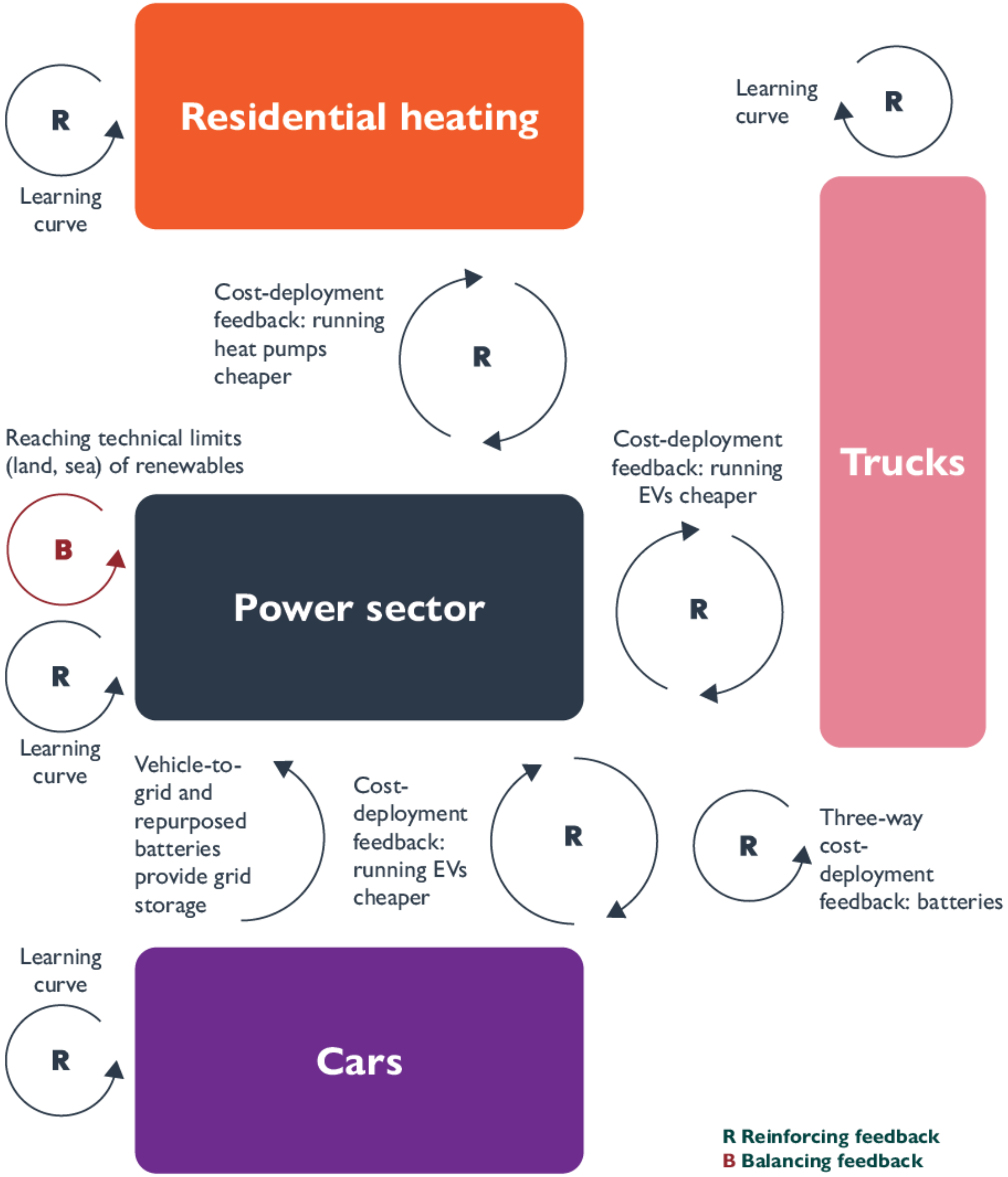

Level of decarbonization
Business-as-usual state
Decarbonized state
Stability
Social tipping interventions

