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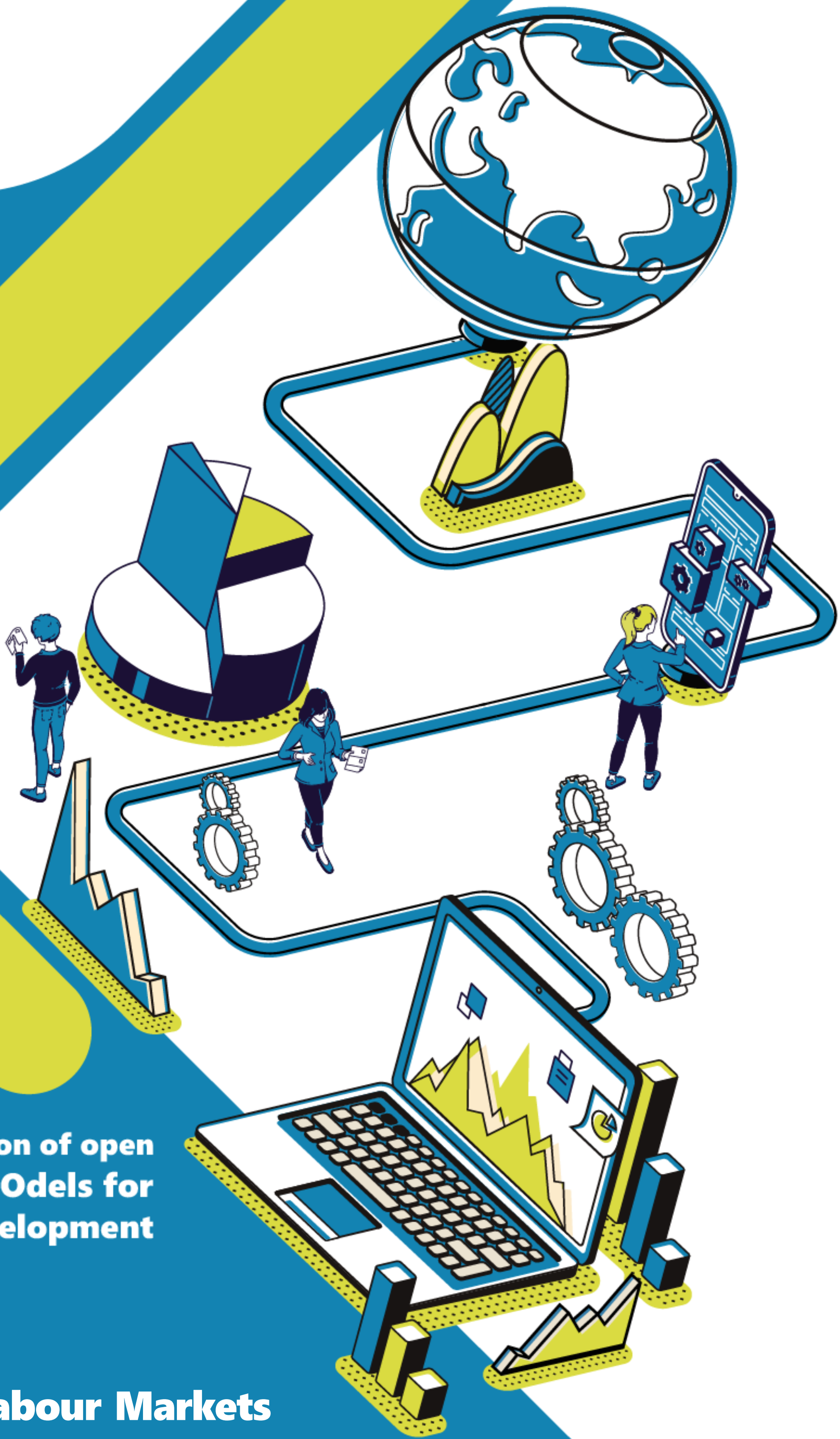

Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development

D4.5 – Financial and Labour Markets and Consumers

WP4 – Integrate and Expand – Beyond the structural

31/05/2026

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EC Summary Requirements

1. Changes with respect to the DoA

As announced in midterm reviews, we have slightly changed the focus of the deliverable early on in the project. The initially proposed work on consumer welfare was replaced by the more fundamental issue of consumer technology adoption. This is because consumer heterogeneity and endogenous technology adoption must be introduced in the models before any useful consumer wellbeing analyses can be conducted. Similarly, the work on the labour market extensions can feed into a full-blown welfare analysis for workers. With the reorientation of our work, however, that full blown welfare analysis is now beyond the scope of this project. We place it (high) on the agenda for future research and believe the work presented below has laid essentials foundations for making that next step..

2. Dissemination and uptake

The various chapters in this deliverable are or will be published in peer reviewed academic journals. Where working papers are already in an advanced state, we have summarized them in the deliverable and added the front pages and links to the most recent versions of our working paper manuscripts in the annex. We will also draft DIAMOND policy briefs based on the results we have obtained and report on these where we present the stakeholder inspired and co-designed policy scenarios in D5.2.

3. Short summary of results (<250 words)

Process Integrated Assessment Models (IAMs) have been central to mapping cost-effective decarbonization pathways, but they typically assume frictionless labour and capital markets and represent technology adoption as cost-driven optimisation by representative agents. These simplifications conceal exactly the frictions that determine how fast, how fairly and at what cost the European green transition can be delivered. DIAMOND deliverable D4.5 takes a structured step beyond these limits. Building on an extensive literature review, complemented by a stakeholder-informed agenda, the report introduces heterogeneity on the supply and demand sides of labour, financial and consumer technology markets and endogenises the matching processes that connect them. Three underlying working papers operationalised this agenda in established IAMs. A directed search-and-matching module reinterprets the CET labour-allocation elasticity as the equilibrium outcome of search frictions, wage bargaining and worker sorting, and is integrated with GEMINI-E3. A financial market module replaces uniform discount rates with technology- and country-specific Weighted Average Costs of Capital in CLEWs-EU and embeds a module in which these WACCs evolve endogenously with financial maturity in NEMESIS. A heterogeneous consumer diffusion module combines liquidity constraints, intertemporal household choice and social-network learning, and is coupled with GCAM-Europe. Together the extensions render unemployment and vacancy dynamics, capital availablity and risk premia and information and affordability thresholds visible inside IAMs, and so enlarge the policy space from carbon pricing and production subsidies to combinations of training and mobility support, green financial regulation, preferential lending, green QE, information interventions and targeted adoption subsidies.

4. Evidence of accomplishment

This report and the papers in the annexes, of which one is already published, two are currently under review, one is close to submission and three are approaching completion.

Preface

DIAMOND will update, upgrade, and fully open six Integrated Assessment Models (IAMs) that are emblematic in scientific and policy processes, improving their sectoral and technological detail, spatiotemporal resolution, and geographic granularity. It will further enhance modelling capacity to assess the feasibility and desirability of Paris-compliant mitigation pathways, their interplay with adaptation, circular economy, and other SDGs, their distributional and equity effects, and their resilience to extremes, as well as robust risk management and investment strategies. This will be done via integration of tools and insights from psychology, finance research, behavioural and labour economics, operational research, and physical science. The project will develop a transdisciplinary scientific approach to legitimise the implementation process and co-create research questions that stretch the frontiers of climate science, as well as establish vibrant communities of practice to transparently open model enhancements and to develop capacities, thereby lowering the entrance barriers to the established IAM community.

ICCS	INSTITUTE OF COMMUNICATIONS AND COMPUTER SYSTEMS	EL
BC3	ASOCIACION BC3 BASQUE CENTRE FOR CLIMATE CHANGE - KLIMA ALDAKETA IKERGAI	ES
CESAR	KRATENA KURT	AT
CICERO	CICERO SENTER FOR KLIMAFORSKNING	NO
CYI	THE CYPRUS INSTITUTE	CY
E4SMA	ENERGY ENGINEERING ECONOMIC ENVIRONMENT SYSTEMS MODELING AND ANALYSIS SRL	IT
HOLISTIC	HOLISTIC IKE	EL
COMILLAS	UNIVERSIDAD PONTIFICIA COMILLAS	ES
ISINNOVA	ISTITUTO DI STUDI PER L'INTEGRAZIONE DEI SISTEMI (I.S.I.S) - SOCIETA'COOPERATIVA	IT
SEURECO	SEURECO SOCIETE EUROPEENNE D'ECONOMIE SARL	FR
UM	UNIVERSITEIT MAASTRICHT	NL
ESMIA	ESMIA CONSULTANTS INC.	CA
USMF	THE UNIVERSITY OF MARYLAND FOUNDATIION INC	US
UMD	UNIVERSITY OF MARYLAND	US
EPFL	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	CH
ETH	EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	CH
UNIBAS	UNIVERSITAT BASEL	CH
Imperial	IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY AND MEDICINE	UK
Oxford	THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD	UK
UCL	UNIVERSITY COLLEGE LONDON	UK

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Executive Summary

This deliverable, *D4.5 — Financial and Labour Markets and Consumers*, is part of Work Package 4 of the DIAMOND project, which aims to push the next generation of Integrated Assessment Models (IAMs) beyond their structural limits. The deliverable focuses on labour, finance and consumer technology markets that jointly determine the speed, cost and distributional consequences of the European green transition. It synthesises an extensive literature review and stakeholder-informed research agenda in a framing chapter, develops three working-paper contributions that extend established IAMs along that agenda, and outlines how the resulting modules will be used to evaluate stakeholder co-designed policy scenarios (in D5.2).

