

Analysing Policy Instruments for GHG Emission Reduction in the Italian Dairy Sector: A Modelling Approach

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Background

Why is dairy decarbonisation challenging?

- Climate
 - Dairy contributes substantially to agricultural GHG emissions.
- Policy
 - EU climate targets require significant emission reductions.
- Economics
 - Policies create trade-offs between competitiveness, farm income and environmental performance.
- The challenge is identifying policy instruments that reduce emissions without compromising the competitiveness and resilience of the dairy supply chain

Background

Alternative strategies for reducing dairy emissions

- Scale Efficiency (Kunari 2020; Lahart et al., 2021)
- Technological change (Gancone et al., 2021)
- Innovative business models (Barth et al., 2022)
- Sufficiency (Canavari and Coderoni, 2020)
- Policies and regulations (York et al., 2018)
 - i.e. nutrition, manure, health, breeding, management

Objective

- Several policy instruments are currently discussed, but their combined effects along the dairy supply chain remain poorly understood.
- Current studies typically:
 - analyse single policy instruments
 - focus on one supply-chain actor
 - overlook strategic interactions between actors.
- Which policy mix delivers the largest emission reductions while preserving competitiveness across the dairy supply chain?

Approach

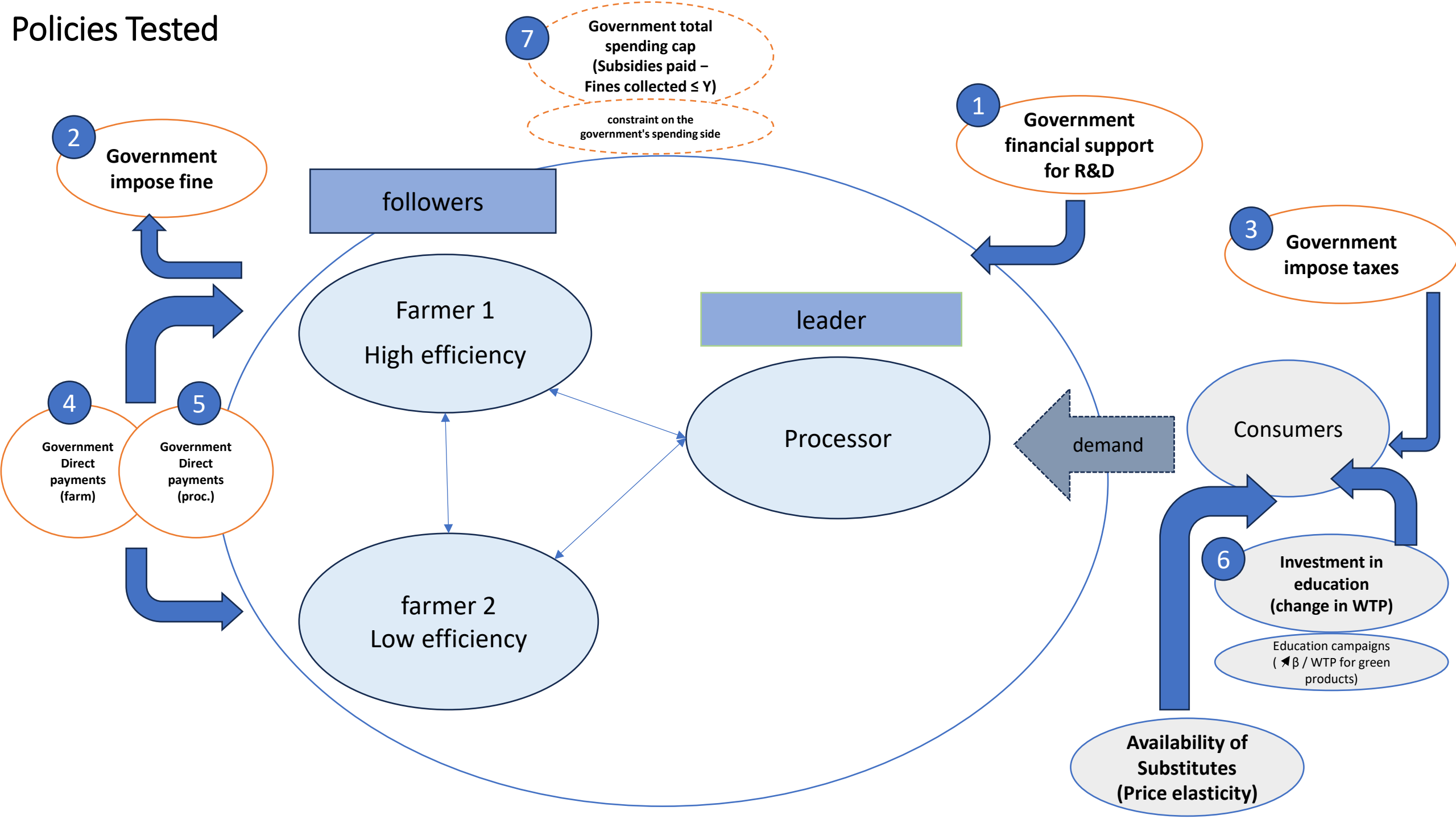
We develop a dynamic bilevel optimisation model that captures interactions among government, processors, farmers and consumers

- *What*
 - Mathematical programs with a hierarchical structure of the decision-making problem
 - Main problem - *upper-level* problem or the *leader*
 - Nested problem - *lower-level* problem or the *follower*
 - Lower-level optimisation in the upper-level constraints
- *Why*
 - Leader-Follower Relationship: Bilevel models naturally capture the hierarchical structure where the leader optimises their objective, anticipating the follower's response
 - Applications:
 - Pricing and competition in economics
 - Supply chain management
 - Network design and traffic flow optimisation
 - Environmental policy planning (taxation)

Model Technicalities

- Time Horizon:
 - Dynamic model (4 periods) covering a multi-year horizon
- Players Involved:
 - 1 Processor
 - 2 Farms (ISMEA 2024):
 - F1: Large farm — higher production, lower unit cost, higher unit emissions
 - F2: Small farm — lower production, higher unit cost, lower unit emissions
 - Government (sets policy parameters: taxes, fines, subsidies, R&D budget)
 - Consumers (respond to price and chain sustainability)
- Optimization Approach:
 - Bilevel programming approach
 - Two Nested Optimizations:
 - Leader Optimization (Processor): Determines milk prices, processed quantity, technology and R&D investment, and aggregate emissions, anticipating farmer response and consumer demand
 - Follower Optimization (Farmers F1, F2): Decide optimal milk production levels and on-farm emission-reduction investment, given the processor's prices and the government's policies

Policies Tested



Equation – Leader Model

Maximisation of processor profit z_m

$$\max z_m = \sum_t [p \cdot d - \sigma \cdot q - \frac{1}{2} \theta_q \cdot q^2 - fine_L \cdot em - \sum_i w \cdot v - (1 - \gamma_m) \cdot B_m - \kappa \cdot B_m^2 - (1 - \gamma_{rd}) \cdot B_{rd} - \kappa \cdot B_{rd}^2 - \varphi \cdot N - h_{inv} \cdot I]$$

- $p \cdot d$ is the retail revenue from consumers
 - $\sigma \cdot q + \frac{1}{2} \theta_q \cdot q^2$ is the linear and quadratic processing cost
 - $fine_L \cdot em$ is the per ton CO_2 fines on processor emissions
 - $(1 - \gamma_m) \cdot B_m + \kappa \cdot B_m^2 + (1 - \gamma_{rd}) \cdot B_{rd} + \kappa \cdot B_{rd}^2$ is the processor share of tech and R&D investment
- σ covers energy, labor, water, packaging,...