Levelized cost of electricity

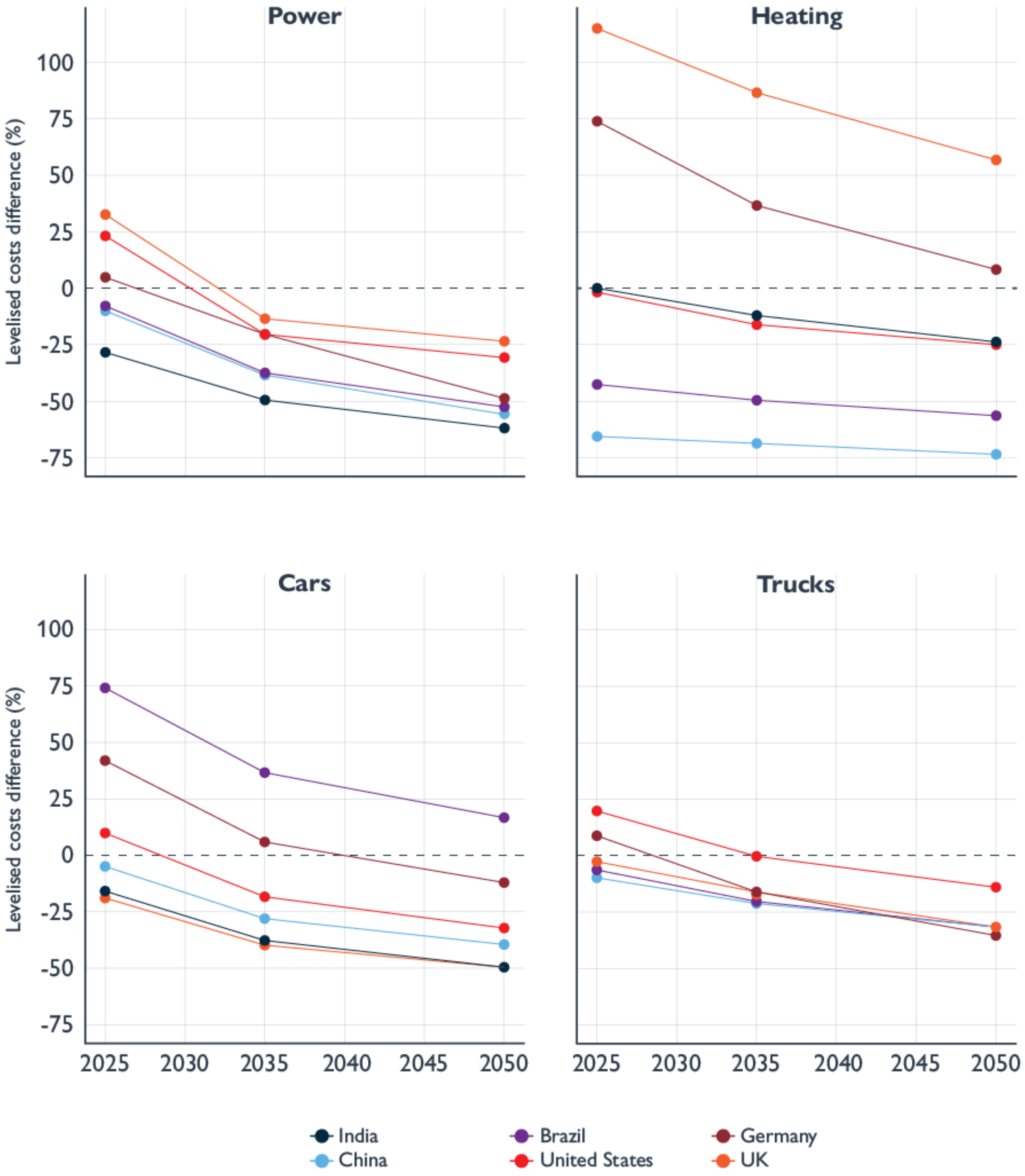


Nijsse et al. (2023) *Nature Communications*

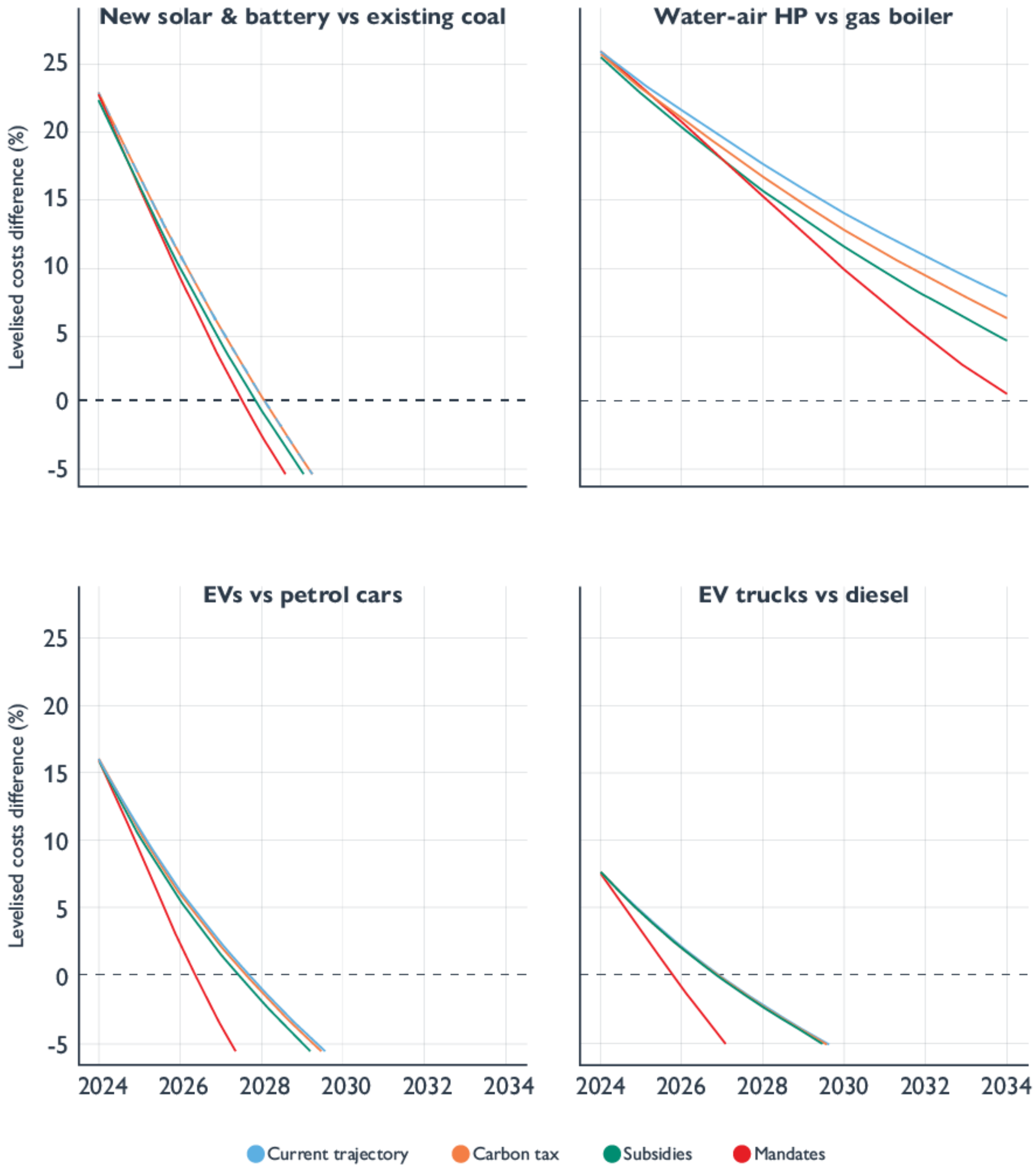
Sectoral coupling

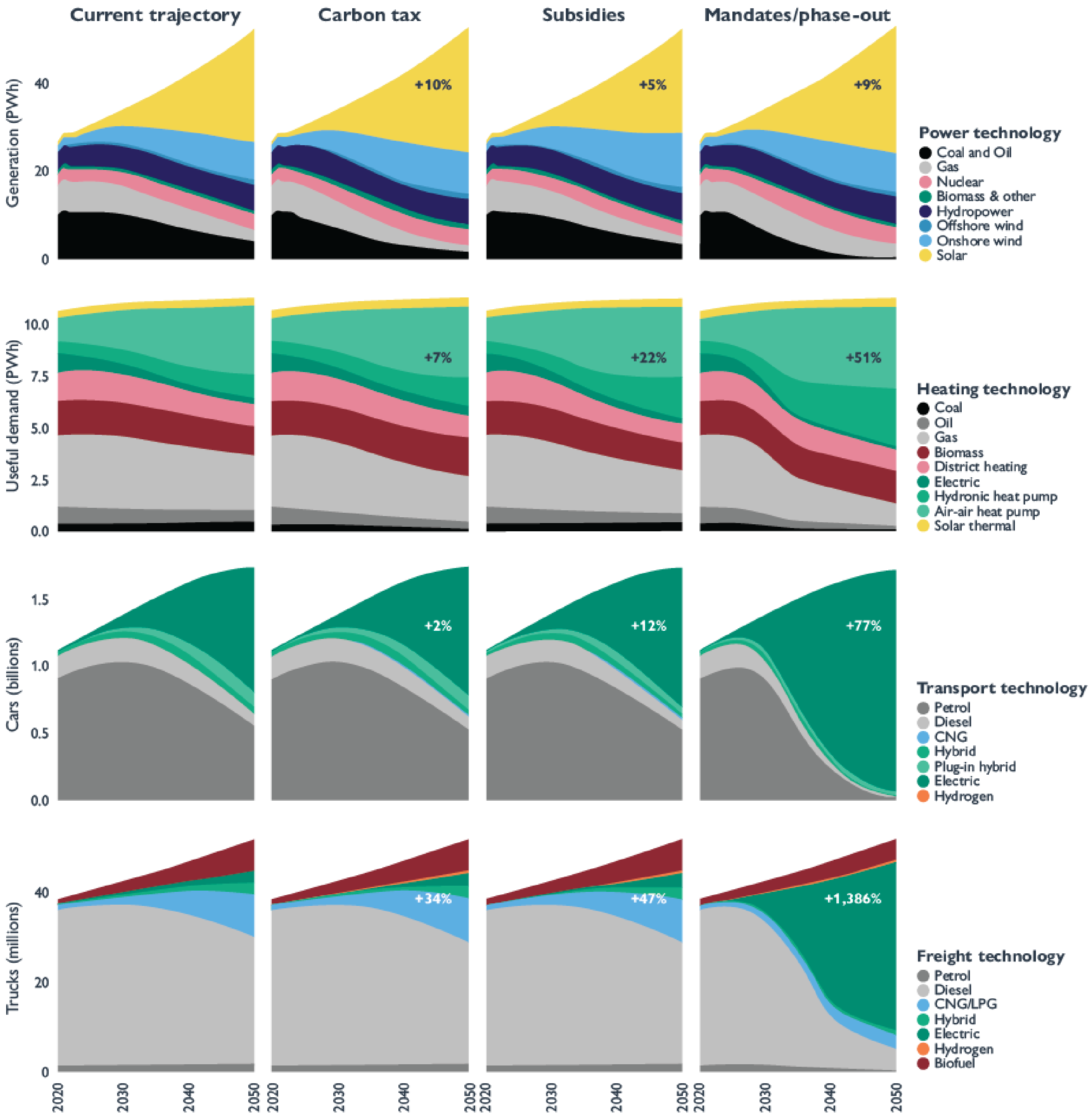


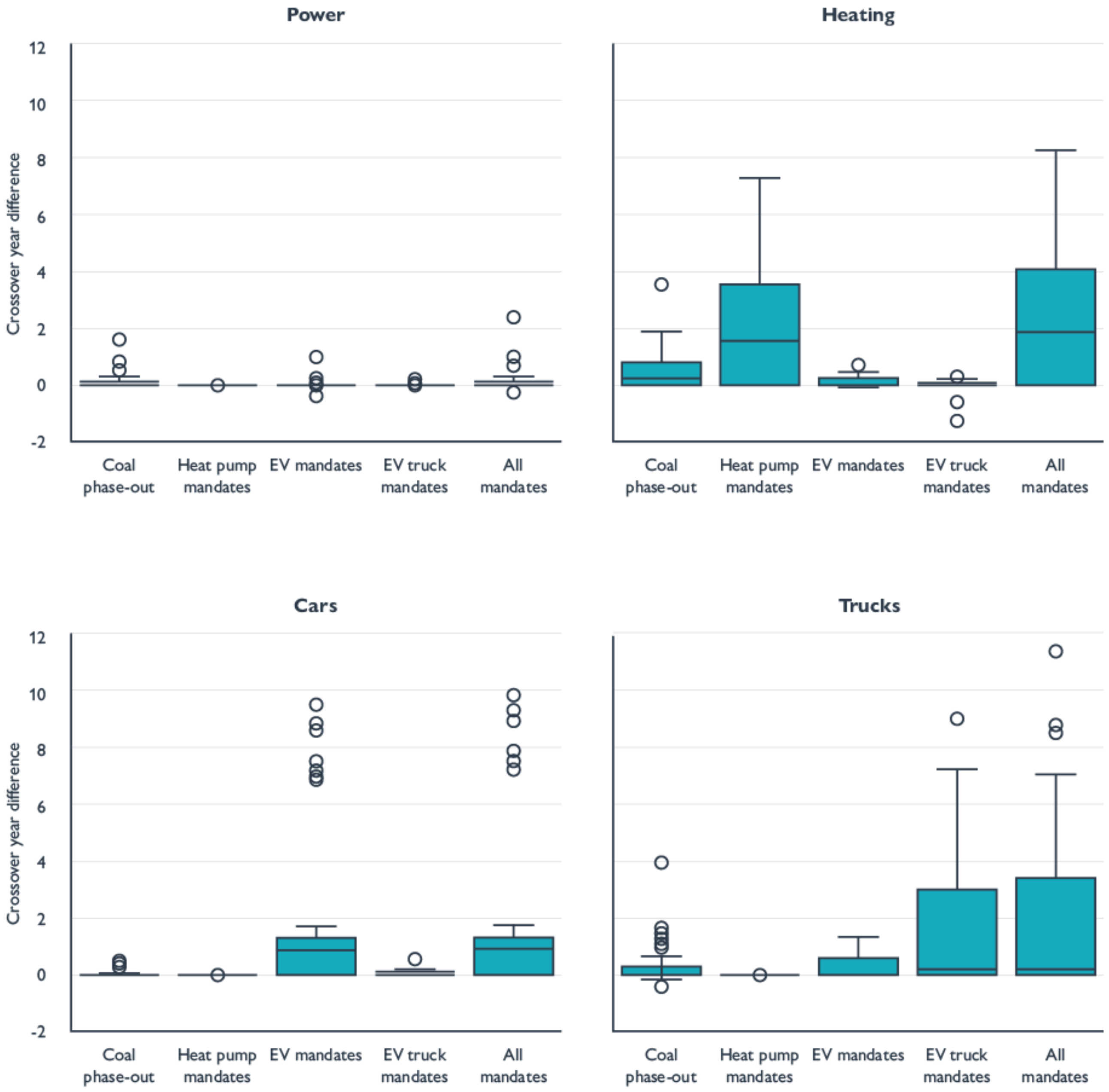
Effect of current policies



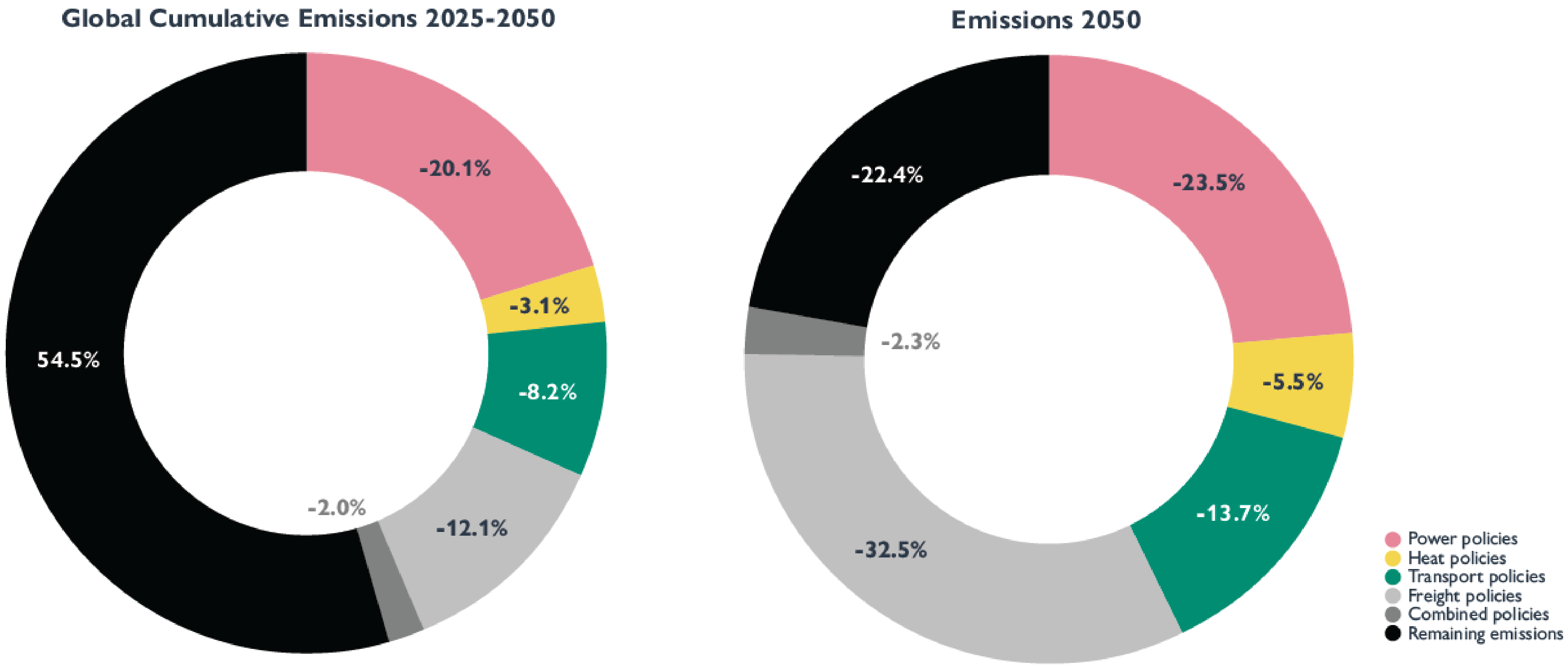
Effect of extra policies




Current trajectory
Carbon tax
Subsidies
Mandates/phase-out
Generation (PWh)
0
20
40
+10%
+5%
+9%
Power technology
Coal and Oil
Gas
Nuclear
Biomass & other
Hydropower
Offshore wind
Onshore wind
Solar
Useful demand (PWh)
0.0
2.5
5.0
7.5
10.0
+7%
+22%
+51%
Heating technology
Coal
Oil
Gas
Biomass
District heating
Electric
Hydronic heat pump
Air-air heat pump
Solar thermal
Cars (billions)
0.0
0.5
1.0
1.5
+2%
+12%
+77%
Transport technology
Petrol
Diesel
CNG
Hybrid
Plug-in hybrid
Electric
Hydrogen
Trucks (millions)
0
20
40
+34%
+47%
+1,386%
Freight technology
Petrol
Diesel
CNG/LPG
Hybrid
Electric
Hydrogen
Biofuel
2020