Motivation. Cost-benefit IAMs have established the rationale for rapid decarbonization, and process IAMs are increasingly being asked to answer a different generation of policy questions: which workers, regions, firms and households will be affected, on what time scale, and through which channel. To answer those questions credibly, IAMs must move beyond representative-agent, frictionless representations of labour, capital and consumer markets. Stakeholder consultations conducted across the DIAMOND project and partner initiatives consistently emphasised three issues: distributional and just-transition impacts in labour markets, financial frictions and unequal access to capital, and behavioural and affordability barriers to clean-technology adoption. Mapping these issues onto a modelling agenda, the deliverable argues that the common methodological response is to introduce heterogeneity on the demand and supply sides of each market and to endogenise the matching processes that connect them.

Labour markets. Building on O'Connell et al. (2026), the deliverable develops a directed search-and-matching module that reinterprets the constant-elasticity-of-transformation (CET) parameter — used in many computable general equilibrium IAMs to govern intersectoral labour mobility — as the equilibrium outcome of search costs, Nash bargaining and worker sorting across submarkets. The module is integrated with the GEMINI-E3 model through a partial-equilibrium inversion strategy that recovers unemployment rates, vacancy rates, job-finding probabilities and unemployment durations consistent with the CGE simulations. Carbon-tax simulations show that aggregate emissions outcomes are relatively insensitive to mobility assumptions, but distributional and transitional outcomes are not. Linking the elasticity to underlying frictions provides, for the first time within this modelling tradition, a quantitative basis for evaluating training subsidies, mobility support and other targeted labour-market policies.

Finance. Building on Serebriakova et al. (2026a), the deliverable develops a financial extension that replaces uniform discount rates with country- and technology-specific Weighted Average Costs of Capital (WACCs) and embeds them in the CLEWs-EU and NEMESIS models. A micro-founded equilibrium framework links investor portfolio choice, firm financing decisions and asset market clearing, and reproduces the empirically observed pecking order in which technologies progress from State Investment Bank loans and venture capital to bank debt, public equity and corporate bonds as their financial maturity increases. The resulting WACC profile is non-monotonic, reflecting the interplay between declining instrument costs and shifting leverage ratios. The module enlarges the policy space and aligns it with current debates around green financial regulation and the role of decarbonisation goals in monetary policy.

Consumers. Building on Morley et al. (2026), the deliverable develops a heterogeneous consumer technology adoption module for residential heating, designed for integration with GCAM-Europe and similar recursive dynamic frameworks. The module replaces static logit choice with an evolutionary diffusion process driven by intertemporal utility maximisation under liquidity constraints, social-network mediated information flows, and homophilous learning. It generates endogenous S-shaped diffusion, persistent income-based adoption gaps and

credible non-price barriers. The module distinguishes the differential effectiveness of price-based, liquidity-based and information-based instruments, and provides a structural reason why carbon pricing alone tends to favour higher-income early adopters and why combined instruments dominate single instruments on equity grounds.

Policy implications. The principal cross-cutting result is that the classical "speed–fairness–cost" trade-off framing climate policy is not a fixed frontier. Once heterogeneity and matching are explicit, well-targeted instruments can relax the frictions and constraints in each market and deliver combinations of speed, fairness and cost that are unattainable with carbon pricing alone.

Limitations and next steps. The three modules are integrated through partial-equilibrium inversion or iterative external coupling rather than full simultaneous integration, calibration is constrained by the available data, and cross-market interactions are not yet operational. These limitations are deliberate trade-offs that preserve computational tractability and comparability with the existing IAM literature. The natural continuation is the systematic evaluation of stakeholder co-designed policy packages in DIAMOND deliverable D5.2.

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1 What is Next for IAMs? Modelling Heterogeneity in Labour, Capital and Consumer Markets[1]

1.1 Introduction

Integrated Assessment Models (IAMs) have been central to formulating climate policy. IAMs help policymakers project climate, energy, and technology interactions, and continue to shape debates on decarbonization (Metcalf & Stock, 2017). The broad and expanding variety of IAMs that link climate change and economic processes can be broadly divided into aggregated cost-benefit analysis IAMs and more detailed process IAMs (Weyant, 2017). These model types differ in their general structure and the level of detail in natural and economic analyses, which means they give insights into distinct climate policy questions.

The first class of cost-benefit analysis IAMs usually provides an aggregate representation of climate change mitigation costs and the economic impacts of climate change. For example, the seminal work by Nordhaus using the DICE model produced global aggregated model outcomes (Nordhaus, 1992) and has been further developed into the most recent version DICE-2023 (Barrage & Nordhaus, 2024). Its regional alternative, RICE, divides the world into several regions (Nordhaus & Yang, 1996). Other influential IAMs in this category are the PAGE model, which estimates economic impacts for different aggregated categories (Hope, 2006), and FUND, which also includes some general sectors, such as agriculture (Anthoff & Tol, 2014). Cost-benefit analysis IAMs have focused on climate policy questions centred around optimal greenhouse gas abatement trajectories and estimating the social cost of carbon for setting the optimal carbon tax (van den Bergh & Botzen, 2015). Moreover, they have been used to study the economic effects of second-best policies such as climate targets (Weyant, 2017).

A rich literature has developed which, for example, adjusted these cost-benefit analysis IAMs to reflect new scientific insights, while also examining their sensitivity to included climate impact categories, risks and assumptions about discount rates, and social welfare functions (for reviews see Botzen & van den Bergh, 2014; Tol, 2018; van den Bergh & Botzen, 2015). Early IAMs were highly sensitive to assumptions about economic damage and discounting, sparking controversy around the optimal speed and timing of emission abatement (e.g. Pindyck, 2017). While open questions remain on the correct representation of social preferences in these models (e.g. Rebonato, 2023), growing evidence on the economic impacts of climate change has now led to a broad consensus that rapid abatement is the optimal strategy (Calvin et al., 2023).

With the Paris Agreement, the focus has shifted to implementing the policies that bring such abatement and monitoring progress (van Beek et al., 2020), thereby directing attention to process IAMs. An expanding suite of these detailed models is gradually developing (e.g. IMAGE, PROMETHEUS GCAM and REMIND) to help policymakers work out effective, cost-efficient and just decarbonization pathways (Wilson et al., 2021). For example, they aim to improve the treatment of risk and uncertainty, incorporate interactions between regions and sectors and involve physical as well as economic impacts of climate change and policies (Weyant, 2017; Wilson et al., 2021). Their increased detail offers insights into adaptation processes and residual climate impacts (e.g. Diaz, 2016). They are able to test the effectiveness and efficiency of policies to achieve climate targets and provide

[1] This chapter is under review at Reviews of Environmental Economics and Policy as Sanders, M., Morley, P., O'Connell, E., Serebriakova, A., Botzen, W., Polzin, F. & Treibich, T. (2026) What Next for Integrated Assessment Models? Modelling Heterogeneity in Labour, Capital and Consumer Markets. The latest version of the manuscript can be found in Annex 1.

implications for sectors (Hollnaicher, 2025).

To the best of our knowledge, however, most process IAMs to date still assume homogenous labour and capital markets, and treat technology adoption as a rational, cost-driven process (see Section 3). These were acceptable simplifying assumptions when the purpose was to weigh the costs and benefits of climate (in)action in the long run or to show that decarbonization is technically and/or economically feasible. But making effective, efficient and fair climate policy now requires that the models account for the real-world frictions that shape the speed, cost and distributional impacts of the transition.

Table 1: Stakeholder Questions and Modelling Gaps

Theme	Examples of Policy Questions	Identified Modelling Gaps	Sources
Labour & Just Transition	How will decarbonization affect employment and regional economic viability? What skill-development and transition policies are required? Can labour shortages slow down the energy transition? How do governance/institutional limits constrain just transition? Which *regions, sectors and occupations* will face job losses or gains from climate policies? How will climate policies affect *job quality*, working conditions, and health/safety risks? What *skills*, retraining needs, and labour-market institutions are required for a fair transition? How to support *vulnerable groups* and prevent widening inequalities?	IAMs and top-down macro models provide *aggregate employment effects* but not disaggregated regional/occupational outcomes. Job quality, health risks, and social impacts are *not represented* in most modelling frameworks. Skill formation, retraining systems, and institutional capacity are *qualitative governance factors* missing from model structures. Short-term dislocation costs are poorly captured due to long-run equilibrium assumptions.	DDPP (2015); IIASA (2023); Jäger et al. (2023); ABN-AMRO (2023); OECD (2025a); Eurofound (2024)
Finance & Investment	What investment levels are required? How do policies affect cost of capital? What barriers inhibit private finance, especially in emerging economies? How to represent investor behaviour and risk? How can capital be mobilised across regions and income groups for a *just and equitable transition*? What financial barriers (risk premia, regulatory uncertainty, credit constraints) slow the deployment of clean technologies? How do climate investments affect *distributional outcomes* and vulnerability across communities? What levers can reduce investment risk for private actors?	Many models assume frictionless capital markets and *ignore risk*, policy uncertainty, and financing conditions. Distributional access to finance (across countries, communities, income levels) is rarely modelled. Investor behaviour under uncertainty and policy shifts is simplified or absent. Capital allocation, labour impacts, and consumer adoption are usually *modelled separately* rather than integrated.	IIASA (2023); Heusaff & Zachmann (2023); I2AM PARIS (2025); OECD & UNDP (2025); Climate Strategies (2018);
Consumer Technology Adoption & Behaviour	What drives/limits household adoption of EVs, heat pumps, retrofits, diets? How do behavioural, cultural, informational and financial factors shape adoption? Which policy mixes accelerate uptake equitably? Which consumers adopt clean technologies and under what conditions? How do *income, affordability, credit access*, and social norms shape adoption rates? How big are *adoption lags* due to building lifetimes, capital cycles, or lack of information? What policies increase *public acceptance* and reduce resistance to change?	IAMs typically assume cost-optimal, smooth technology diffusion, neglecting *behavioural heterogeneity* and non-price barriers. Affordability constraints and credit access are largely absent from model structures. Timing constraints (e.g., retrofit cycles) and real-world delays are rarely represented. Political acceptability, trust, and social norms are *qualitative drivers* outside standard IAM frameworks.	Jäger et al. (2023); Van Vliet & Takama (2018); OECD (2025b); EEA (2024);

In this report we focus on labour, finance and consumer technology markets because labour and (investment in new) capital are the key factors driving output and emissions on the production side, whereas green technology adoption in consumer markets drives emissions on the consumption side. Emission reduction policies therefore imply shifting labour, in- and divesting in different types of capital and changing consumption baskets, creating significant frictions and adjustment costs. In turn, these costs impact on workers, investors and consumers, who are key constituencies determining political support for climate policy.