Equation – Leader Model

$$z_m = \sum_t [p \cdot d - \sigma \cdot q - \frac{1}{2} \theta_q \cdot q^2 - fine_L \cdot em - \sum_i w \cdot v - (1 - \gamma_m) \cdot B_m - \kappa \cdot B_m^2 - (1 - \gamma_{rd}) \cdot B_{rd} - \kappa \cdot B_{rd}^2 - \varphi \cdot N - h_{inv} \cdot I]$$

s.t.

- $d_t = \overline{d_t} - \alpha \cdot p_t - \alpha \cdot tax_c(em_{eff} + \sum_i e_{eff}) + \beta \cdot (\sum_i xk + xhm + xrd + xrm)$ (*demand*) (α : large alpha meaning demand is elastic – consumers can easily switch to away when milk gets pricier (substitutie available: e.g. soy milk) (small alpha, demand is inelastic – consumers stick with milk hence no good substitutes)
- $q_t \geq d_t$ (*market clearing*)
- $\sum_i v_{i,t} = q_t$ (*supply balance*)
- $em_{eff,t} = \overline{em_t} - xhm_t - xrd_t - xrm_t$ (*processor per-unit emissions*)
- $em_t = em_{eff,t} \cdot q_t$ (*processor total emissions*)
- $xhm_t = xhm_{t-1} + \beta_h \cdot B_{m,t}$ (*tech innovation*)
- $xrd_t = xrd_{t-1} + \beta_{rd} \cdot B_{rd,t-2}$ (*R&D innovation, 1-period lag taking part in the medium term*)
- $xrm_t = \psi \cdot (N_{t-1} - N_t)$ (*organisational innovation*)
- $N_t = \eta_t \cdot q_t + \omega_{t-1} \cdot I_{t-1}$ (*waste computation*)
- $\sum_i \gamma_f \cdot B_{i,t} + \gamma_m \cdot B_{m,t} + \gamma_{rd} \cdot B_{rd,t} - fines \leq Y_t$ (*government budget*)

Equation – Follower

Maximisation of farmer profit (for each farm type $i \in \{i1, i2\}$)

$$\max \pi_f(i) = \sum_t [w_{i,t} * v_{i,t} - c_{i,t} * v_{i,t} - (1 - \gamma_f) * B_{i,t} - \kappa \cdot B_{i,t}^2]$$

s.t.

$$xk_{i,t} = xk_{i,t-1} + \beta_{k,i} \cdot B_{i,t} \text{ (farm tech innovation)}$$

$$e_{eff,i,t} = \bar{e}_{i,t} - xk_{i,t} \text{ (farm per - unit emissions)}$$

$$er_{i,t} = e_{eff,i,t} * v_{i,t} \text{ (farm total emissions)}$$

$$v_{i,t} \leq s_{i,t} \text{ (farm capacity)}$$

Policies Tested

Lever	Def	Model
Emission Fines	Revenue from sales	$\text{fine_L (processor)}$
Consumer carbon tax	Linear processing cost	tax_c
Farm subsidy	Quadratic processing cost	γ_f
Processor subsidy	Fines on processor emission	γ_m
Government innovation budget	Payment to farmers	γ_{budget}
Consumer awareness	Processor share of	β
Price sensitivity	PMP adjustment cost on tech	α

Results

Policy/reg intervention	Low	Medium	High
Carbon Tax	-6.6641	-13.0828	-18.9128
Emission fines	-6.4322	-12.7637	-19.0348
Consumer awareness	-4.5615	-9.2873	-14.2453
Price sensitivity	-1.3486	-4.1916	-5.1500
Farm subsidy	-1.2617	-2.4992	-3.8010
R&D budget	-0.1248	-0.2611	-0.4143
Processor subsidy	-0.0021	-0.0040	-0.0050

(% change with respect the baseline)

Results

Intervention	Effect on emissions	Main trade-off
Carbon tax	High	Acceptability
Emission fines	High	Lower farm income
Consumer awareness	Medium	Long-term effect
Price sensitivity	Low	Depends on substitutes
R&D budget	Low	Limited short-term effect
Farm subsidy	Low	Weak environmental impact
Processor subsidy	Very low	Negligible effect

Discussion (Multilevel perspectives)

- Long-term measures:
 - Investing in education to improve consumer awareness.
 - Establishing rules and regulations for private standards (risk of greenwashing)
 - Encouraging public-private investment in R&I
- Short-term measures:
 - Rewarding farmers through carbon farming
 - Redesigning direct payment schemes to support investments in climate-smart innovations, particularly for large and intensive farms (e.g., improving feeding efficiency)
 - Providing income support for small farms and low-emission producers

Next steps

- Improvements
 - Time frame (from period to year)
 - Differentiation of agents (farmers and processors)
 - Technology and R&I
 - Scenarios of policy and intervention

Thank you

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Discussion (Context)

- Complex socio-political and economic shifts
- Green deal GHG targets
- Food security and supply chain resilience
- Increasing consumers' willingness to pay for lower-emission dairy products
- Call for effective policy intervention

Discussion

- **Demand side**

- benefits from investment in education and the development of substitutes (e.g., plant-based dairy products)
- WTP for lower CO₂-emitting products (considering the role of private standards) & need for a harmonised approach to MRV
- Taxes effectively reduce CO₂ emissions, but their acceptability remains a challenge
- Challenges in achieving significant emission reductions solely through consumer-driven demand

- **Supply chain**

- Changes in government R&D budgets relatively small impact on CO₂ reduction.
- Fines (similar to taxes) are effective in reducing CO₂ emissions, but costs charged to farmers (low price paid)

- **Farmers**

- Low effectiveness of direct payments BUT argument in favour of maintaining the status quo, as reducing direct payments may lead to a relaxation of EU regulations (such as the Nitrate Directive) and pressure farm type 2 to reduce or even to exit

Background

- Strong dairy sector's carbon footprint
- EU commitments on decarbonising the EU dairy sector (Green Deal and F2F)
- Tensions and polarised political debate
 - Acceptability, consistency of sustainable transformation of dairy sector
 - Policy mix
 - Winners and losers
 - Innovative Business models & co-benefits
 - Targets,
 - ...
 - Vulnerability and exposure to climate change (Guzman-Luna et al. 2022)