2030
2040
2050

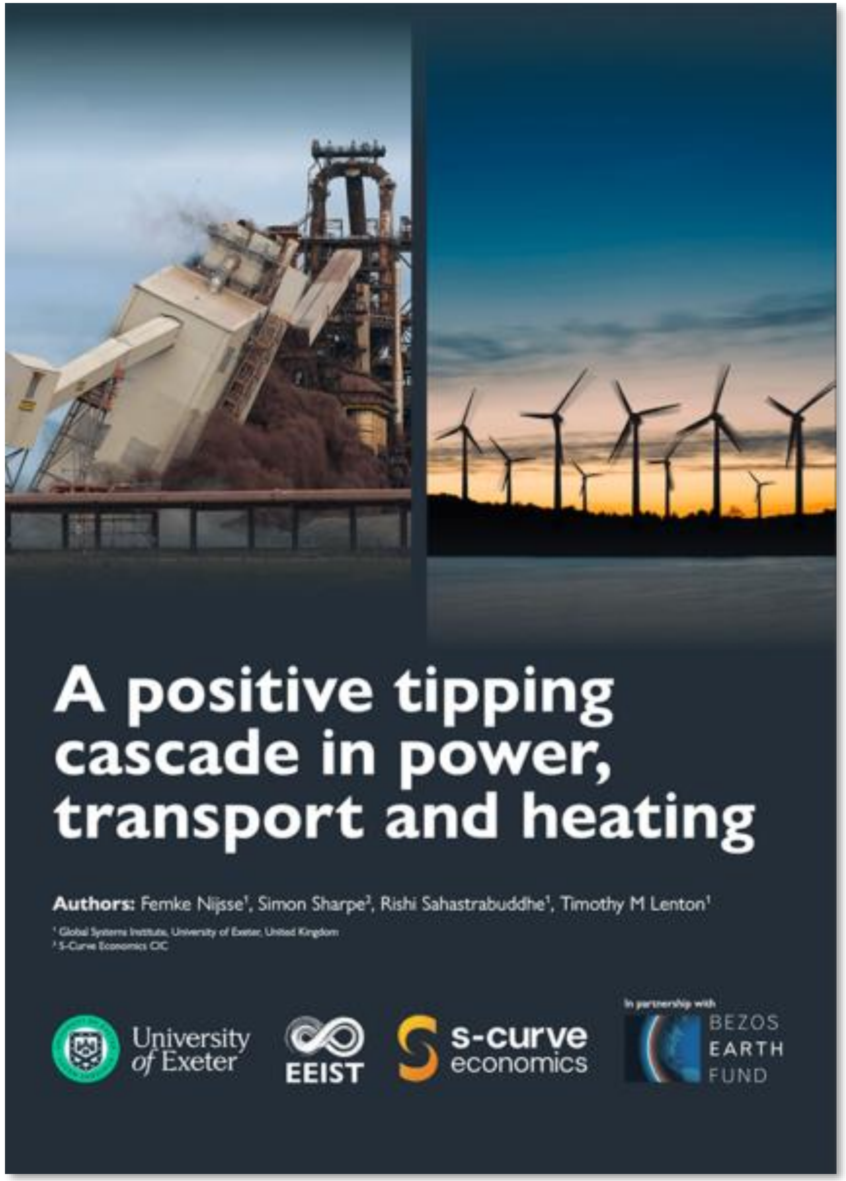

Power
Heating
Cars
Trucks
Crossover year difference
12
10
8
6
4
2
0
-2
Coal phase-out
Heat pump mandates
EV mandates
EV truck mandates
All mandates

Effect on emissions



Key messages

- Regulatory mandates are the most powerful policies for bringing forward positive tipping points.
- Mandates can bring forward tipping points in the power, transport and heating sectors by up to 3 years globally, significantly more than carbon prices or subsidies.
- Policies to advance the transition in one sector also tend to bring forward positive tipping points in other sectors.
- A coal phaseout policy brings forward positive tipping points in the heating and heavy road transport sectors by up to 4 years in some countries.
- A zero-emission vehicle mandate in light road transport brings forward the positive tipping points in heavy road transport by nearly 2 years in some countries, and up to a year for power and heating.