We see this interest also reflected in stakeholder focus groups. Table 1 above synthesises stakeholder-informed policy questions relating to labour markets, finance and investment, and consumer technology adoption taken from several stakeholder engagement reports (e.g. CHIPS, 2022; DDPP, 2015; Heussaff & Zachmann, 2023; I2AM PARIS, 2025; IIASA, 2023; Jäger et al., 2023; NAVIGATE, 2022) and widely cited international assessments (e.g. EC, 2021; EEA, 2024; Eurofund, 2024; OECD, 2023, 2025b, 2025b; OECD & UNDP, 2025)

For labour, these reports emphasise that policy makers are concerned about distributional impacts. They are interested in which regions, occupations, and demographic groups are likely to face job losses, skill mismatches, or deteriorating job quality. Addressing such questions in process IAMs invariably requires that we leave homogenous, representative agent models behind and zoom in on differences in groups of workers and types of jobs on the geographical, skill and wage dimensions. We will refer to this as *heterogeneity* on the supply (workers) and demand (jobs) sides of the labour market. To then go beyond tracking the impacts on these groups and also evaluate policies that intervene in labour markets we will also need to *endogenize* the matching process between heterogenous supply and demand, for example by including the effects of education and training decisions on the supply of specific skills, or by considering the links between the energy transition and the demand for skills across sectors and regions.

In the finance and investment domain we find a similar situation. What stands out is the need to account for the differences in access to finance, the level of risk premia, the impact of regulatory uncertainty and the resulting financial market frictions that could delay or increase the price of the transition. These questions point to persistent modelling gaps related to investment barriers, financial investors' behaviour, and unequal capital allocation across regions, technologies, sectors or income groups. Arguably, we can relate all these questions, as above, to the need to introduce *heterogeneity* on the supply (financial investors and financial assets) and demand (investment projects in firms) sides of financial markets, as well as *endogenizing* the matching process by modelling how demand and supply are intermediated through markets for e.g. bank credit, corporate debt and private and traded equity.[2]

Finally, for consumer technology adoption, the table lists questions expressing interest in understanding behavioural heterogeneity (i.e. the drivers of preferences for green products), affordability constraints, adoption lags (who are the early vs. late adopters), and non-price barriers such as information, trust and social norms. Again arguably, these questions reveal the need to introduce *heterogeneity*, primarily on the demand side in this case, as the different (consumer) technologies are typically already well represented in process based IAMs. Different (groups of) consumers, however, differ importantly in their preferences, access to information and income and wealth levels. Again, to go beyond tracking the impact on different consumer groups, their technology adoption must be *endogenized* to evaluate policy interventions in this space.

In sum, stakeholders call for introducing relevant *heterogeneity* on the demand and supply sides of relevant

[2] Note that in most finance papers and the popular press the provider of funds is referred to as the "investor". To clearly distinguish supply from demand, we refer to the providers of finance as the "financial investor", which includes private and institutional savers, such as pension funds and insurance companies. We refer to agents seeking finance to purchase real productive assets such as windmills, factories and machinery as the "investing firms". Between these agents, "financial intermediaries", such as (investment) banks, fund managers and brokers, match the supply and demand for (different types of) finance. Agents wanting to put their wealth in stocks, bonds or equity are therefore financial investors supplying financial resources (typically to or through intermediaries) to investing firms (re)building the capital stock in the economy.

markets, as well as *endogenizing* the matching processes in these markets.[3] In exploring the space for improvement in process IAMs e.g. Keppo et al. (2021) already called for and discussed: a) introducing heterogeneity across agents to better track different responses and impacts; to better represent b) technology diffusion and c) finance and investment; and to d) improve the energy-economy feedbacks in the models. With this chapter, we develop this research agenda further by specifically reviewing the literatures that can help us build these extensions. Moreover, we discuss how introducing heterogeneity and endogeneity of adjustment processes opens the models to hitherto unexplored policy instruments that may achieve better outcomes at lower (private or societal) costs.
In the remainder of this chapter, we therefore first ask: How can the literatures on labour markets, financial investment and consumer technology adoption inform the urgent extensions to existing IAMs? Sections 1.2, 1.3 and 1.4 will synthesise relevant facts, take stock of process IAMs and draw inspiration from the literature to extend these IAMs, respectively. In section 1.5 we discuss tentative policy implications based on the literature reviewed and in our concluding section 1.6 we propose the agenda for the rest of this report and start to fill the identified gaps.

1.2 Labour, Finance and Consumer Technology Adoption – Relevant Facts

To identify the fundamental characteristics of labour, financial and consumer markets to be integrated into IAMs, we first draw on the respective empirical literatures and present a series of stylized facts in Tables 2 I-III. These facts are well established in the extensive literatures on labour market dynamics, financial markets and consumer product adoption, respectively, and the tables list only the most foundational references.

For labour, Table 2-I establishes that skills require investment (L1), wages drive labour reallocation (L2) but searching and matching in the labour market are not frictionless (L3) and therefore mobility of labour across sectors and regions is costly (L4).

There are different ways to measure the relevance of human capital supporting L1 (UNECE, 2016), but the literature would put the average human capital investment between 3.5 and 6% of GDP (OECD, 2020; Paczos et al., 2023) when we look at expenditures on education, whereas estimates of the value of human capital range between 10-25% of GDP (Christian, 2017; Jorgenson & Fraumeni, 1991; Jorgenson & Pachon, 1983). The importance of wage differentials in driving labour (re-)allocations (L2) is discussed in e.g. Blanchard et al. (1992), Kambourov and Manovskii (2009) and Autor et al. (2016). Labour (re-)allocations are slow and costly, due to a number of frictions in labour markets (Autor et al., 2013), supporting facts L3 and L4.

[3] We use the term "matching" here loosely to refer to workers matching with jobs, financial investors matching with investing firms and consumers matching with (green) technologies to fulfil their needs and desires.

Table 2-I: Stylized Facts for Labour

Stylized Fact		References	Description
L1	*Labour market outcomes are contingent on human capital accumulation.*	Schultz (1961); Becker (1962); Mincer (1974); Angrist & Krueger (1991)	Education and skill acquisition are investments in people that increase productivity and earnings; General training benefits workers, while firm-specific training benefits employers; Wages rise with schooling and experience; Compulsory schooling laws demonstrate that education drives better labour outcomes.
L2	*Wage differentials influence the labour supply*	Roy (1951); Willis & Rosen (1979); Borjas (1987); Jensen (2010)	Workers sort into occupations where their skills yield the highest returns; Individuals pursue higher education when expected lifetime wage gains outweigh costs; Higher returns to skill attract more educated workers and generate positive selection; When students learn that schooling brings higher wages, they stay in school longer.
L3	*Search and matching frictions exist between vacancies and jobseekers.*	Diamond (1982); Pissarides (1985); Mortensen & Pissarides (1994); Shimer (2005)	Workers and firms may fail to coordinate efficiently, leading to search externalities where unemployment and vacancies coexist even in equilibrium; Even with open jobs and job seekers, unemployment persists because the matching process is imperfect and hiring takes time; Wages negotiated after a match influence job creation; If firms expect higher bargaining costs, fewer vacancies are posted, increasing equilibrium unemployment; Recessions sharply reduce job-finding rates relative to job separations, causing large cyclical movements in unemployment and vacancies; Rapid job destruction from shocks outpaces the creation of new matches, generating unemployment in the presence of costly search and matching frictions;
L4	*Labour mobility is hindered by sectoral and regional frictions.*	Sjaastad (1962); Harris & Todaro (1970); Lilien (1982); Blanchard & Katz (1992); Kennan & Walker (2011)	Workers weigh multiple relocation costs such as financial, social, and psychological factors, making migration a cost that deters movement despite potential long-term gains; Migration occurs when expected urban income exceeds rural income so regional mobility depends on expected wage and unemployment differentials; Structural shifts in labour demand across industries create mismatches in skills and employment; Adjustment to shocks remains slow because migration responds sluggishly to wage gaps; Migration decisions are impeded by uncertainty and risk. This discourages movement even when large wage disparities exist.

When we turn to finance, Table 2-II establishes that different financial investors have different risk-return preferences (F1) and that the mix of available financing instruments, and consequently the cost of capital for investing firms differs over location, technology, and maturity (F2). Moreover, although less pronounced than in labour markets, financial markets fail to frictionlessly match supply to demand causing capital misallocation, which can be exacerbated by limited market development and credit constraints from asymmetric information and banking regulation (F3). Finally, a more recent literature has established that important physical and transition risks related to climate change are not accurately priced into financial markets, raising concerns over instability (F4).

The empirical relevance of facts F1 and F2 becomes apparent when we consider the implications for firms' weighted average cost of capital (WACC). Firms typically finance their investment portfolio with a mix of liabilities, including traded and over the counter (OTC) instruments for debt and equity. Financial investors' risk appetites translate into different required returns on different types of liabilities (Friend & Blume, 1975; Mazzucato & Semieniuk, 2018), where Fama and French (2002) put the historical equity premium between 2.5 and 4.3%. Due to differentiated access to these funds, the WACCs differ widely between investing firms (F2).