Calibration – Based on Lit. Rev. - Cost Parameters

Parameter	Definition	Value	Reference
$c(i1)$	intensive farm cost	84 Gkg/block (≈ 14 Mt/year $\times$ 6 years)	EU FADN Dairy Report 2021 (DG-AGRI); Italian operating costs $\approx$ €256/t
$c(i2)$	extensive farm cost	1.22 ($\varepsilon = -0.55$)	EU FADN Dairy Report 2021 (DG-AGRI); Italian operating costs $\approx$ €256/t +15% size adjustment
σ_t (processor per cost derived from industries)	processor cost	70-85% (raw milk)	IMARC Group 2026
π_{i1}	Reservation profit (i1)	18	EU FADN Dairy Report 2021 (DG-AGRI)
π_{i2}	Reservation profit (i2)	4.5	EU FADN Dairy Report 2021 (DG-AGRI)

Calibration – Based on Lit. Rev. - Emission Parameters

Parameter	Definition	Value	Reference
$e_{b,i1}$	Farm emissions (intensive)	1.4 kg CO ₂ eq/kg	Ferronato et al. (2025), Animals 15(6):811 (Po Valley)
$e_{b,i2}$	Farm emissions (extensive)	1.6 kg CO ₂ eq/kg	Lo Fiego et al. (2016), Sustainability 8(8):728 (Umbria)
$\overline{em}$	Processor emissions	0.05 kg CO ₂ eq/kg	Ferronato et al. (2025), processing = 1.27% of chain

Calibration – Based on Lit. Rev. - CAP Parameters

Parameter	Definition	Value	Reference
γ	Gov innovation budget	2.0 (€ bn/block)	EU CAP Network "CAP Strategic Plan Factsheet: Italy" (Oct 2024); 12% dairy share of innovation envelope
γ_f	Farm investment subsidy rate	0.65	Regulation (EU) 2021/2115, Art. 91 + EC SWD(2022) 418 final
γ_m	Processor investment subsidy rate	0.50	Same Regulation, Arts. 73-74
γ_{rd}	R&D subsidy rate	0.80	Same Regulation, Art. 77 (EIP-AGRI Operational Groups)

Calibration – Based on Lit. Rev. - Scale Parameters

Parameter	Definition	Value	Reference
$\overline{d_t}$ (dbar)	Italian dairy demand baseline	84 Gkg/block (≈ 14 Mt/year $\times$ 6 years)	Eurostat (2024), "Milk and milk product statistics", Statistics Explained, November 2025 update.
α (alpha_b)	price elasticity of demand	1.22 ($\epsilon = -0.55$)	Femenia (2019), meta-analysis of 76 EU dairy estimates
β (beta_b)	green WTP	0.5 ($\approx 9\%$ price premium for low-CF milk)	Canavari & Coderoni (2020), Agricultural and Food Economics 8(4)

Calibration – Based on Lit. Rev. - Tier 2 Parameters

Parameter	Definition	Value	Reference
η_t	Fraction of milk lost during processing	0.045	OECD-FAO Agricultural Outlook 2024-2033, p.178
ω_t	Fraction of milk lost during storage/distribution	0.025	OECD-FAO Agricultural Outlook 2024-2033, p.178
$\beta_k(i_1)$	Effectiveness of farm tech investment for intensive farms: per-kg emission reduction per unit of capital invested in cleaner technology	0.6	Calibration; implied max abatement within IPCC ceiling (38%, Project Drawdown 2024)
$\beta_k(i_2)$	Same, for extensive farms	0.4	Same justification as above
β_h	Effectiveness of processor tech investment: per-kg emission reduction per unit of capital invested in cleaner processing	0.6	Calibration
β_{rd}	Effectiveness of processor R&D investment: per-kg emission reduction per unit of capital invested in research	0.5	Consistent with 20-40% 3-NOP meta-analysis (Kebreab et al. 2023, <i>J. Dairy Sci.</i>)

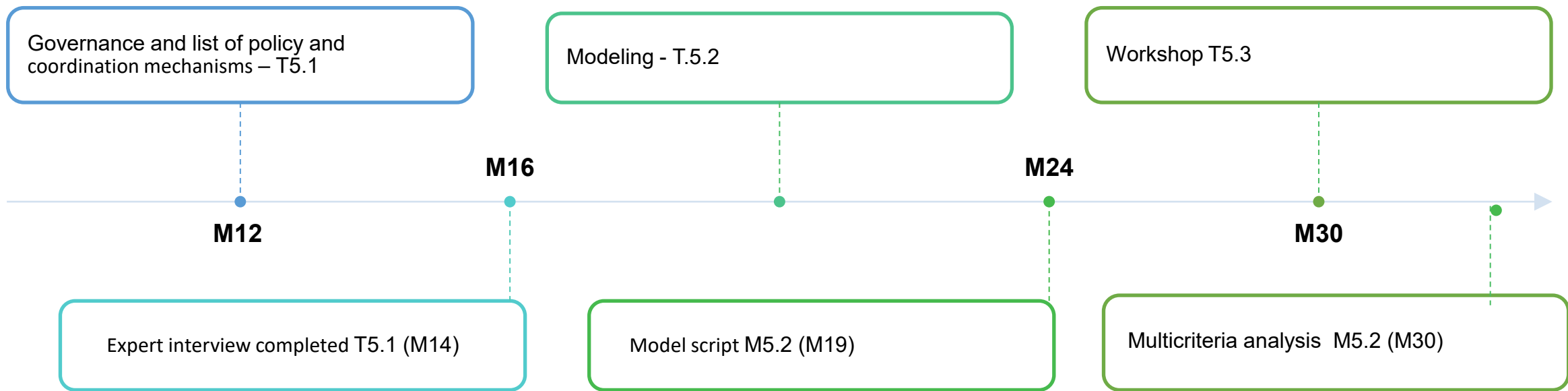
Implications

“With effective policies that reward good practices and approaches tailored to specific needs, there is room to further decrease emissions from agriculture faster while enhancing carbon removals in the land sector, in soils and forests. For prevailing emissions from livestock, the recommendations from the livestock work stream will serve as the basis for the further development of a toolbox of tailored measures to support the sector and regions in their efforts to reduce emissions.

***Technological advancements**, including in feeding strategies, will also contribute. Linked to this, the **future CAP will** assess how to support farmers best in reducing further greenhouse gas emissions from their farming and livestock activities.”*