A positive tipping cascade in power, transport and heating

Authors: Femke Nijsse[1], Simon Sharpe[2], Rishi Sahastrabuddhe[1], Timothy M Lenton[1]

[1] Global Systems Institute, University of Exeter, United Kingdom
[2] S-Curve Economics CIC

University of Exeter
EEIST
s-curve economics
In partnership with
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Thank you

Discussion by Dries Dumortier

Mandates & bottlenecks

How are bottlenecks represented when mandates are implemented?

FTT models accounts for growth constraints by

Incumbency advantage → Prevailing capacity share (S_i^{t-1})

Speed of capacity replacement → Diffusion rate ($\mathrm{A}_{\mathrm{i,j}}$)

Investors minimise costs

For FTT:Power model

Cost minimisation ≠ profit maximisation

Renewable energy farm characteristics	**Wholesale spot market characteristics**
- Nearly zero marginal cost	- Marginal pricing
- High debt requirement	- Price volatility
- Uncertain generation levels	- Day-ahead market
- Lower generation costs	- Who profits?

Table 1: Misalignments between characteristics of renewables and wholesale spot market

Climate policy support

Potential risk:

Mandates could undermine public support for climate policies

Clarification:

Mandates for producers or also for consumers?

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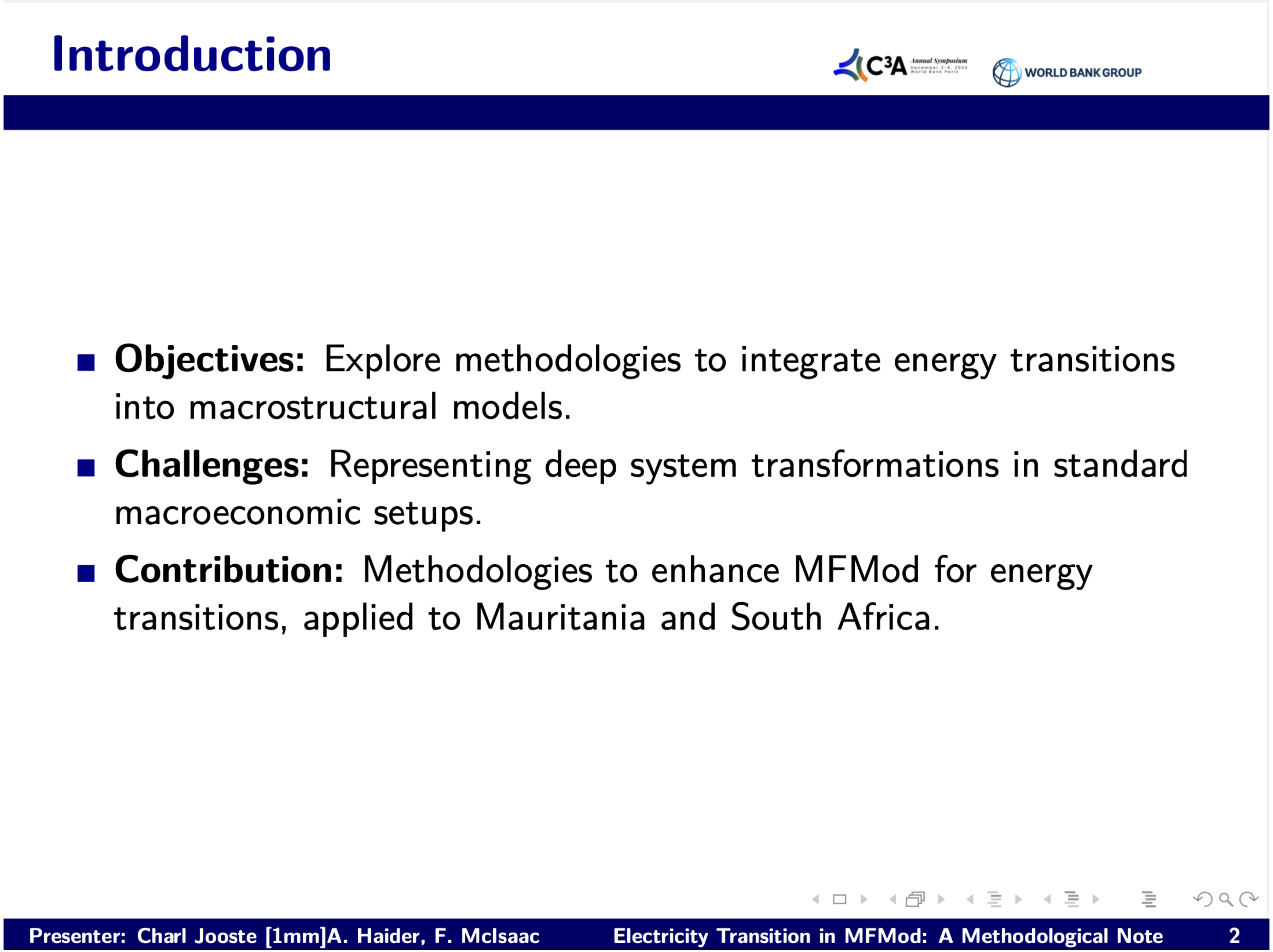
Electricity Transition in MFMod: A Methodological Note

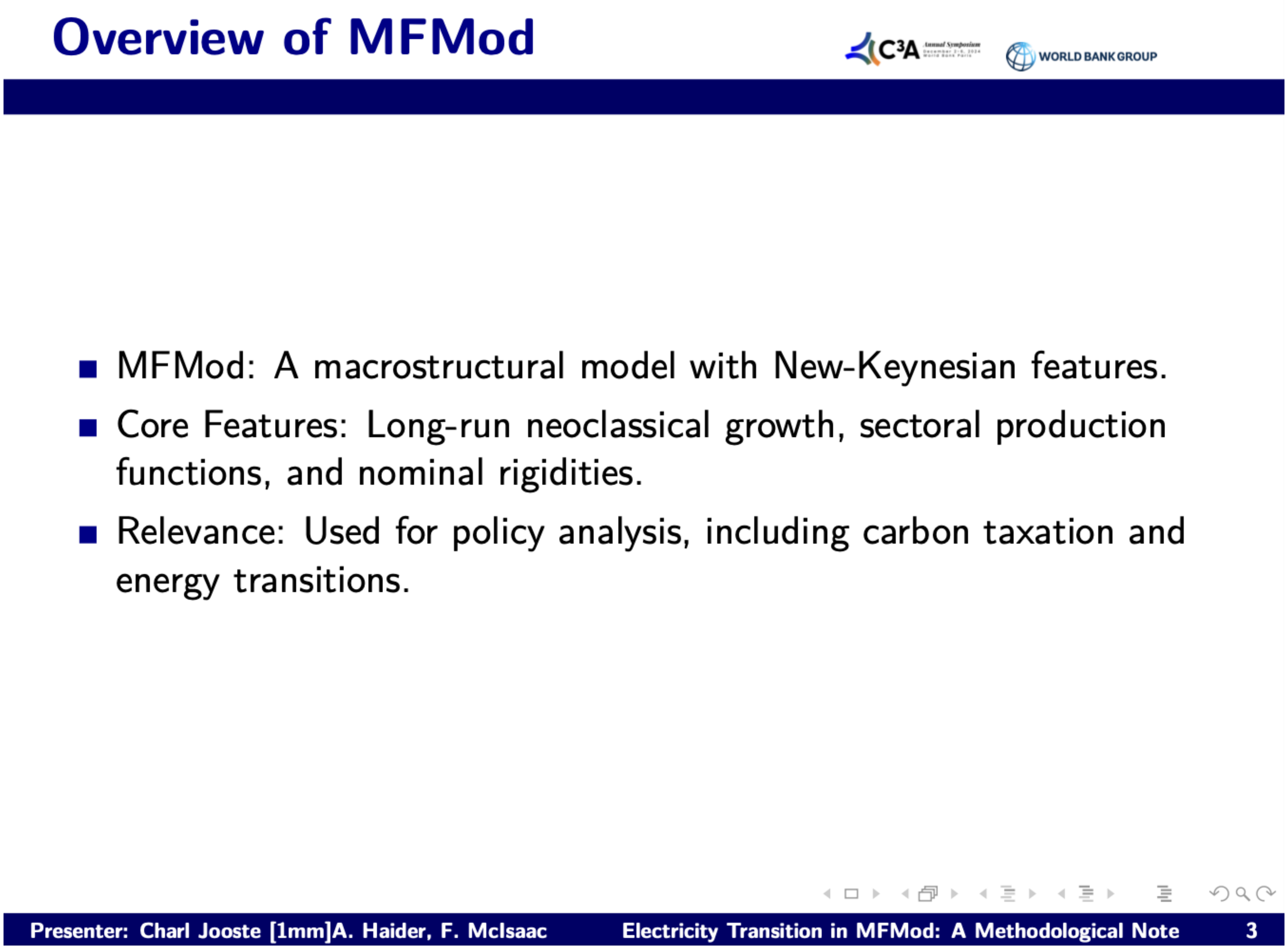
Presenter: Charl Jooste A. Haider, F. McIsaac