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Table 2-II: Stylized Facts for Finance

Stylized fact		References	Description
F1	*Appetites for risk, maturity, and ticket size vary by financial investor type*	Friend & Blume (1975); Ferreira & Matos (2008); Mazzucato & Semieniuk (2018)	Different financier types (including individuals, investment banks, institutional investors, venture capital, governments) prefer to finance projects with low / high risk, short / long time horizons, small / large volumes.
F2	*Assets and projects differ on risks and returns, affecting costs of capital for investors on spatial and time dimensions*	Abel & Blanchard (1986); Kiyotaki & Moore (1997); Fama & French (2004); Frank & Shen (2016); Egli et al. (2018)	Risk and return are positively related; financing investments is achieved through issuing a mix of liabilities, including types of debt and equity, each with costs and benefits, aggregated into WACC; Heterogeneity based on firm and technological characteristics, as well as macro-financial national conditions matter; Financing costs change over technology life cycles.
F3	*Financial market development and credit constraints can cause financial frictions and misallocation*	Stiglitz & Weiss (1981); Rajan & Zingales (1998); Allen & Gale (2004)	Credit rationing can be an equilibrium outcome under information asymmetry, mediated through banking relationships; Institutional history in part determines the structure of debt and equity markets, which affects firm growth and technological development.
F4	*Climate risks are incompletely priced, creating future threats to financial stability*	Battiston et al. (2012); Semieniuk et al. (2021)	Physical risks ensue from climate events and transition risks from climate policy; Sudden devaluation of stranded assets, indebtedness from the transition, and other climate outcomes can significantly contribute to future bank losses and financial crises.

For energy technologies specifically, Hatton et al. (2025) find a range of WACCs for 2022 that vary from 5.7 percent for onshore wind in Germany, to 16.6 percent for solar PV in Turkey and over 20% for countries with significant risk of macroeconomic instability. These differences vary systematically with the maturity of a firm, technology and sector. Abudy et al. (2016) show that privately held (smaller, younger and more innovative) ventures pay a premium of between 2-15% over (more mature) publicly traded firms. Firms in technologically immature sectors, particularly when investing in R&D and initial deployment, experience a “funding gap” (Hall & Lerner, 2010), and are therefore reliant on risk-seeking public agencies and venture capital, where the latter can command up to a 50% return (Cochrane, 2005). Importantly, this implies that the WACC also tends to fall as firms and technologies mature (Egli et al., 2018; Polzin, 2017).

Facts F3 and F4 suggest we need to model the matching of financial supply and demand as imperfect and containing frictions. Asymmetric information implies that cashflow and retained earnings are preferred sources of funding (Gilchrist & Himmelberg, 1995), meaning that established firms with locked-in interests in mature technologies can expand and maintain their capital stock at lower costs than the challengers that seek to replace them (Perez & Soete, 1988). Moreover, given the strong focus on stability in financial regulation, these firms also have a competitive advantage in acquiring bank loans, issuing bonds and listing equity. This was shown, for example, by looking at the impact of ECB bond purchases, that benefited established (polluting) firms more than younger green ones (Papoutsi et al., 2021).

A large share of emissions is related to production and depends on the aggregate behaviour of firms, employing workers and financing investments. To complete the picture, however, we also need to consider the behaviour of their customers, consuming their outputs. Especially choices related to high emission intensity consumption, such as mobility, residential heating and solar panel installations have an important aggregate impact. Papers listed in Table 2-III have firmly established that technology diffusion typically follows a logistical curve (C1), starting slow, then speeding up and levelling off as a market saturates. In search of explanations for this pattern, diffusion has been found to interact with price and budget (C2) and information constraints (C3) that have been linked to information cascades in homophilic social networks (C4), where people learn from and emulate the behaviour of others in a social network with a disproportionately high share of demographically similar neighbours.

Table 2-III: Stylized Facts for Consumption of Green Technology

Stylized Fact		References	Description
C1	*Adoption of new technologies follows a logistic curve*	Rogers (2003); Fisher & Pry (1971); Geroski (2000)	When new technologies are introduced, only a small group of avant garde consumers will adopt it initially. Only after some time, the technology becomes normalized and more risk averse consumers choose to adopt, diffusion speeds up and ultimately slows as the market approaches saturation, resulting in the characteristic S-shaped diffusion curve.
C2	*Low-income households are less likely to adopt green technologies*	Ameli & Brandt (2015); Heiskanen & Matchoss (2017); Lee et al. (2025); Best & Madlener (2025)	In efficient credit markets there should also be no income effect in the adoption of net present value positive technologies. However, high-income households are more likely to adopt solar panels, electric vehicles, and residential energy efficiency improvements compared to low-income ones.
C3	*Uptake of new technologies depends on information diffusion*	Bandura (1977); Zhang et al. (2024); Axsen et al. (2013)	To adopt a new technology, consumers first need to learn about it. Theoretically, this can be linked to Social Learning Theory. Empirically, we see that diffusion of information about and adoption of green consumer technologies is influenced by both geospatial proximity to adopters.
C4	*Social networks exhibit homophily and segregation*	McPherson et al. (2001); van Ham et al. (2021)	Social networks and their composition is relevant to technology diffusion. Empirical research has shown that these networks typically exhibit homophily. That is, people network with others like themselves. Such segregation also manifests geospatially, although the evidence is mostly given for large cities like New York and LA in the US.

Fact C1 is well established (Fisher & Pry, 1971; Geroski, 2000; Rogers, 2003) for pretty much all new technologies and goes back to early work by e.g. Grilliches (1957), who fitted logistic growth functions to data on the adoption of hybrid corn in the US. Fact C2 is supported by e.g. Heiskanen and Matchoss (2017) who find that investment cost and availability of capital (household income) to be frequently identified predictors of green technology adoption. In addition, Ameli and Brandt (2015) found that the probability to invest in energy efficient appliances rises by 10% between 15 and 45 thousand dollars of net household income, but only by 3% from 60 to 95 thousand dollars. They also show that these estimates vary significantly across green technologies and the 12 OECD countries in their sample. For some technologies, like electric vehicles, adoption viability depends on the local availability of complementary systems, and this can lead to even larger persistent inequalities in adoption when consumers are geospatially segregated by income (Lee et al., 2025).

In addition to financial constraints, information constraints constitute a significant barrier to the adoption of efficient green technology alternatives (C3). For instance, Bollinger and Gillingham (2012) find that an additional solar PV installation in California increases the probability of adoption of the technology by 0.78% for households within the same zip code. There is also evidence of spatial spillovers in the uptake of various technologies (e.g. Min, 2025). In the presence of network effects that facilitate information cascades, information-based interventions can be surprisingly effective, with cumulative and persistent effects (Allcott & Rogers, 2014). McPherson et al. (2001), however, provide evidence that social networks tend to be strongly homophilic and households that share demographic characteristics, such as income, are also likely to cluster socially and geographically (van Ham et al., 2021) (C4). To model different consumers adopting different technologies at different points in time, we first need to introduce heterogeneity among consumers on income, social networks and preference dimensions. To adequately represent feedback effects and interactions the technology adoption decisions must also be endogenized, so we may explore policy interventions that use the endogenous diffusion dynamics to their benefit.

In what follows, we first review to what extent the heterogeneity in labour supply, financial markets and consumer demand are already represented in the state of the art (process-based) IAMs, before turning to the respective literatures in labour, finance and technology adoption by consumers for inspiration on how to build these extensions.

1.3 Labour, Finance and Consumer Technology Adoption - State of the Art in IAMs

To gauge the state of the art in process IAMs Table 3 below reviews eleven models. These include models in the European Horizon project "DIAMOND", (GCAM, GEMINI-E3, NEMESIS, PROMETHEUS, TIAM-UCL) extended with other widely used IAMs (E3ME, GEM-E3, IMAGE, MESSAGEix, REMIND-MAgPIE and WITCH). This selection was contingent on the availability publicly accessible documentation, necessary to systematically evaluate how labour matching, financial markets, and final consumption are represented. Although the resulting set of eleven models is certainly not exhaustive, we believe it covers a representative range of prominent, process-based IAMs (see e.g. Keppo et al., 2021).

In the above we have argued that for labour, finance and final consumption the models need to allow for heterogeneity on the demand and/or supply side and endogenize matching in the different markets. For labour, we focus on search and matching frictions between skills and jobs, and how these characteristics can endogenously evolve. For finance, we differentiate between firms seeking finance for different technologies and projects, so that endogenous processes of how financial investors, through markets and intermediaries, determine the WACC for these firms can be assessed. In final consumption of green technologies, we must consider heterogeneity in consumer preferences, social networks and income/wealth, such that we can endogenize the adoption of new technologies with different characteristics in different geographies.

We have investigated the latest published model descriptions and scored the models on their level of heterogeneity (from 1=homogenous, 2=two representative agents, 3=three (or more) representative agents, 4=single continuous distribution, 5=continuous distributions on all relevant dimensions) and endogeneity (1=static exogenous, 2=dynamic exogenous, 3=static iterative consistent, 4=dynamic iterative consistent, 5=recursive dynamic) on these dimensions. One should read for example line 1 in Table 3 as: E3ME, as described in Cambridge Econometrics (2022), features 1=no (heterogeneity in) search and matching, but features 3=three or more wage levels and no labour mobility constraints between these featured labour markets, while the model distinguished no skill level differences (human capital accumulation is 1=homogenous). In the endogeneity column, we see that E3ME features 1=exogenous static for search and matching frictions, labour mobility constraints and human capital accumulation (because they are assumed absent) while it features 3=dynamic iteratively consistent wage differentials. This means that wages are computed to equate supply and demand, after which these wages are used as exogenous inputs in the next iteration of the model. In short, the E3ME model recognizes different sectors between which there is no labour mobility, and real wages adjust endogenously to prices and productivity, such that wage differentials can persist in equilibrium. Consequently, it fails to address stylized facts L1 and L3, as it has iteratively consistent wage differentials and assumes mobility constraints, but has no human capital accumulation nor matching frictions. If we go down the list, we observe that for labour, the levels of heterogeneity and endogeneity rarely exceed 2 as most process IAMs, even in their most recent versions, still feature a homogenous and frictionless labour market.