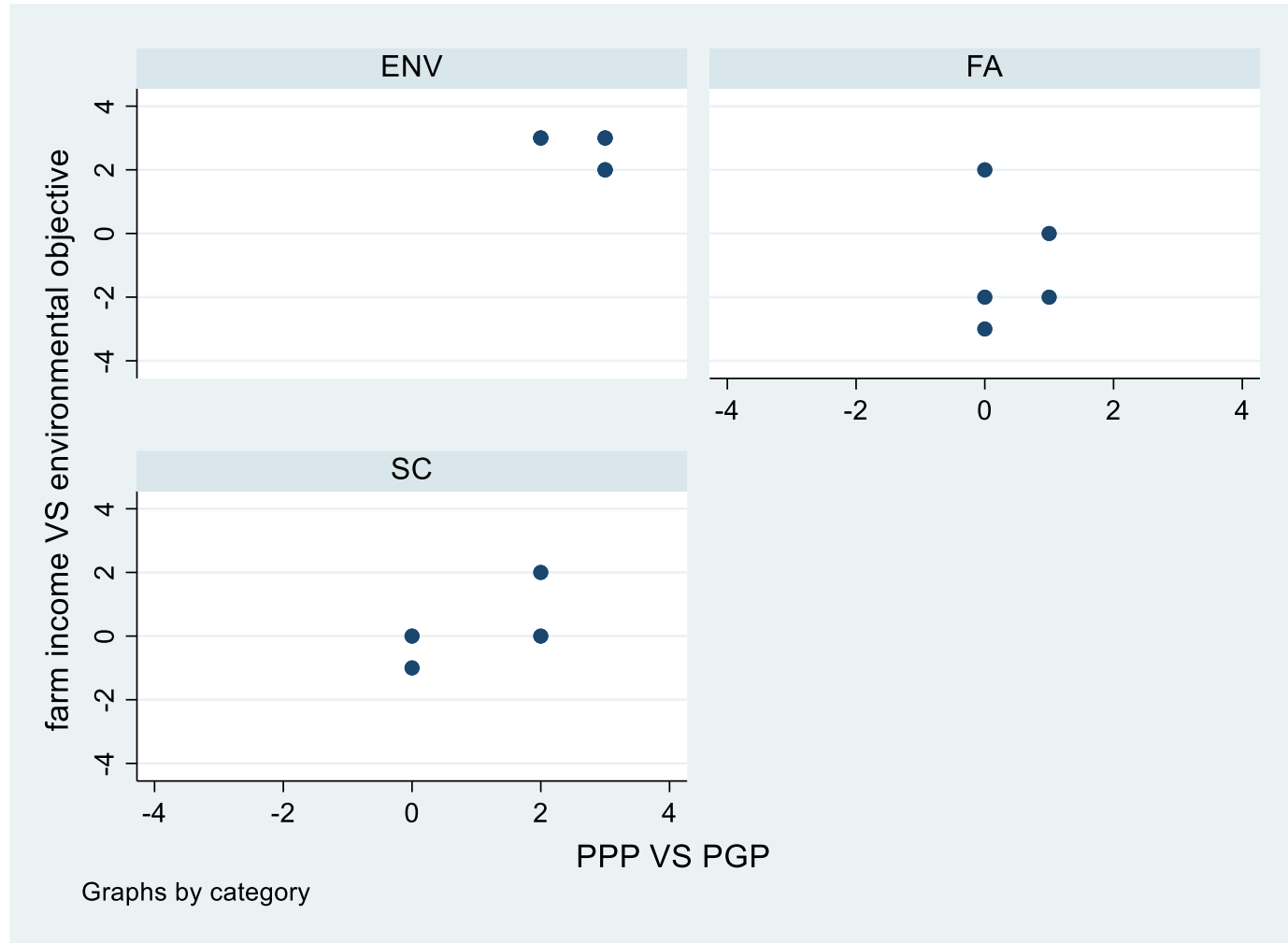
Implications

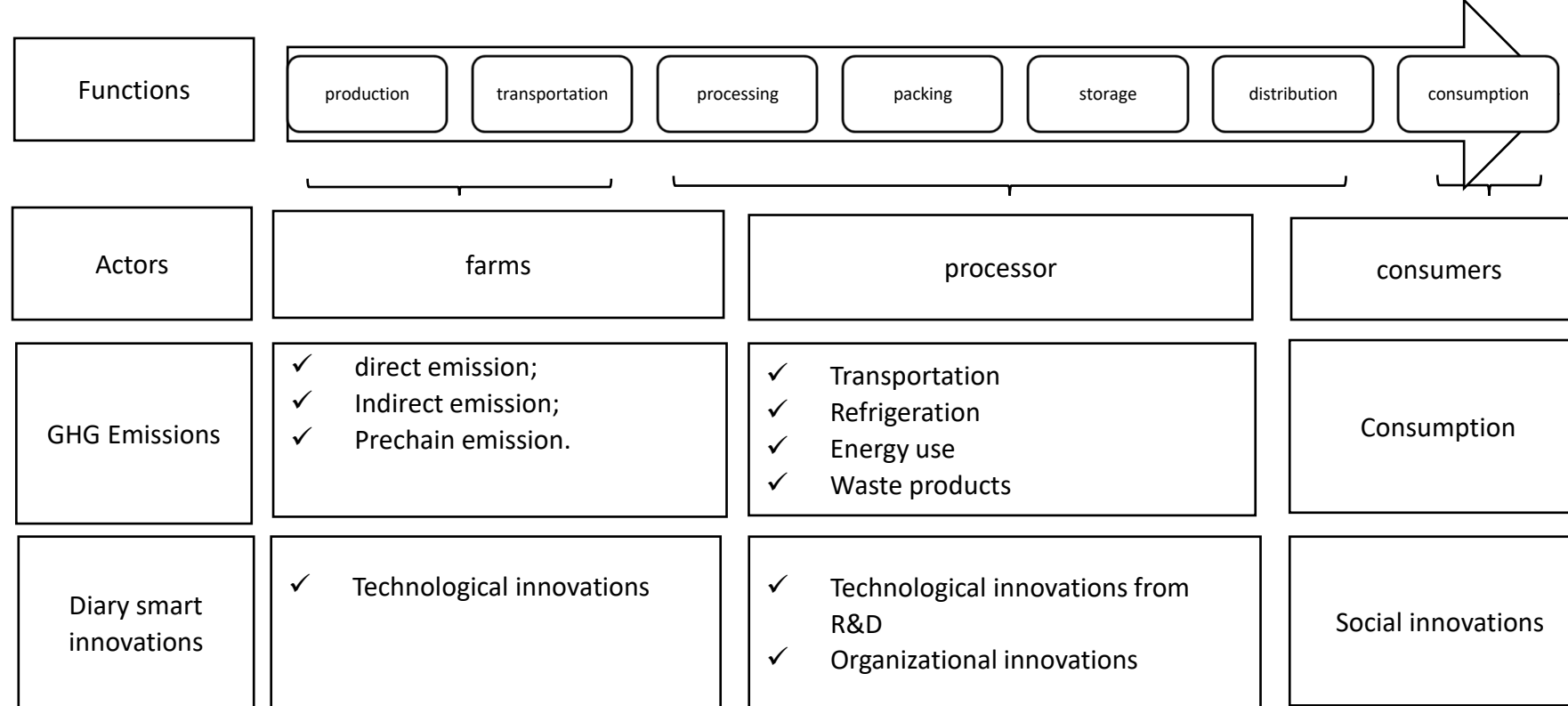
- *Emphasis on adaptation but..*
- *Sustainability as a way to ensure long-term resilience & food security*
- *Focus on R&I and technological changes in agrifood*
- *Revise CAP instruments and roles (administrative burden and transaction costs)*
- *“Incentivising sustainability”*
 - *Finance incentive for private (i.e. supply chain actors)*
 - *Better informed consumers’ choice*
 - *Voluntary benchmarking system for on-farm sustainability assessments*
 - *agrifood compass indicators (<https://agridata.ec.europa.eu/extensions/compass/compass.html>)*
 - *Carbon Removal and Carbon Farming (CRCF) certification framework*



- WP5 main results

Key results (stakeholders' preferences)





direct emission: Animal, Housing facility, Manure storage, Crop and pasture-land, Fuel combustion, Lime decomposition