Contact: t.m.lenton@exeter.ac.uk



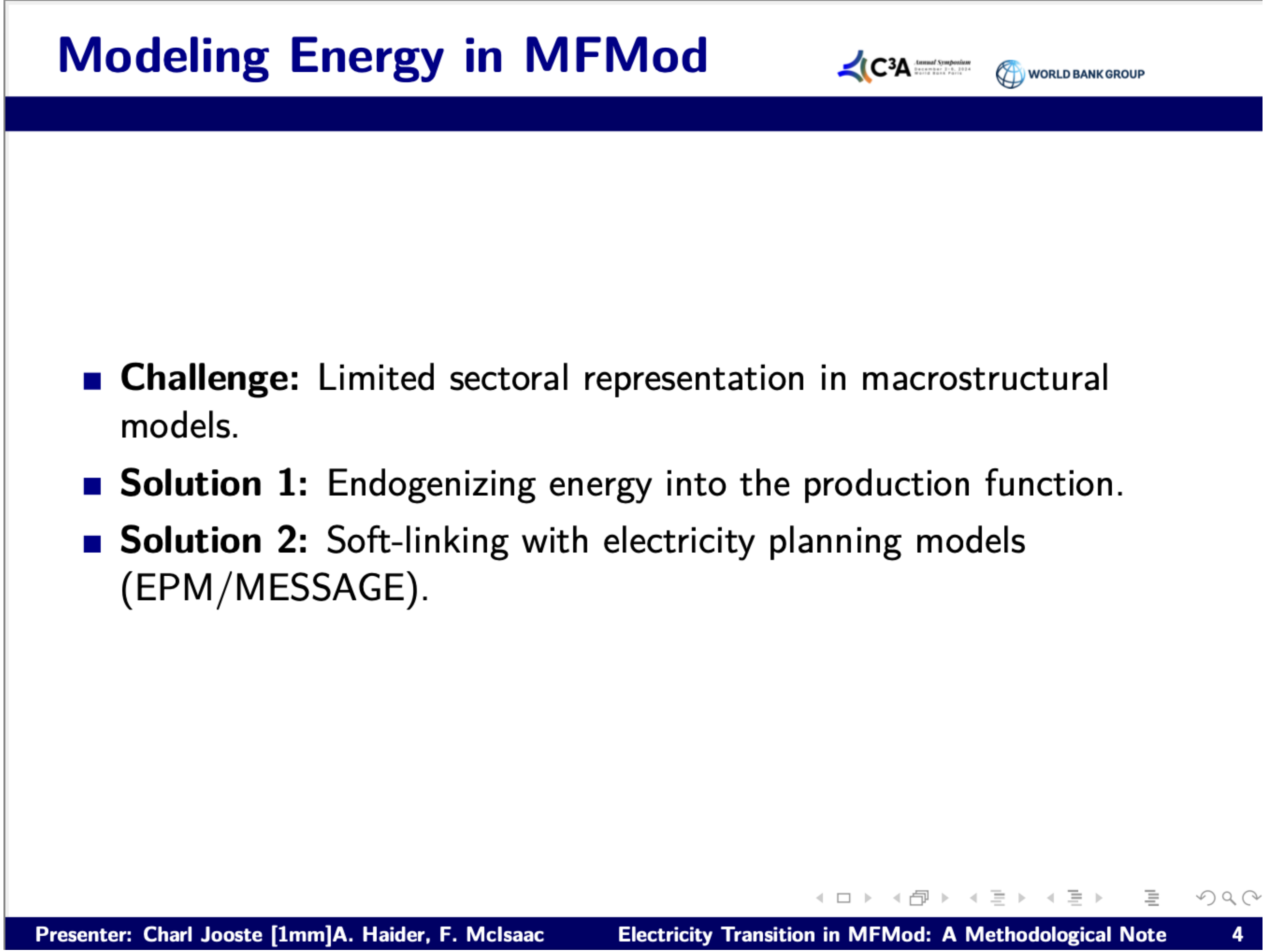
Introduction

- **Objectives:** Explore methodologies to integrate energy transitions into macrostructural models.
- **Challenges:** Representing deep system transformations in standard macroeconomic setups.
- **Contribution:** Methodologies to enhance MFMod for energy transitions, applied to Mauritania and South Africa.



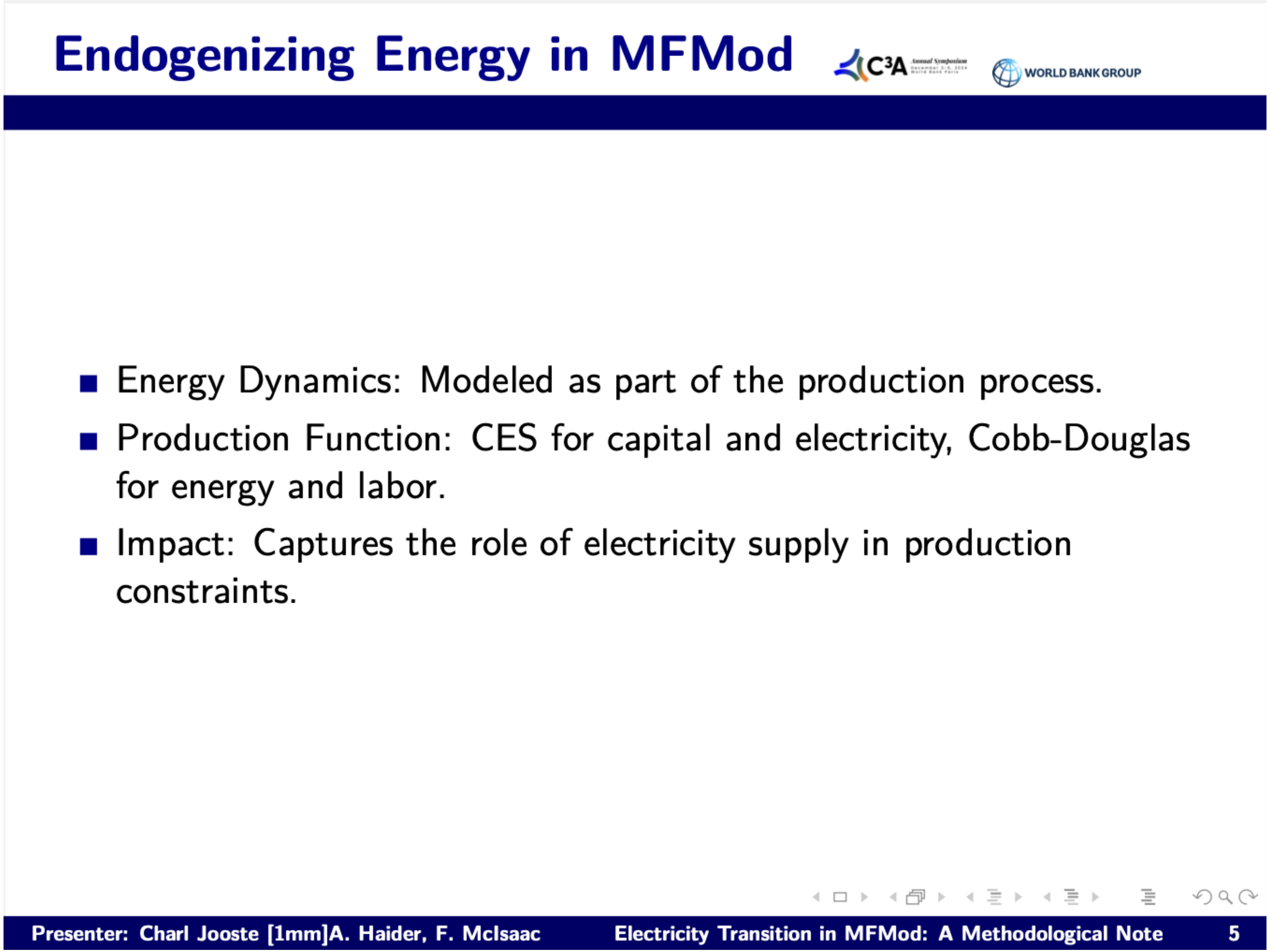
Overview of MFMod

- MFMod: A macrostructural model with New-Keynesian features.
- Core Features: Long-run neoclassical growth, sectoral production functions, and nominal rigidities.
- Relevance: Used for policy analysis, including carbon taxation and energy transitions.