Turning to finance, we find that few state-of-the-art IAMs feature high levels of heterogeneity on relevant dimensions. As an outlier, GEM-E3 can accommodate multiple assets, such as bonds, loans, retained profits and traded equity as sources of finance for investment; these can also differ in price (required return) within asset types

Table 3: State of the Art in (Process) IAMs

Model	Reference	Labor				Finance				Consumers			
		Dimension	Heterogeneity	Endogeneity	Stylised facts *not* addressed	Dimension	Heterogeneity	Endogeneity	Stylised facts *not* addressed	Dimension	Heterogeneity	Endogeneity	Stylised facts *not* addressed
E3ME	Cambridge Econometrics, 2022	Search & Matching Frictions	1	1	L3, L1	Financiers	2	1	F1, F4	Geography	1	1	C2, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	4	1	
		Wage Differentials	3	3		Investors/Projects	2	2		Technology	1	5	
		Human Capital Accumulation	1	1		Macro-Monetary	3	4		Income/Wealth	1	1	
GCAM	PNNL, 2020	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	2	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	1	1		Income/Wealth	4	2	
GEM-E3	ICCS, 2017	Search & Matching Frictions	1	1	L3, L1	Financiers	3	1	F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	2	2		Assets	4	3		Preferences	1	2	
		Wage Differentials	2	2		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	3	3		Income/Wealth	1	4	
GEMINI-E3	EPFL, 2025	Search & Matching Frictions	1	1	L3, L1	Financiers	1	1	F1, F2, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	1	
		Wage Differentials	2	2		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	2	1		Macro-Monetary	2	2		Income/Wealth	1	1	
IMAGE	PBL, 2022	Search & Matching Frictions	1	1	L1, L2, L3	Financiers	1	1	F1, F3, F4	Geography	2	1	C1, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	3	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	2	1		Income/Wealth	3	2	
MESSAGEix	IIASA, 2020	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	2	1		Income/Wealth	1	2	
NEMESIS	ERASME, 2025	Search & Matching Frictions	1	1	L3	Financiers	2	2	F3	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	2	1		Preferences	1	1	
		Wage Differentials	2	1		Investors/Projects	2	2		Technology	1	1	
		Human Capital Accumulation	2	2		Macro-Monetary	3	2		Income/Wealth	1	5	
PROMETHEUS	E3M, 2018	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	2	1		Income/Wealth	1	2	
REMIND-MAgPIE	PIK, 2020	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F4	Geography	1	1	C1, C2, C4
		Labour Mobility Constraints	1	1		Assets	2	1		Preferences	1	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	5	
		Human Capital Accumulation	1	1		Macro-Monetary	2	1		Income/Wealth	1	1	
TIAM-UCL	IER, 2020	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	2	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	1	1		Income/Wealth	1	2	
WITCH	EIEE, 2019	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	1	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	1	1		Income/Wealth	1	2	

Note: To have a rough first impression we (generously) scored the models on heterogeneity 1-homogenous, 2=two representative agents, 3= three or more representative agents, 4-one dimension of heterogeneity continuous, 5=all relevant dimensions continuously distributed. And on endogeneity 1=exogenous static, 2=exogenous dynamic, 3-iterative consistent static, 4-iterative consistent dynamic and 5-recursive dynamic. We report a "0" for absent or insufficient information or not applicable. It is hard (impossible) to score these very different models very precisely on these categories and the reader is referred to the references in the table for precise details.

(E3-Modelling, 2017). This corresponds best to a heterogeneity level 4 (three or more representative types with at least one dimension as a continuous distribution). Other models also feature some granularity in the representation of technology costs, even if they do not always link this to heterogeneity among financial investors, asset markets or investing firm types. In the model manuals, IAMs including MESSAGE, REMIND, and TIAM, still consider finance to be homogenous on the supply side, exemplified by uniform discount rates (Hatton et al., 2025), and are graded as a heterogeneity level 1.

This assumption would imply, against the evidence described in the stylized facts, that all investments can be fully financed at the same cost of capital. By leaving financial markets implicit and costs of capital uniform, the market-clearing mechanisms in CGE IAMs leave little room to account for realistic mismatch and frictions (Pollitt & Mercure, 2018). As explained in the following section, Calcaterra et al. (2024) have shown that differentiating WACCs by country and technology to account for risk, already has significant effects on IAM model outcomes.

The two macro-econometric IAMs in our survey (E3ME and NEMESIS) have made the most significant inroads into the representation of finance in macroeconomic and monetary terms (Cambridge Econometrics, 2022; SEURECO ERASME, 2019). For E3ME, this includes endogenizing interest rates according to central bank targeting rules, tracking regional and sectoral debts, modelling credit-led money creation, and introducing bounded rationality in the allocation of financial resources; this corresponds best to an endogeneity level 4. GEM-E3 (E3-Modelling, 2017) distinguishes assets in a financial CGE framework, without the capacity for including financial frictions (F3). This is indicative of many IAMs reviewed here: the level of heterogeneity and endogeneity they achieve can partially address the financial stylized facts, but none can reproduce all the dimensions of the references included in Table 2-II. Further endogenizing the matching of financial investors to investing firms through intermediaries and asset markets could bring financial policy interventions in scope of our models. Stock-Flow-Consistent (SFC) and Agent-Based Modelling (ABM) approaches show the most promise in achieving this endogeneity (Hafner et al., 2020). Endogenous matching in finance would also serve to explore financial instability concerns, as stylized fact (F4) is mostly overlooked by existing IAMs.

Concerning end-use energy technology adoption by consumers, some of these IAMs have introduced either significant heterogeneity or endogeneity on one or two relevant dimensions, but never both. The geographic location (e.g. urban/rural, solar irradiation for PVs, etc.) is often important in determining the viability and desirability of various technologies, but only TIAM-UCL has included differentiated urban and rural consumers, though population flows are not modelled. Income is made heterogeneous in some versions of GCAM and in IMAGE by representing income quintiles or deciles as a set of distinct representative agents. Income endogeneity, i.e. income depending on endogenous growth, is present in few of the models. However, except for IMAGE's income-dependent discount rates, household income has no direct impact on technology substitution decisions in any of these IAMs. Preferences exhibit some heterogeneity together with income in those versions of GCAM, where the income decile affects technology utilization and therefore lifetime variable costs, and in IMAGE, where consumers apply endogenous income-dependent discount rates to cost comparisons. While information availability is homogenous in all the models, E3ME uses the FTT family of technology substitution modules, where diffusion speed dynamically depends on instantaneous market shares, and this is interpreted in part as an endogenous representation of information diffusion.

The stylized facts on end-use technology substitutions are largely ignored by the state-of-the-art models. The relevance of C1 is widely recognized, but it is often only loosely approximated by exogenous imposition through mechanical constraints and exogenous trends in preferences. C2, C3, and C4 are all largely absent. E3ME stands out, as its FTT decision modules endogenously generate sigmoid diffusion curves, reproducing C1, and they do so by accounting for the availability of information in the decision function, reproducing C3.

In conclusion, although the situation looks best for heterogeneity in finance and endogeneity in green technology adoption by consumers, in all three areas, IAMs would benefit greatly from introducing and enriching the heterogeneity and matching on both sides of relevant labour, financial and final goods markets. In final goods markets, the representation of technologies and financial constraints for groups of consumers seems most advanced. But the adoption process would still require careful specification as in this market non-financial considerations (behavioural biases, information cascades and network effects) are likely to be important. Financial and especially labour markets seem to have been somewhat neglected in the IAMs to date. Nevertheless, stakeholders and policy makers indicate that the matching of (displaced) workers to new, green jobs and the intermediation of finance to energy transition projects are crucial ingredients in policy relevant IAMs (cf. Table 1). In the next section we will draw inspiration from the respective specialized literatures to map feasible and desirable next steps in IAM development.

1.4 Labour, Finance and Consumer Technology Adoption - Extending the IAMs

This fourth section builds on the previous two by reviewing examples of papers that consider the relevant dimensions of heterogeneity and endogeneity and are therefore able to explain and replicate our stylized facts, as presented in Tables 4 I-III below.

In Table 4-I we have selected papers modelling labour dynamics in general (Carrillo-Tudela & Visschers, 2023; Oikonomou, 2023; Wasmer, 2006) and specifically focusing on labour in the energy transition (e.g. Aubert & Chiroleu-Assouline, 2019; Hafstead et al., 2022) as well as several studies presenting IAM-extensions going in the directions proposed here (e.g. Fragkos & Fragkiadakis, 2022; GUIVARCH et al., 2011; Mu et al., 2018; van der Zwaan et al., 2013). If we take the paper by Aubert and Chiroleu-Assouline (2019) as an example, we see in the table that this paper features only two skill levels (high and low skilled) but fully endogenizes, in a general equilibrium setting, these workers' rational, forward-looking search behaviour. This allows the model to track skill specific levels of friction unemployment (for low skilled workers only) and relative wage levels. This extension directly allows the models to track the impacts of (transition and climate) policies (and other exogenous shocks and scenarios) on low versus high skilled workers. But more importantly, because the model fully endogenized workers' and employers' searching efforts, it can also assess the workers' response to e.g. ploughing back carbon taxes through proportional versus progressive income tax rebates, which is impossible in IAMs that do not endogenize searching and matching in labour markets. The more general Wasmer (2006) paper provides inspiration to extend the search and matching framework with endogenous human capital investment decisions. The intuition here is that the incentives to train and educate are driven by their expected returns, which in turn depend on search- and matching driven unemployment and wages. Carrillo-Tudela and Visschers (2023) show we can model endogenous search and link this to the reallocation of workers across occupations and sectors, whereas Oikonomou (2022) explicitly models migration decisions where high and low skilled workers decide to migrate when facing geographic frictional migration costs. In sum, the first three papers on labour market extensions listed in Table 4-I, show us how the behaviours underlying unemployment and wage formation across skill and job types have already been endogenized *outside* the IAM-literature, so that we have "shoulders-to-stand-on" in extending our IAMs in these directions. It makes sense, however, to only do so when the shocks and policy scenarios we are interested in requiring such enrichment.