Indirect emission: Housing facility, Manure storage, Crop and pasture-land

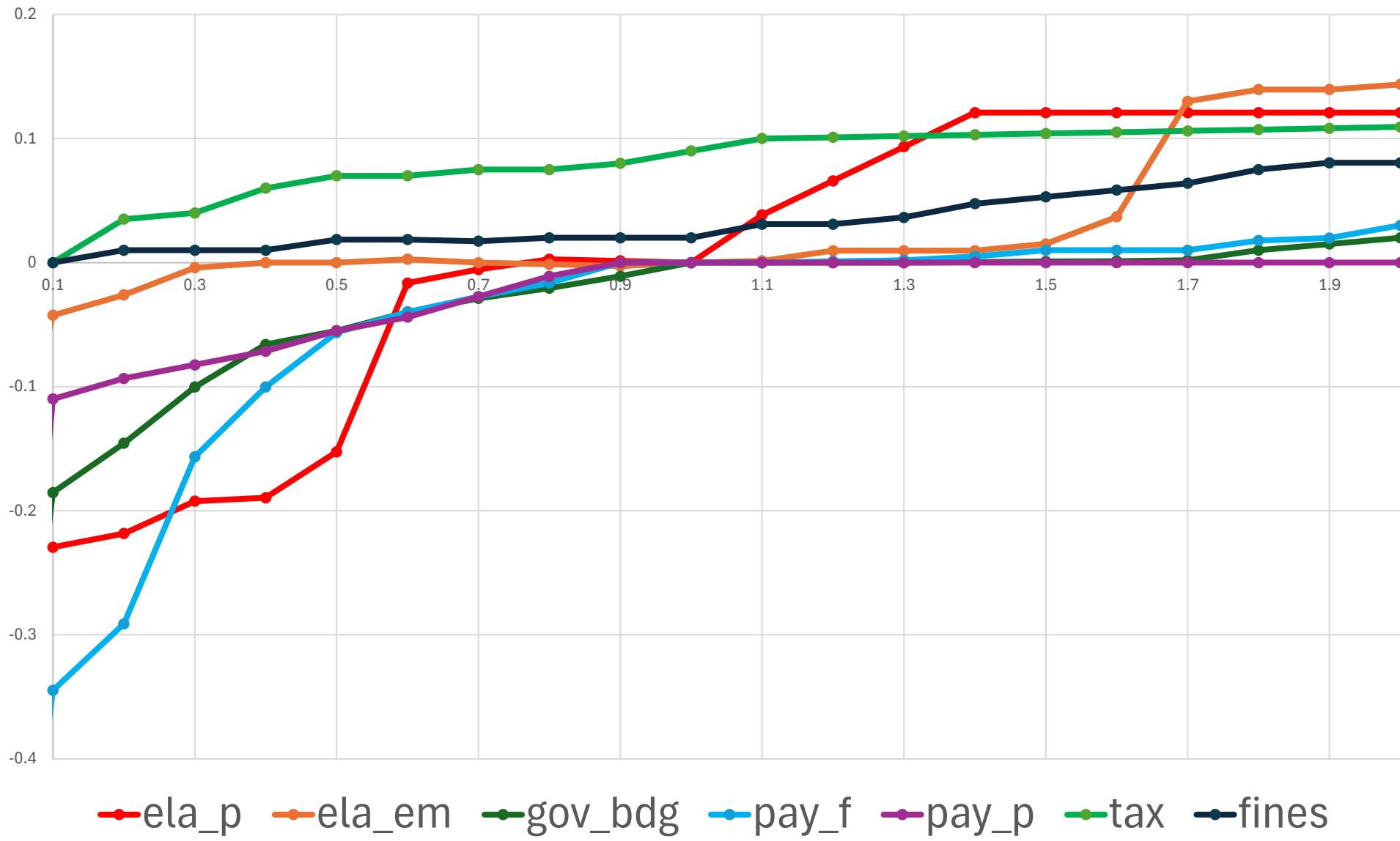
Prechain emission: Resource inputs

Technological innovations: Innovations that require investment in the initial period.

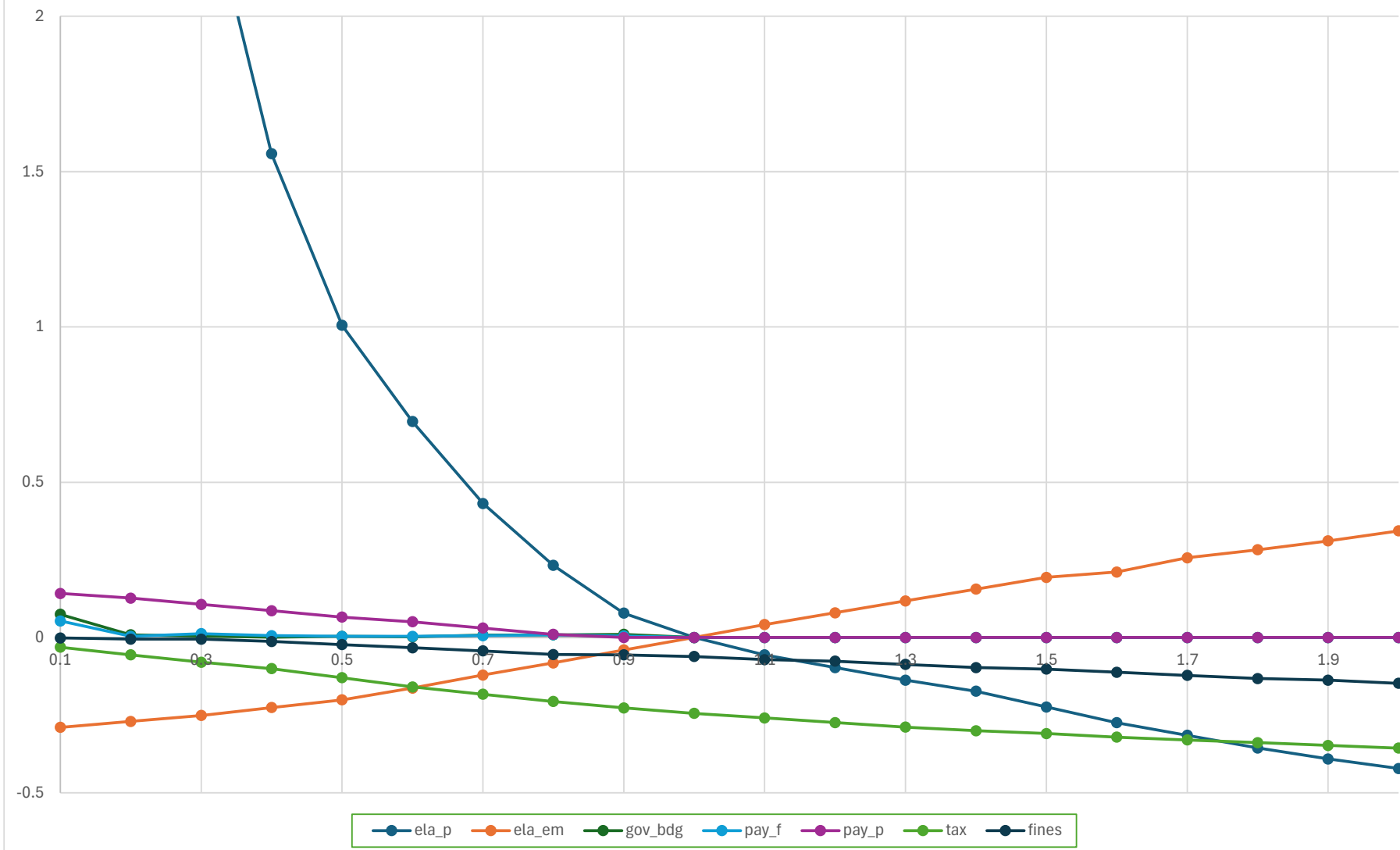
Organizational innovations: Innovations that do not require initial investment and result in waste reduction and efficiency.