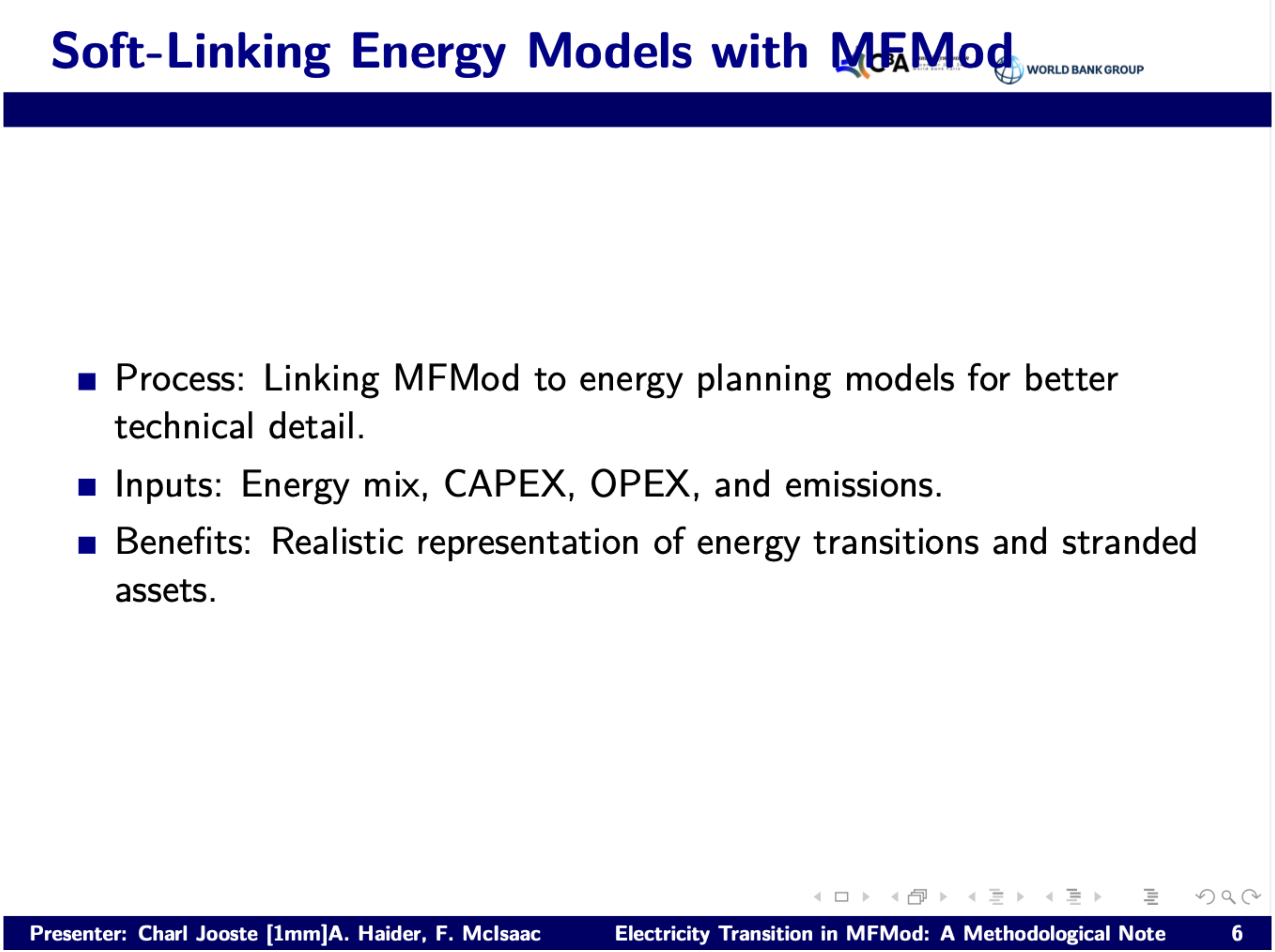
Modeling Energy in MFMod

- **Challenge:** Limited sectoral representation in macrostructural models.
- **Solution 1:** Endogenizing energy into the production function.
- **Solution 2:** Soft-linking with electricity planning models (EPM/MESSAGE).



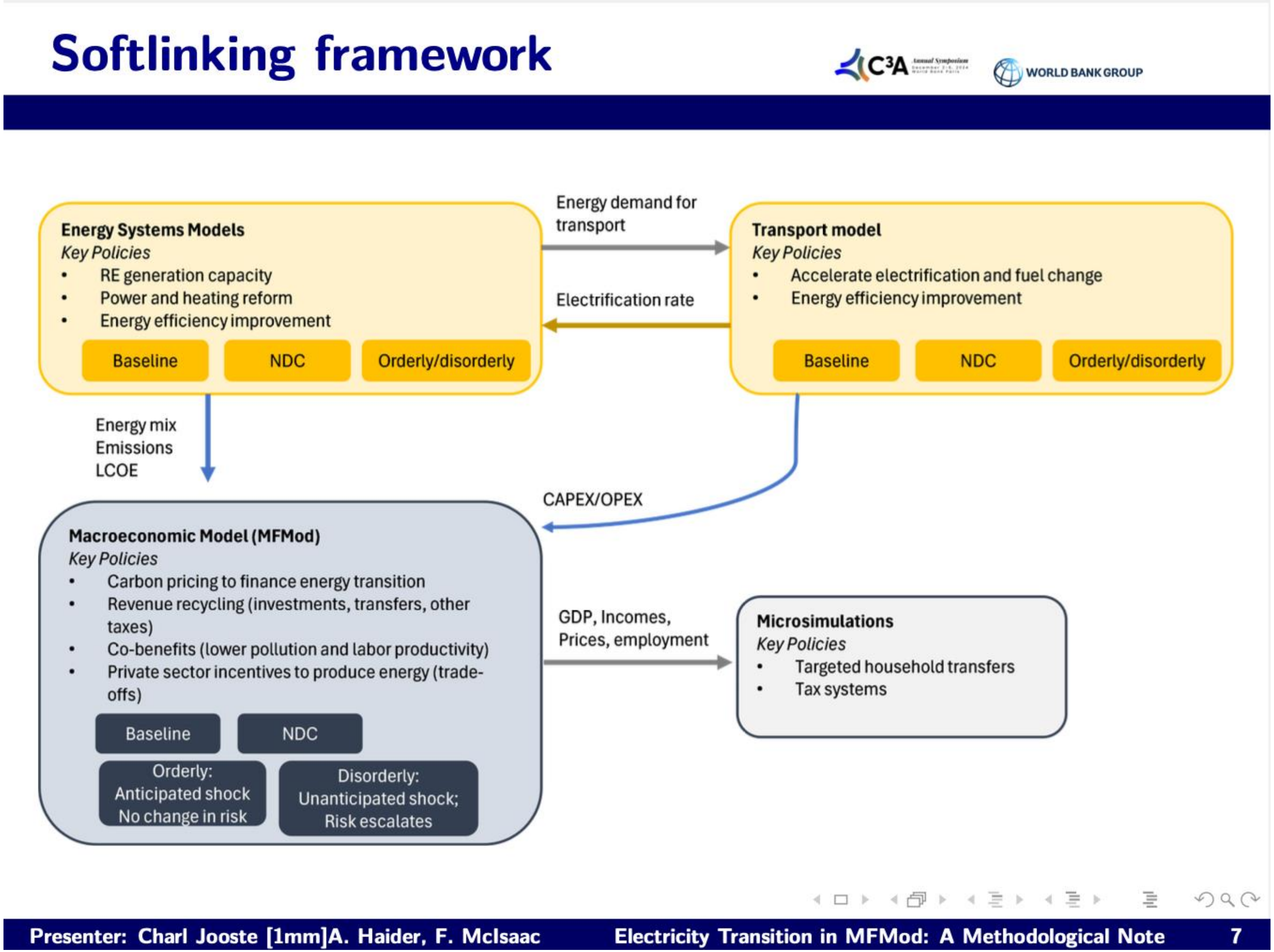
Endogenizing Energy in MFMod

- Energy Dynamics: Modeled as part of the production process.
- Production Function: CES for capital and electricity, Cobb-Douglas for energy and labor.
- Impact: Captures the role of electricity supply in production constraints.



Soft-Linking Energy Models with MFMod

- Process: Linking MFMod to energy planning models for better technical detail.
- Inputs: Energy mix, CAPEX, OPEX, and emissions.
- Benefits: Realistic representation of energy transitions and stranded assets.