Table 4-I: Inspirational Models Labour Market Extensions

Type	Reference	Stylized facts	Explanation	Dimension	H	E
Inspirational Models	Carrillo-Tudela & Visschers (2023)	L1; L2; L3; L4	The paper develops a multisector business cycle model with heterogeneous workers, occupation-specific human capital, idiosyncratic productivity shocks, and search and reallocation frictions to examine how cyclical patterns of occupational mobility influence unemployment volatility and the distribution of unemployment durations.	Human Capital Accumulation	4	4
				Wage Differentials	4	4
				Search and Matching Frictions	5	5
				Labor Mobility Constraints	5	5
	Oikonomou (2023)	L1; L3, L4	The paper presents a small open-economy DSGE model with search-and-matching frictions, endogenous cross-border migration, and high- and low-skill households. Production features capital–skill complementarity, migration alters both labor and skill supply composition, feeding back into capital demand, unemployment, and output.	Human Capital Accumulation	2	2
				Wage Differentials	0	0
				Search and Matching Frictions	4	5
				Labor Mobility Constraints	4	5
	Wasmer (2006)	L1; L3	The paper develops a search-and-matching model with endogenous worker choice of human capital under firing costs and matching frictions, determining equilibrium unemployment, turnover, and skill regimes.	Human Capital Accumulation	2	5
				Wage Differentials	0	0
				Search and Matching Frictions	2	5
				Labor Mobility Constraints	0	0
	Zaussinger et al. (2025)	L1; L4	The paper analyzes labor market exposure to the low-carbon transition using a skills-based, occupation-level classification framework. They identify which occupations are at risk based on their technological decarbonization prospects and maps their skill profiles, sectoral distribution, and regional concentration across Europe.	Human Capital Accumulation	5	1
				Wage Differentials	0	0
				Search and Matching Frictions	0	0
				Labor Mobility Constraints	5	1
	Lankhuizen et al. (2022)	L3, L4	The paper presents a multiregional Leontief input-output model with a matching model featuring spatial and sectoral frictions to identify potential regional labor market bottlenecks and vacancies created by the energy transition.	Human Capital Accumulation	0	0
				Wage Differentials	0	0
				Search and Matching Frictions	3	5
				Labor Mobility Constraints	5	1
IAM-style Models	Aubert & Chiroleu-Assouline (2019)	L1; L2, L3	The paper presents a general equilibrium model of the labor market featuring high and low skilled workers with different searching and matching behavior resulting in endogenous unemployment and wages by skill.	Human Capital Accumulation	2	2
				Wage Differentials	2	5
				Search and Matching Frictions	2	5
				Labor Mobility Constraints	0	0
	Hafstead & Williams III (2018)	L3	The paper introduces a general-equilibrium two-sector search model with homogeneous workers to examine employment shifts between regulated and unregulated sectors under a carbon tax compared to a performance standard.	Human Capital Accumulation	0	0
				Wage Differentials	0	0
				Search and Matching Frictions	2	5
				Labor Mobility Constraints	0	0
	Castellanos & Heutel (2024)	L3; L4	The paper develops a CGE model of the US economy that features involuntary unemployment and cross-sectoral labor mobility, and uses it to analyze how climate policy design and revenue recycling affect aggregate and sectoral jobs	Human Capital Accumulation	0	0
				Wage Differentials	0	0
				Search and Matching Frictions	2	5
				Labor Mobility Constraints	2	5
	Fragkos & Fragkiadakis (2022)	L1; L2	The paper uses the global multi-sectoral CGE model (GEM-E3-FIT) with endogenous education decisions and efficiency wages to assess how ambitious decarbonization pathways affect macroeconomic outcomes and global employment.	Human Capital Accumulation	5	5
				Wage Differentials	5	5
				Search and Matching Frictions	0	0
				Labor Mobility Constraints	0	0
	Guivarch et al. (2011)	L2	The paper uses the IMACLIM-R hybrid recursive CGE model to investigate how labor market imperfections influence the macroeconomic costs of climate stabilization in a second-best setting. Their model represents an economy with short-run adjustment constraints, fixed production technologies, sectorally immobile installed capital, and rigid real wages.	Human Capital Accumulation	0	0
				Wage Differentials	1	5
				Search and Matching Frictions	0	0
				Labor Mobility Constraints	0	0
	Marten, Schreiber & Wolverton (2024)	L2, L4	The paper uses a CGE framework with a CRETH function to examine how occupational heterogeneity and limited labor mobility shape the distribution of regulatory costs across household income groups.	Human Capital Accumulation	0	0
				Wage Differentials	4	4
				Search and Matching Frictions	0	0
				Labor Mobility Constraints	5	5
	Hafstead, Williams III & Chen (2022)	L3	The paper presents a multisector CGE with three alternative labor market specifications: full employment (FE-CGE), a reduced-form wage curve unemployment approach (Balisteri-CGE), and a structural search and matching model (search-CGE) with wage and hours bargaining. This assesses how labor market frictions influence the reliability of aggregate and sectoral employment predictions under carbon taxation.	Human Capital Accumulation	0	0
				Wage Differentials	0	0
				Search and Matching Frictions	3	5
				Labor Mobility Constraints	0	0
	Mu et al. (2018)	L2; L4	The paper utilises a CGE model with endogenous wage determination via wage curves and a constant elasticity of transformation (CET) function to compare the employment effects of financing renewable energy feed-in tariffs through different tax mechanisms.	Human Capital Accumulation	0	0
				Wage Differentials	4	4
				Search and Matching Frictions	0	0
				Labor Mobility Constraints	3	3

Note: We have scored the models on (**H**) heterogeneity 1=homogenous, 2=two representative agents, 3= (at least) three representative agents, 4=one dimension of heterogeneity continuous, 5=all relevant dimensions continuously distributed. And on (**E**) endogeneity 1=exogenous static, 2=exogenous dynamic, 3=iteratively consistent static general equilibrium, 4=iteratively consistent dynamic and 5=recursive dynamic. We report a "0" for absent or insufficient information or "not applicable". It is hard (impossible) to score these very different models very precisely on these categories and the reader is referred to the references in the table for precise details.

The second set of papers in the Table present mostly (IAM-like) CGE-models that include labour market extensions. Fragkos and Paroussos (2018) is the first and a good example. From the Table we see that the paper uses the GEM-E3 model to assess the employment effects of renewable energy source (RES) deployment in accordance with the EU Clean Energy Package (CEP) consistent (exogenously given) deployment scenario. IAM-modelers are more inclined to introduce heterogeneity than to introduce endogenous search- and matching behaviour. We can only speculate that this is the case because exogenous heterogeneity, although requiring a significant amount of data collection and analysis, does not interfere with the internal mechanics of the models. Therefore, stability and convergence in the often large and complicated models themselves is not compromised. Introducing endogeneity in searching and matching, in contrast, is typically less data intensive but may disrupt the complex internal mechanics of the models in unpredictable and computationally challenging ways.

We may tentatively conclude that the non-IAM labour market models are conceptually rich, even if they sometimes lack a firm empirical basis and, by construction, ignore the important feedback from shocks and policies to emissions and then the economy at large. The list of partially extended IAMs, in contrast, is typically well-founded in the data and introduces the required heterogeneity on the demand and supply side of the labour market but tends to shy away from endogenizing searching behaviour and matching dynamics. Moreover, the extended IAM models still typically assume that labour is immobile across countries. These limitations prevent the IAM models from yet fully accounting for labour mobility across sectors and geographies, making it difficult for European policymakers to track the distribution of employment and wage effects of climate policy.

The review suggests that IAM-modelers take inspiration from the labour market literature listed in Table 4-I, which can be implemented in the following five steps:

1. Introduce the desired heterogeneity (skill level and job type) in all relevant sectors and regions;
2. Specify search costs and matching technology within and between all relevant sectors and regions;
3. Endogenize search effort in all relevant sectors and regions;
4. Endogenize wage formation in all relevant sectors and regions;
5. Endogenize skill acquisition through education and training.

With these steps, a model would predict unemployment and wage consequences of existing policies and more accurately predict the speed of the energy transition, to the extent that it is driven by the reallocation of labour. Finally, these would open up the possibility of assessing policies that affect the search costs, wage formation and skill acquisition of (groups of) workers specifically in these models.

Table 4-II similarly presents the papers for the finance topic. They include inspiration papers analysing paths for transition investment and financial stability (e.g. Diluiso et al., 2021; D'Orazio & Valente, 2019; Ferrari & Landi, 2024; Lamperti et al., 2020; Monasterolo & Raberto, 2018) and the few papers presenting IAM-extensions going in the directions here proposed (Calcaterra et al., 2024; Pollitt & Mercure, 2018). While the inspiration papers from the stock flow consistent (SFC) and agent-based-modelling (ABM) literatures manage to represent some vital financial mechanisms, in contrast to IAMs they do so only on an abstracted dimension of "green" and "brown" projects. These papers show us how financial markets intermediate between financial investors and investing firms through a limited range of financial contracts. For example, Dunz et al. (2021) introduce retained earnings and bank loans as sources of finance for investing firms, mediated by a representative banking sector that engages in endogenous money creation under capital requirement restrictions. ABM models have expanded the heterogeneity further, with dichotomous financial sectors (public and private, with and without a green mandate) (D'Orazio & Valente, 2019), and decision rules for banks to rank loan applicants on perceived credit worthiness (Lamperti et al., 2020).