Social innovations: Innovations that increase consumer awareness about the importance of reduction in emission.

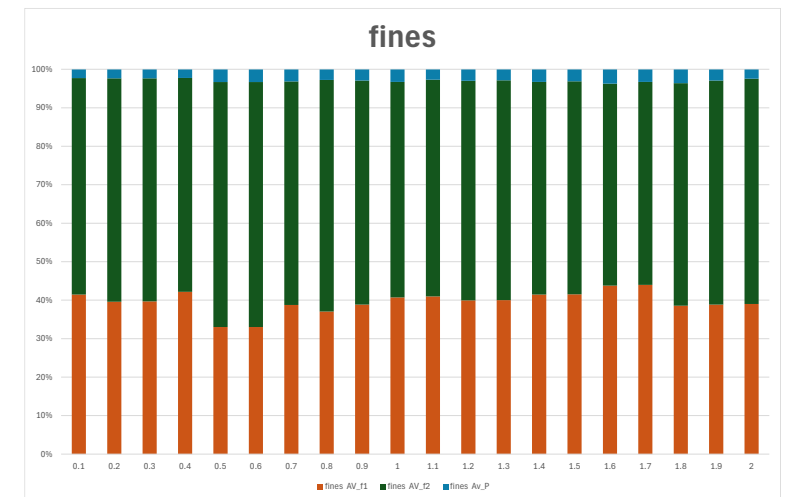
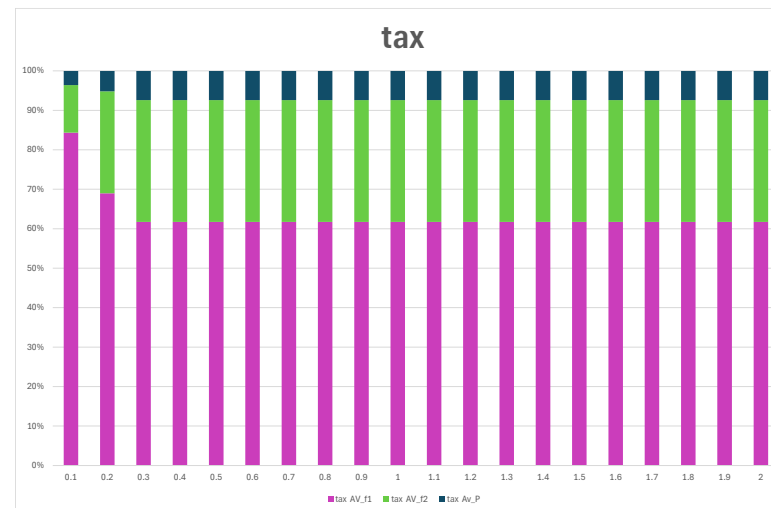
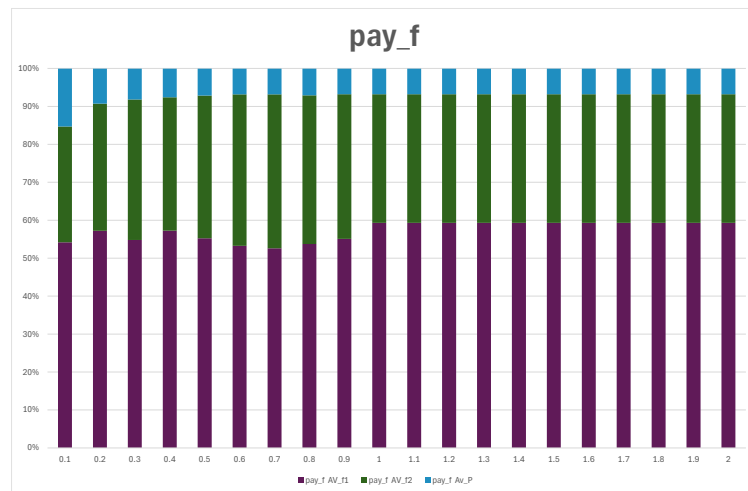
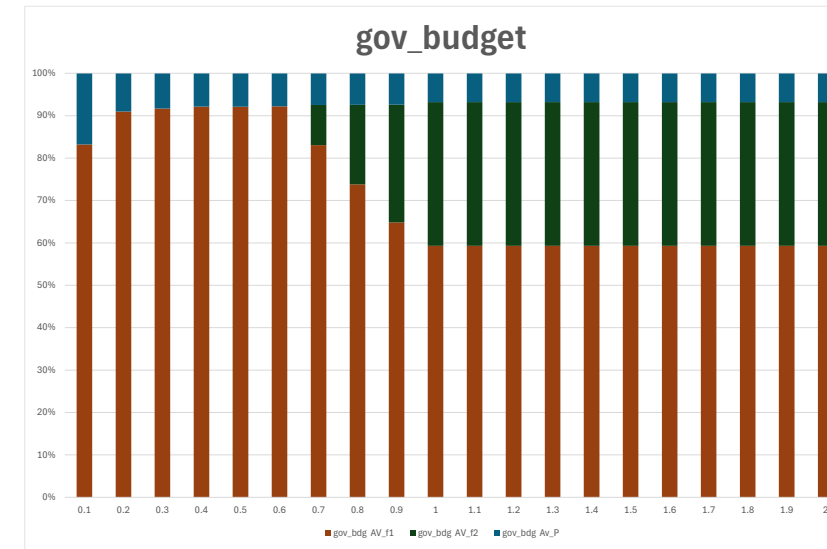
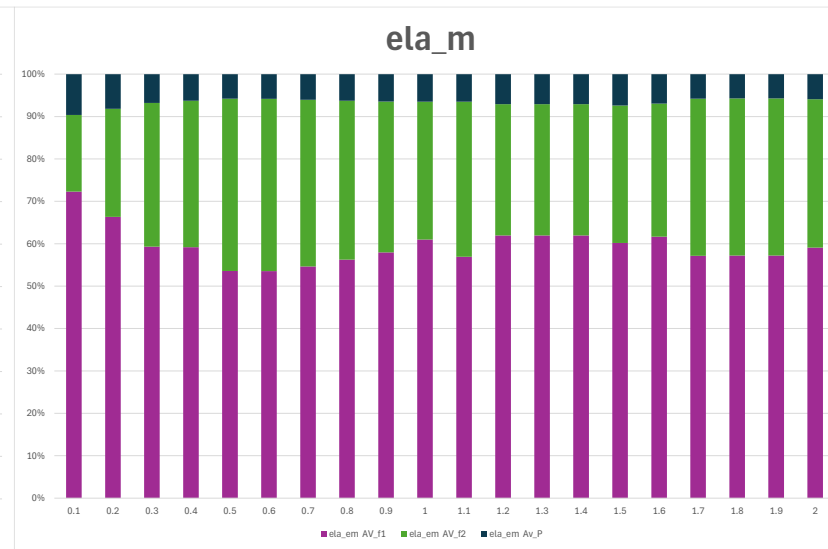
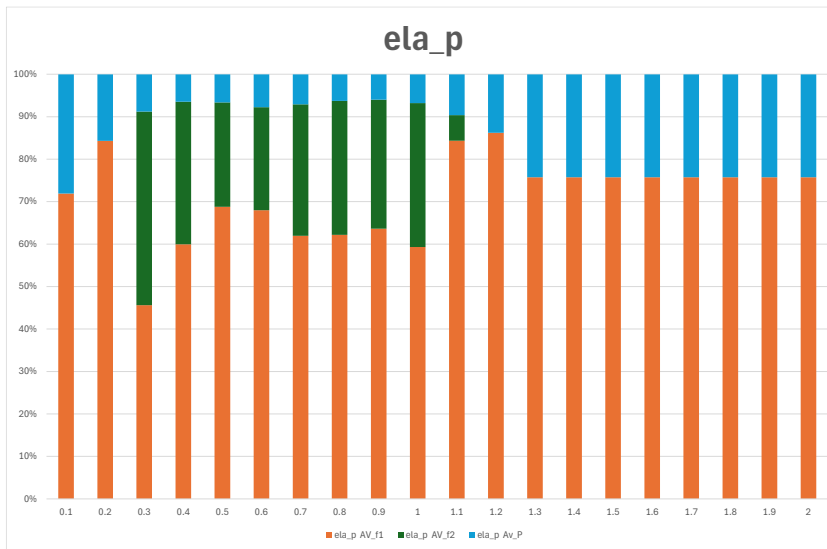
reduction of emission %