Softlinking framework

Energy Systems Models

Key Policies

- RE generation capacity
- Power and heating reform
- Energy efficiency improvement

Baseline | NDC | Orderly/disorderly

Energy demand for transport

Electrification rate

Transport model

Key Policies

- Accelerate electrification and fuel change
- Energy efficiency improvement

Baseline | NDC | Orderly/disorderly

Energy mix
Emissions
LCOE

CAPEX/OPEX

Macroeconomic Model (MFMod)

Key Policies

- Carbon pricing to finance energy transition
- Revenue recycling (investments, transfers, other taxes)
- Co-benefits (lower pollution and labor productivity)
- Private sector incentives to produce energy (trade-offs)

Baseline | NDC

Orderly:
Anticipated shock
No change in risk

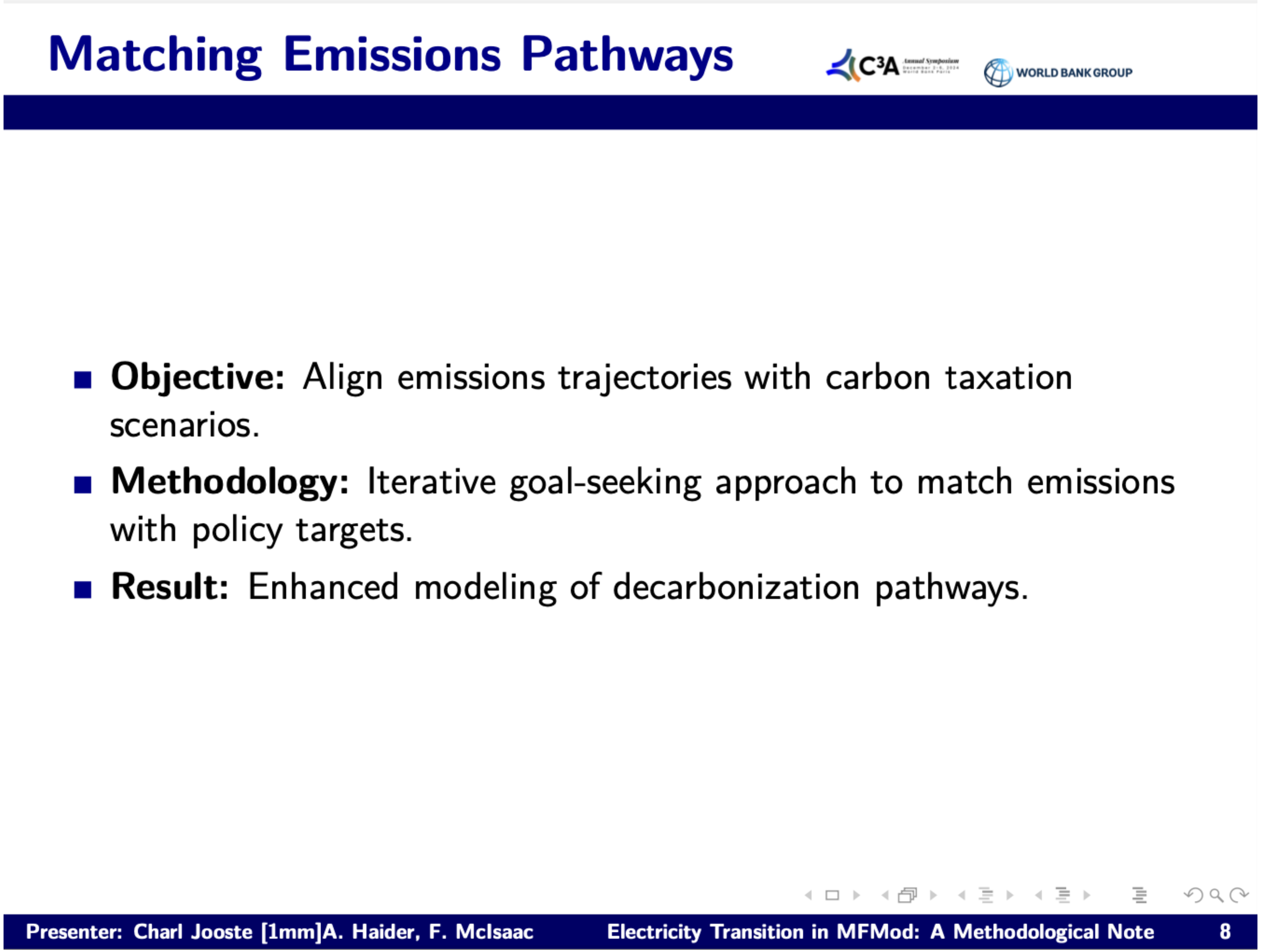
Disorderly:
Unanticipated shock;
Risk escalates

GDP, Incomes,
Prices, employment

Microsimulations

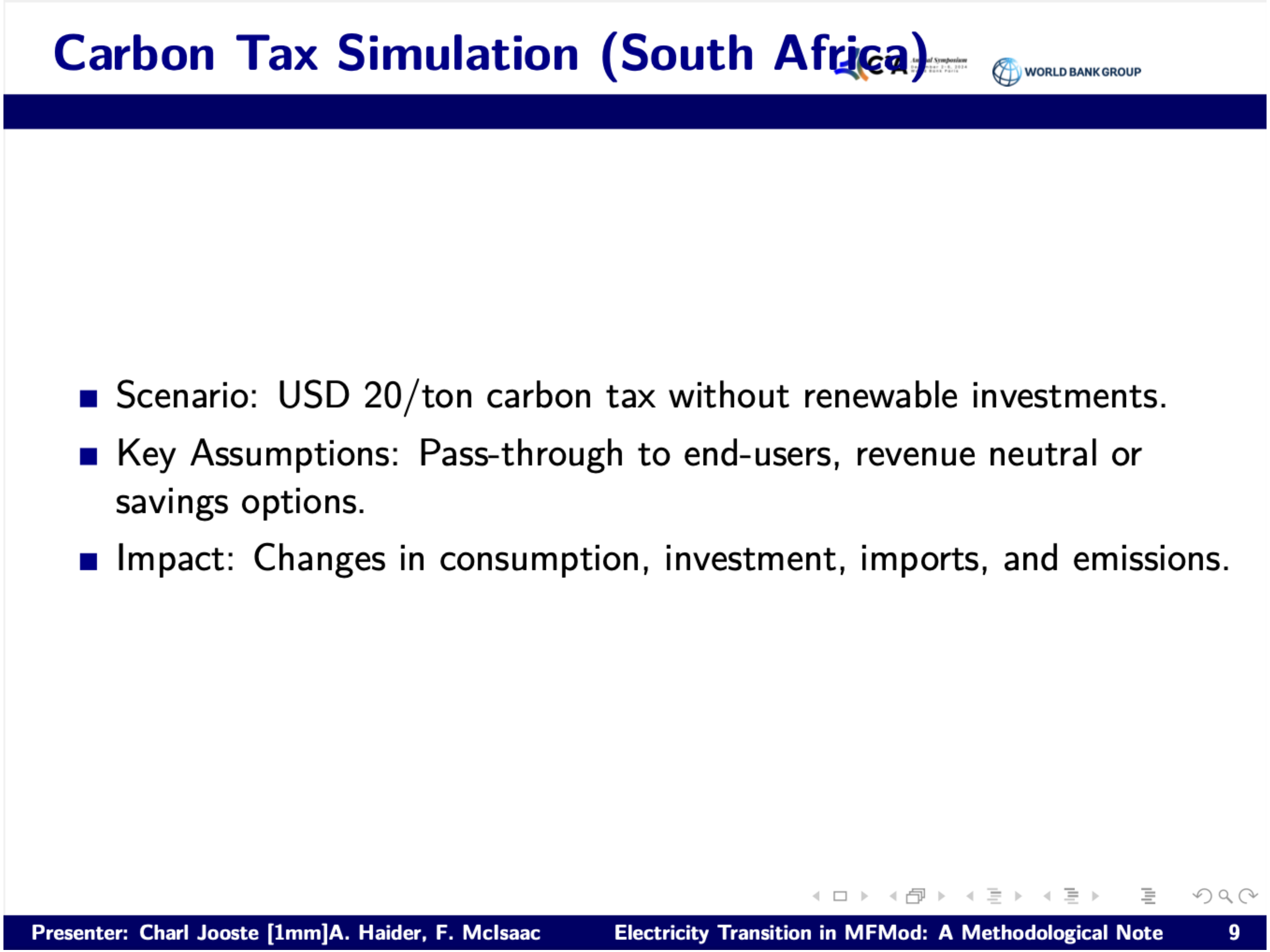
Key Policies

- Targeted household transfers
- Tax systems



Matching Emissions Pathways

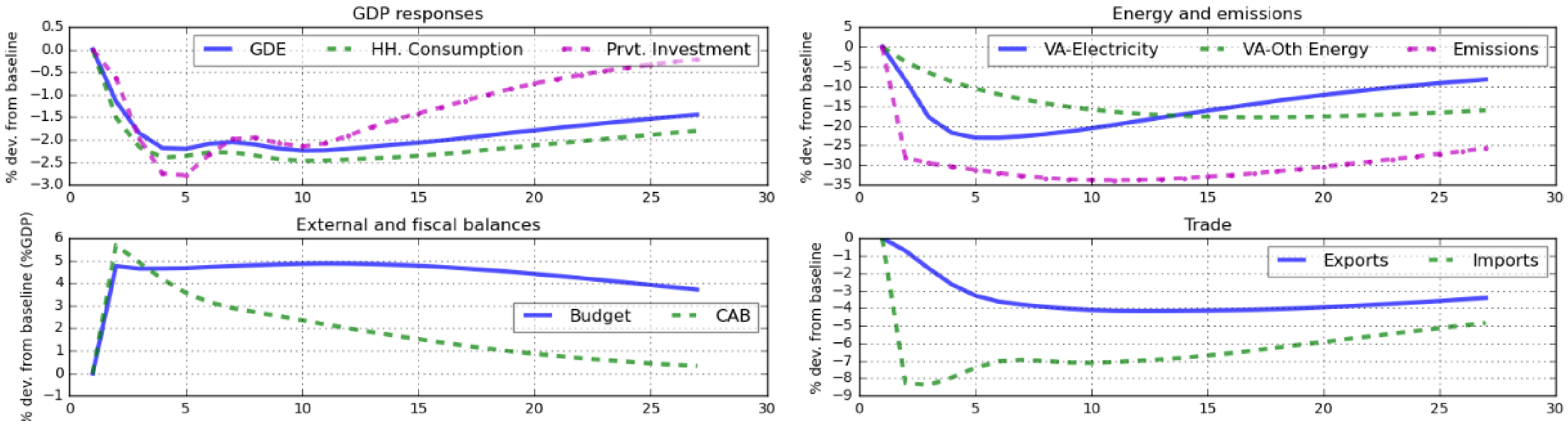
- **Objective:** Align emissions trajectories with carbon taxation scenarios.
- **Methodology:** Iterative goal-seeking approach to match emissions with policy targets.
- **Result:** Enhanced modeling of decarbonization pathways.