Table 4-II: Inspirational Models Financial Market Extensions

Type	Reference	Stylized facts	Explanation	Dimension	H	E
Inspirational Models	Lamperti et al. (2021)	F1; F2; F3; F4	The paper develops an agent-based macro-financial model (ABM) to study the interaction between climate change, credit and economic dynamics. Consumption-good firms rely on credit to finance investment and production, heterogeneous in productivity, financial vulnerability and emissions. Commercial banks provide credit to firms based on their ranked creditworthiness.	Financial Investors	3	2
				Assets	3	2
				Investment Projects	2	1
				Macro-Monetary	4	4
	Diluiso et al. (2021)	F1; F2; F3; F4	The paper uses a Euro Area-calibrated DSGE model with multiple assets and financial frictions. Credit conditions can vary between green and brown sectors, financial shocks can fuel inflation and welfare losses, and central bank policymaking is modelled explicitly.	Financial Investors	3	4
				Assets	4	3
				Investment Projects	2	1
				Macro-Monetary	4	4
	Dunz, Naqvi & Monasterolo (2021)	F1; F2; F4	The paper shows a Stock-Flow Consistent (SFC) macroeconomic model with climate sentiments. Banking Sector provides loans, holds deposits, and adjusts interest rates based on climate sentiments and financial stability metrics. Firms finance investments through retained earnings and loans.	Financial Investors	3	4
				Assets	4	4
				Investment Projects	2	1
				Macro-Monetary	4	4
	D'Orazio & Valente (2019)	F1; F2; F4	The paper presents an agent-based model (ABM) with household sector (varying preferences for product characteristics (user quality, environmental quality, and price efficiency), production sector, and financial sector (commercial and state investment bank with green mandate). The banking sector can offer loans (standard or green).	Financial Investors	3	3
				Assets	1	1
				Investment Projects	2	2
				Macro-Monetary	1	1
	Dafermos, Nikolaidi & Galanis (2018)	F2; F4	The paper presents a Stock-Flow Consistent (SFC) ecological macroeconomic model, based on Godley-Lavoie and Georgescu-Roegen approaches. Finance affects the macroeconomy and investment plans. Production can be financed by green or conventional capital. Green capital is characterised by lower energy intensity, material intensity and a higher recycling rate.	Financial Investors	3	3
				Assets	4	3
				Investment Projects	2	1
				Macro-Monetary	3	3
	Monasterolo & Raberto (2018)	F1; F2; F4	The paper offers an SFC approach with ABM elements, evaluating the consequences of green bonds and green fiscal policy in the EU, particularly on financial stability from climate risk and carbon stranded assets. Commercial banks and central bank act as intermediaries, which deal in deposits, loans, reserves, and (green vs. brown) bonds, used by households, firms, and the government sector.	Financial Investors	3	2
				Assets	4	3
				Investment Projects	2	3
				Macro-Monetary	4	4
	Bovari, Giraud & McIsaac (2018)	F2; F4	The paper creates a Stock-Flow Consistent (SFC) macroeconomic model with climate feedbacks, focused on financial instability and endogenous money creation. The macroeconomic module includes production, labor, private corporate debt, and monetary dynamics.	Financial Investors	2	1
				Assets	3	2
				Investment Projects	2	1
				Macro-Monetary	4	3
	Ponta et al. (2018)	F2; F4	The paper presents an agent-based model (ABM) that examines the role of fiscal policies in fostering the energy transition and its macroeconomic effects. Specifically, a feed-in tariff for renewable energy, and whether this leads to any crowding-out effects. Provides a financial market for firm and bank stocks, and government bonds; banks provide short term loans and long term mortgages.	Financial Investors	3	3
				Assets	4	3
				Investment Projects	2	1
				Macro-Monetary	4	3
	Ferrari & Nispi Landi (2024)	F2; F4	The paper formulates a Euro Area-calibrated DSGE model with green and brown sectors. A central bank can purchase bonds to finance production sectors, underpinned by increased bank reserves.	Financial Investors	3	3
				Assets	3	3
				Investment Projects	2	1
				Macro-Monetary	4	3
IAM-style Models	Pollitt & Mercure (2018)	F2; F3; F4	The paper reviews the theoretical and computational differences between CGE and Macroeconometric approaches to money and finance in climate-economy modelling, including the underlying assumptions and common simulation outcomes. Does not run its own analysis.	Financial Investors	3	1
				Assets	4	1
				Investment Projects	3	1
				Macro-Monetary	5	1
	Calcaterra et al. (2024)	F2	The paper introduces regionally and technologically differentiated financing costs, in the form of empirically calibrated WACCs, to 5 global IAMs (GCAM, IMACLIM, IMAGE, TIAM,WITCH). Iteratively consistent financial learning dynamics are implemented in 3 out of 5 models.	Financial Investors	1	2
				Assets	1	1
				Investment Projects	3	3
				Macro-Monetary	2	1

Note: We have scored the models on (**H**) heterogeneity 1=homogenous, 2=two representative agents, 3= (at least) three representative agents, 4=one dimension of heterogeneity continuous, 5=all relevant dimensions continuously distributed. And on (**E**) endogeneity 1=exogenous static, 2=exogenous dynamic, 3=iteratively consistent static general equilibrium, 4=iteratively consistent dynamic and 5=recursive dynamic. We report a "0" for absent or insufficient information or "not applicable". It is hard (impossible) to score these very different models very precisely on these categories and the reader is referred to the references in the table for precise details.

Despite the empirical relevance of technology life cycle stages to investment decisions in the energy sector (Mazzucato & Semieniuk, 2018), and the abundance of endogenous technical change dynamics in both IAMs (e.g. REMIND) and the ABM literature (e.g. D'Orazio & Valente, 2019), none of the models we have surveyed explicitly link the risk-return profiles or financing mix of energy projects to the choice between available debt and equity financial instruments, nor match them to different financial investor types with their own risk preferences. Singular exceptions to this oversight focus on the private and state investment banks, where the latter can exhibit a green mandate; this makes inroads in capturing the role of risk-seeking public investors in R&D and deployment of immature technologies (Dhruba, 2018; Mazzucato & Semieniuk, 2018), as included in stylized fact F1.

Like the labour market IAM extensions discussed above, finance extensions to IAMs also tend to first introduce data-driven exogenous heterogeneity in, for example, WACCs across countries, technologies and time (Calcaterra et al., 2024). The same pragmatic reasons apply here too. This is an essential first step to build models to handle heterogeneous risk preferences and consider investment across sectors, technologies and geographies, allowing us to track the effects of monetary policy and financial reforms on the energy transition.

The models presented in Table 4-II again suggest five steps can be taken on the dimensions of Assets and Investment Projects:

1. Introduce the desired heterogeneity (investing firms/projects) in all relevant sectors and regions;
2. Exogenously specify WACCs within and between all relevant sectors and regions;
3. Endogenize the mix of assets/liabilities of investing firms over the technology life cycle stage in all relevant sectors and regions;
4. Endogenize the WACC in all relevant sectors and regions;
5. Endogenize costs of capital by asset/liability type in response to demand and supply.

Finally, for consumers, we present a number of studies in Table 4-III below, modelling green technology diffusion and adoption (e.g. Brugger & Henry, 2019; Eppstein et al., 2011; Rai & Robinson, 2015) as well as a reference to the few papers presenting IAM-extensions going in the directions here proposed (e.g. Edelenbosch et al., 2018; Knobloch et al., 2021). These papers take some first steps in modelling how green technology diffusion can be endogenized, such that the IAMs can handle heterogeneous preferences, networks and income/wealth levels, allowing us to track also the distributional income, wealth and wellbeing effects of climate policy.

Holanda et al. (2003), Eppstein et al. (2011), and Brugger and Henry (2019) present models which show how local information constraints and agent heterogeneity compound to slow innovation diffusion and impact the effectiveness of transition policies. These papers each employ different decision models and various sets of heterogeneous characteristics, behavioural constraints, and network assumptions. Rai and Robinson (2015) and Charlier and Risch (2012) construct models to investigate the impact of heterogeneity and bounded rationality on the effectiveness of policy incentives. Peralta et al. (2022) produce highly accurate short-term predictions of PV adoption with a model that relies on local information constraints.