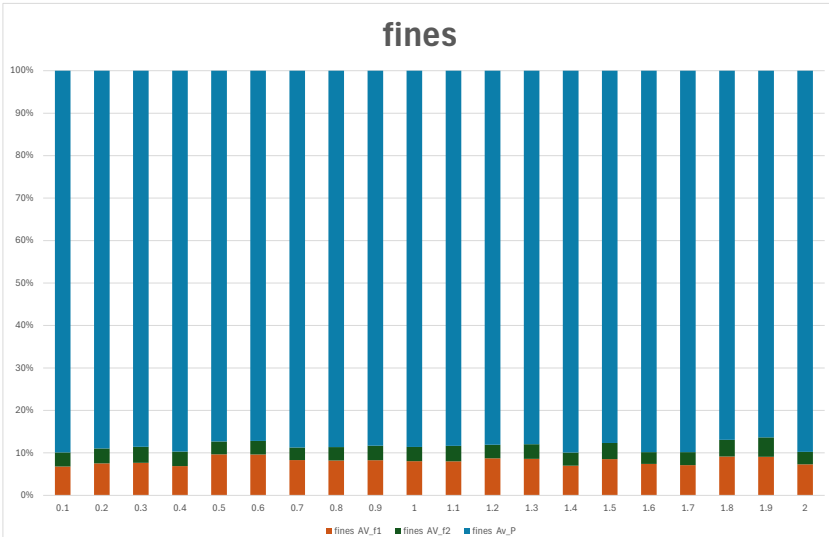
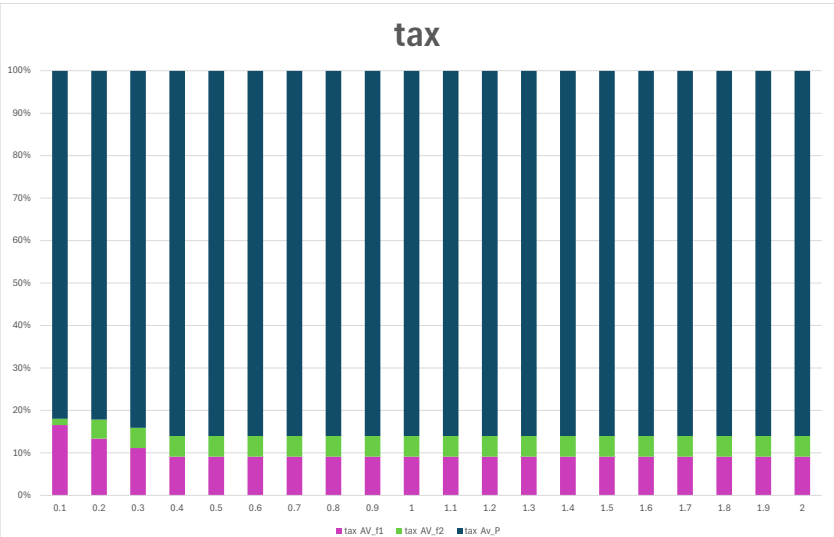
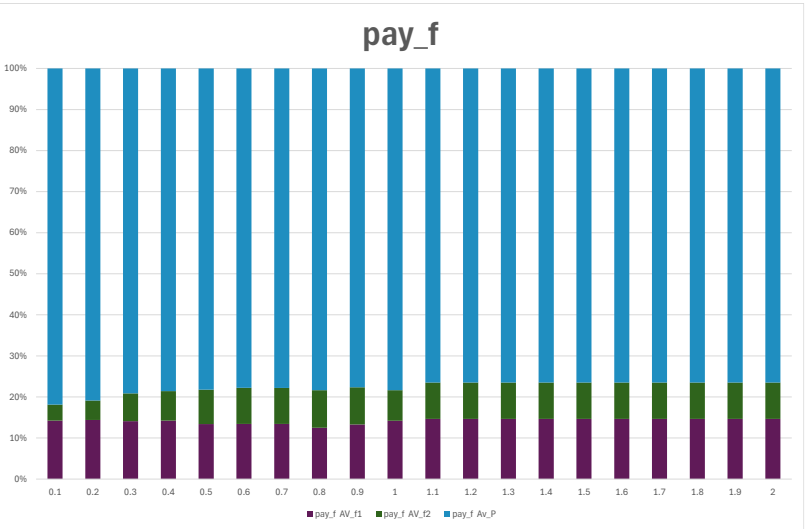
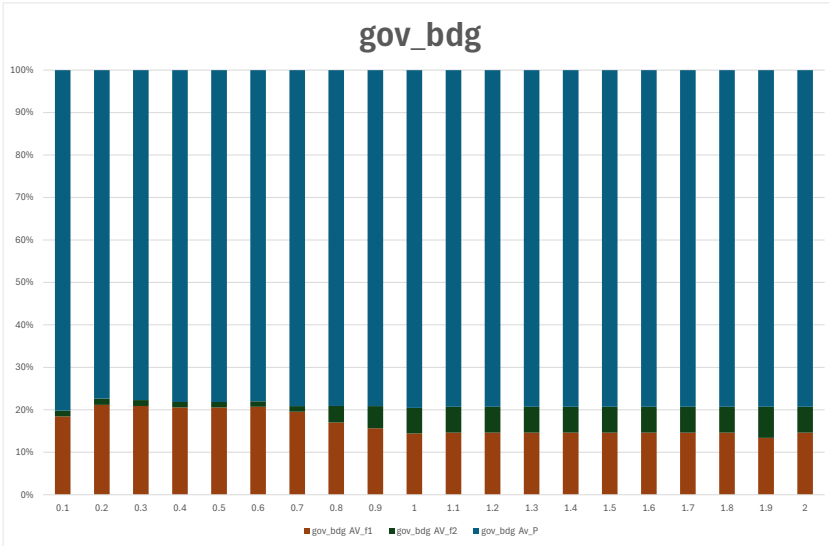
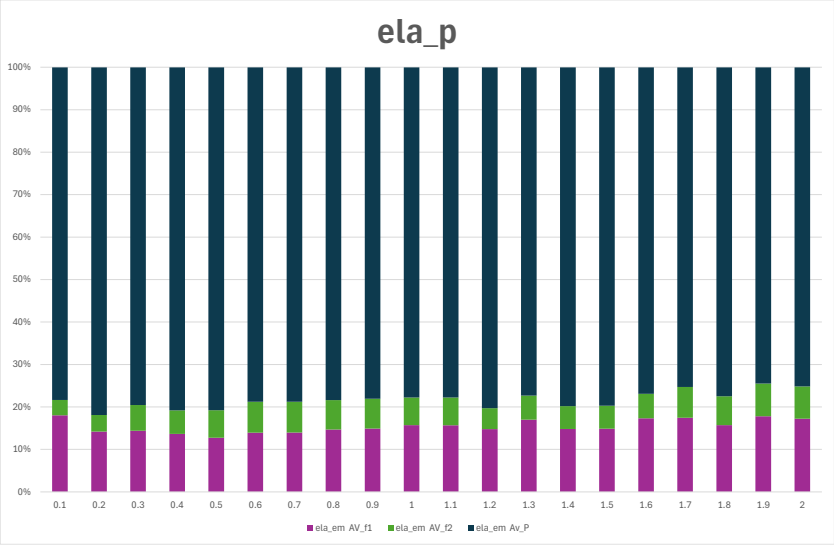
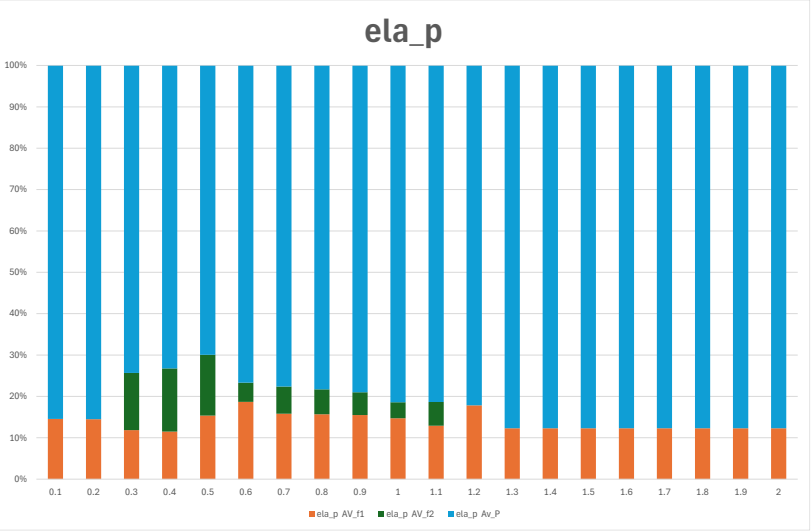
price processor (% of change)