Carbon Tax Simulation (South Africa)

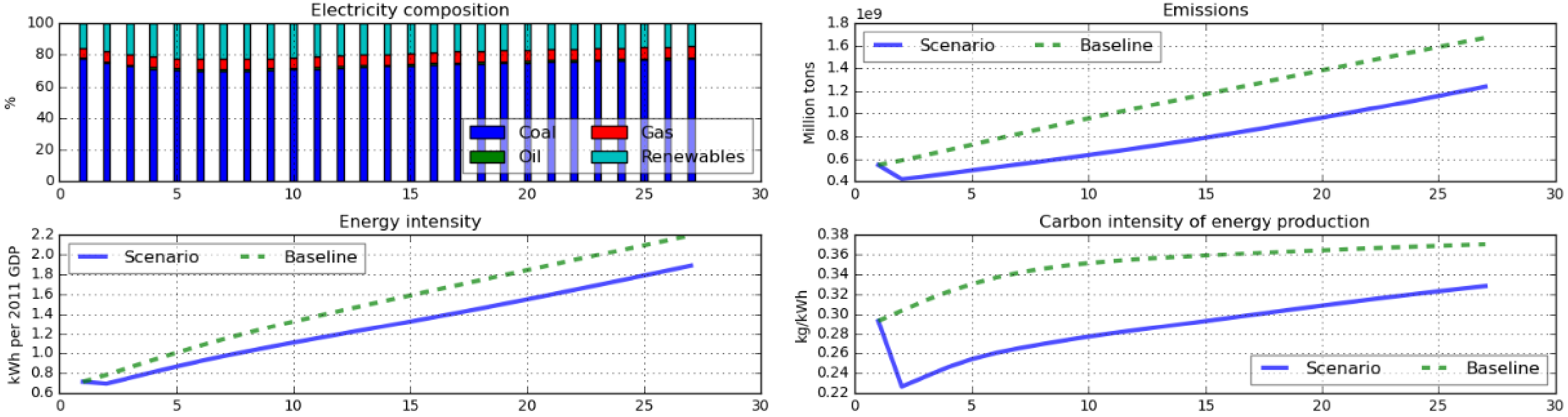
- Scenario: USD 20/ton carbon tax without renewable investments.
- Key Assumptions: Pass-through to end-users, revenue neutral or savings options.
- Impact: Changes in consumption, investment, imports, and emissions.

Results - Carbon Tax in South Africa



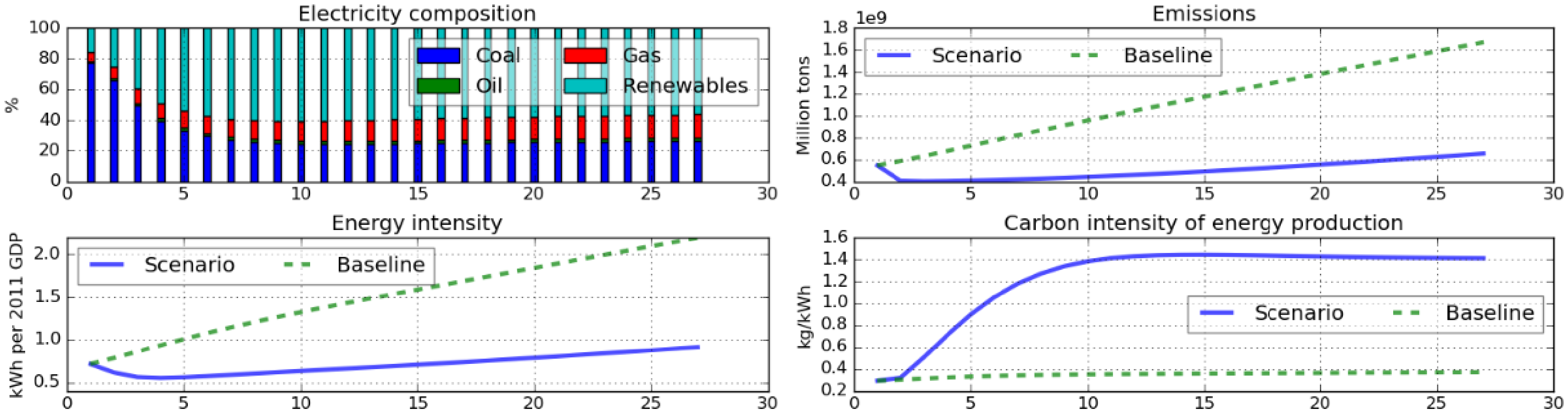
- Without recycling and inelastic demand for fossil fuels we get a sharp reduction in output.
- Significant gains to revenue - tax base does not shrink.
- Opportunity cost implies that other goods demanded falls.

Results - Carbon Tax in South Africa



- Total emissions fall.
- But this is only because demand is contracting.
- Electricity composition stays the same.

Elasticity Sensitivity in Carbon Tax

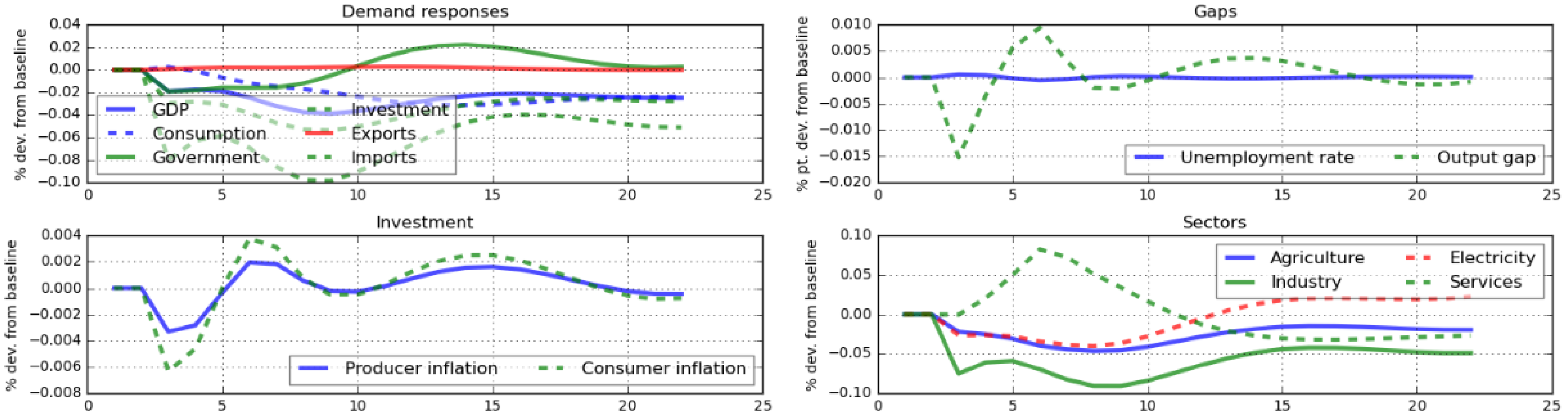


- Scenario: Higher elasticity of substitution ($\sigma = 5$).
- Impact: Faster energy transition and increased renewable share.
- Insights: **Cannot just tax fossil fuels without providing alternative renewables.**

Soft-Linking Results (Mauritania)

- Scenario: Sahel electricity integration with emissions reduction.
- Inputs: Energy mix assumptions and CAPEX/OPEX projections.
- Role of Government: Financing grid integration and renewable transitions.

Results - Mauritania Energy Transition



- Decrease in CAPEX relative to baseline.
- Changes in consumption, investment, and sectoral outputs.
- Implications for energy reliability and productivity.

Concluding Remarks

- Summary: Enhanced methodologies for energy integration in MFMod.
- Findings: Carbon tax and soft-linking approaches provide insights into energy transitions.
- Contribution: Blueprint for macroeconomic modeling of low-carbon transitions.

Future Work

- Opportunities: Iterative integration with techno-economic models.
- Extensions: Sector-specific labor adjustments and stranded asset modeling.
- Policy Relevance: Improved tools for decarbonization policy simulations.

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Discussion by Timothy Lenton