Share of C02 emissions

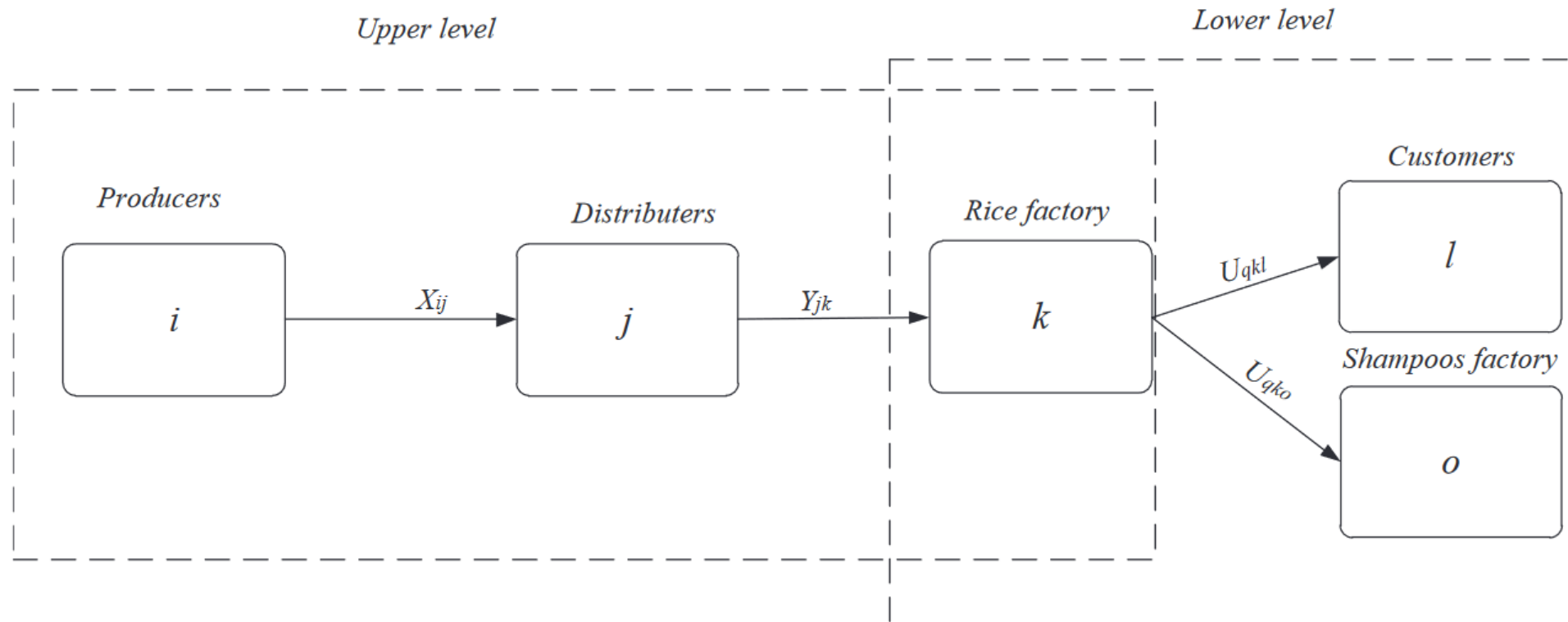


Distribution of added value



Literature review

Designing and solving a bi-level model for rice supply chain using
(Cheraghalipour et al., 2019)



Literature review

A multi-period bi-level model for a competitive food supply chain with sustainability considerations
(Manteghi et al., 2021)