Table 4-III: Inspirational Models Consumer Technology Adoption Extensions

Type	Reference	Stylized facts	Explanation	Dimension	H	E
Inspirational Models	Holanda et al. (2003)	C2; C3	The paper constructs an agent-based (cellular automata) version of Bass diffusion model. Demonstrates that a local information constraint slows diffusion relative to a global information model. Further, the presence of agent preference heterogeneity compounds the effect of the information constraint.	Geography	1	1
				Preferences	2	1
				Information	3	5
				Income/Wealth	1	1
	Rai & Robinson (2015)	C2; C3; C4	The paper presents a Theory of Planned Behavior (TPB)-based PV installation ABM, geospatially explicit with modeled homophilious consumer networks. The goal was to create an empirically robust representation of bounded rationlity. Limited to a single metropolitan area due to heavy data requirements.	Geography	4	1
				Preferences	5	5
				Information	4	5
				Income/Wealth	4	1
	Eppstein et al. (2011)	C2; C3; C4	The paper presents an heuristic tech adoption model (hybrid vehicles), geospatially explicit (i.e. geospatial networks) and with homophilic social networks. Also includes media influence with heterogeneous susceptibility. Applies both affordability thresholds, based on heterogeneous income, and social influence thresholds, based on adoption within idiosyncratic networks.	Geography	5	1
				Preferences	4	5
				Information	4	5
				Income/Wealth	4	1
	Peralta et al. (2022)	C1; C3	The paper presents a geospatially explicit PV adoption ABM, using neural networks to define behavioral decision function. Limited to one municipality (data requirements). Highly accurate predictions on short term adoption. Agents are not individual households, but geospatial areas. Income is a factor in the decision function, but it's not clear how, given the black box neural network methodology. Main input to decision function is current market penetration nearby.	Geography	5	1
				Preferences	4	1
				Information	4	5
				Income/Wealth	1	1
	Brugger & Henry (2019)	C1; C3; C4	The paper presents ABM with stochastic decision making on PV adoption. Investigates the impact of different network topologies, which can be interpreted as varying network homophily, on the effect of different policies on diffusion speed.	Geography	1	1
				Preferences	2	1
				Information	4	5
				Income/Wealth	2	1
	Charlier & Risch (2012)	C2	The paper presents a housing stock model of energy-saving renovation decisions. 12 housing types, each as a representative agent. Includes affordability threshold.	Geography	1	1
				Preferences	3	1
				Information	1	1
				Income/Wealth	3	1
IAM-style Models	Edelenbosch et al. (2018)	C3	The paper presents a simple Rogers-based social learning model, where higher adoption reduces a risk premium for potential adopters. Applies model inside of IMAGE IAM. Demonstrates that social learning and technological learning are both important, and complement one another.	Geography	1	1
				Preferences	4	1
				Information	1	5
				Income/Wealth	1	1
	Knobloch et al. (2019) Knobloch et al. (2021)	C1; C3	The papers present an evolutionary technology diffusion model with representative agent, based on replicator equation dynamics. Endogenously generates s-shaped diffusion curves, and the instantaneous rate of diffusion depends on instantaneous market penetration, i.e. availability of information. One paper incorporates loss aversion in the switching decision.	Geography	1	1
				Preferences	4	1
				Information	1	5
				Income/Wealth	1	1

Note: We have scored the models on (**H**) heterogeneity 1=homogenous, 2=two representative agents, 3= (at least) three representative agents, 4=one dimension of heterogeneity continuous, 5=all relevant dimensions continuously distributed. And on (**E**) endogeneity 1=exogenous static, 2=exogenous dynamic, 3=iteratively consistent static general equilibrium, 4=iteratively consistent dynamic and 5=recursive dynamic. We report a "0" for absent or insufficient information or "not applicable". It is hard (impossible) to score these very different models very precisely on these categories and the reader is referred to the references in the table for precise details.

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Some authors have incorporated agent heterogeneity and bounded rationality in decision models in conjunction with complete IAMs. Edelenbosch et al. (2018) emphasize the complementarity between social learning and technological learning in policy simulations using the IMAGE model, while Knobloch at al. (2021) include endogenous behavioural path dependence in an evolutionary diffusion model of the residential heating sector within E3ME. The Future Technology Transformations (FTT): Heat model of Knobloch et al. (2021), along with a family of related models for various sectors, is a permanent component of E3ME. Knobloch et al. (2019) also extend the model's representation of bounded rationality by including loss aversion behaviour.
This set of papers indicates that a lot is known on how to leverage heterogeneity and endogeneity to model consumer adoption of new technologies in general and green technology in particular. The steps needed to extend process IAMs in this direction can be summarized as:

1. Introduce the desired heterogeneity (preferences, income, wealth) among consumers in all relevant regions;
2. Specify social and/or geographic network structures for consumers;
3. Endogenize information flows through social networks in all relevant regions;
4. Endogenize adoption decision by consumers in all relevant regions;
5. Endogenize costs of technologies in response to demand.

1.5 Policy Strategies and an IAM Research Agenda for their Evaluation

In our final Table 5, we present a selection of the inspiration studies we discussed in the previous section, now with a focus on the policies that these models (and similarly extended IAMs) allow us to analyze, evaluate and assess.

First, the better representation of heterogeneity and endogeneity of relevant actors and mechanisms improves our understanding of policies already tested in IAMs (e.g. carbon taxes, regulation and feed-in-tariffs). Indeed, the first, rather obvious point to make, is that introducing heterogeneity implies we can track the distributional impacts of existing and proposed climate policies on different (groups of) workers and employers, financial investors and investing firms, and consumers and suppliers. But more importantly, the extensions also open the possibility of assessing alternative, targeted tools that exploit new mechanisms to achieve a faster, fairer or cheaper green transition (e.g. targeted taxing, pricing and subsidy schemes, green financial regulation, educational and migration policies etc.).

When we consider the modelling of labour markets, introducing frictions within the search and matching process allows authors to assess the (aggregate) impacts on (groups of) workers in terms of income and (un)employment risks (e.g. Lankhuizen et al., 2023; Zaussinger et al., 2025). Moreover, a range of different carbon tax and tax recycling schemes has been assessed (Aubert & Chiroleu-Assouline, 2019; Castellanos & Heutel, 2024; GUIVARCH et al., 2011; Hafstead et al., 2022), typically improving environmental performance (a + on "faster") while shifting the burden away from the most vulnerable workers (a + on "fairer"), whereas Oikonomou (2023) and Wasmer (2006) illustrate how migration and training policies that specifically target the labour market, will help to make the transition fairer.

When financial markets are explicitly modelled, the policy toolkit expands mostly in the direction of differentiated funding conditions, such as subsidized, or guaranteed green lending by a public investment entity (D'Orazio & Valente, 2019) and supervisory (positive) discrimination of green investing firms by e.g. a green support factor (Dunz et al., 2021; Lamperti et al., 2020). These policies improve the financing conditions specifically for green vis-à-vis brown investing firms and thereby typically speed up the transition from green to brown, even if this sometimes comes at the cost of cost-efficiency and/or fairness.

Table 5: Policies and Policy Implications

Theme	Reference(s)	Policies Assessed	Policy Results	Policy Prescriptions to make the Transition…	…Faster, Cheaper and/or Fairer
Labor Policies	Hafstead & Williams III (2018)	Carbon Tax and Carbon Regulation	Performance standards generate smaller sectoral employment shifts than emissions taxes while keeping aggregate unemployment effects small.	Implement apprenticeship support and hiring credits aligned with performance-standard changes	(+) Faster (+) Fairer (-) Cheaper
	Aubert & Chiroleu-Assouline (2019); Castellanos & Heutel (2024); Guivarch et al. (2011); Hafstead, Williams III & Chen (2022)	Carbon Tax and Revenue Recycling	Carbon pricing is fairer and more effective when revenues are recycled progressively rather than uniformly, as it offsets regressivity and can reduce low-skilled unemployment.	Implement carbon-tax funded progressive labor-tax recycling policies, such as payroll tax cuts for low-wage workers, EITC expansion, mobility and hiring support for displaced workers, work share credits,	(+) Faster (+) Fairer (-) Cheaper
	Zaussinger et al. (2025); Lankhuizen et al. (2023)	Decarbonization	Decarbonization headwinds can be mapped ex ante and mitigated through occupational and regional exposure to high-carbon job risk.	Implement training and education policies to address predictable shortages and support vulnerable sectors and regions	(+) Faster (+) Fairer (-) Cheaper
	Wasmer (2006)	Employment Protection	Stronger EPL supports specific-skill accumulation and job stability but raises hiring and separation costs.	Implement Retention-Conditional Training and Accreditation and a Layoff Tax	(-) Faster (+) Fairer (-) Cheaper
	Mu et al. (2018)	Feed in Tariff	Feed-in tariffs yield net job gains when financed via lump-sum taxation rather than electricity consumption surcharges, since electricity-fee financing raises power costs and induced job losses offset green-job creation.	Finance feed-in tariffs from general or carbon revenues, not electricity or other utility surcharges and use renewable auctions funded from broad revenues instead of fixed feed-in tariffs.	(+) Faster (+) Fairer (-) Cheaper
	Oikonomou (2023)	Migration Policy	Mitigate skill-draining outflows / promote skilled return to avoid a deeper, more protracted downturn via weaker investment and reduced supply capacity, and to limit inequality increases.	Implement skill retention-oriented migration policies, such as return programs and targeted tax relief	(-) Faster (+) Fairer (-) Cheaper
	Marten, Schreiber & Wolverton (2025)	Regulation	If compliance with regulation relies on high skill non-routine cognitive labor, demand and wages for those workers rise.	Implement task-modular compliance standards and stackable transition credential bridges	(+) Faster (+) Fairer (+) Cheaper
Financial Policies	Monasterolo & Raberto (2018)	Regulation, Green Fiscal Support and Green QE	Regulation against brown sector reduces emissions and resource imports. Green fiscal support reduces emissions but dampens growth and raises unemployment. Green QE reduces emissions but raises public debt.	Implement a mix of green policies to increase speed of transition, but with risk of lower employment, higher public debt and tax burdens on households.	(+) Faster (-) Fairer (+/-) Cheaper
	Ponta et al. (2018)	Feed-in-Tariff	Feed-in tariffs increase share of renewables in energy mix.	Implement higher feed-in tariffs for faster green transition; this also raises the public cost burden, which is distributed to households.	(+) Faster (-) Fairer (0) Cheaper
	Dunz, Naqvi & Monasterolo (2021)	Carbon Tax and Green Capital Requirements	Green capital requirements (supporting factor) increase green capital share moderately, and rate of non-performing loans (stranded assets). Carbon taxes increase green capital share sharply but dampen aggregate demand.	Implement green capital requirements and taxes to speed up transition, at the expense of financial instability. Effects on household budgets require additional redistributive policies.	(+) Faster (-) Fairer (-) Cheaper
	Lamperti et al. (2020)	Green Capital Requirements, Green Public Guarantees and Carbon Risk Ratings	Favorable capital requirements help green sector growth, reduce aggregate emissions, and act pro-cyclically. Green public guarantees reduce aggregate emissions and act counter-cyclically. Carbon risk ratings reduce emissions least.	Implement mix of all three policies to help green transition speed, while maintaining financial stability, manageable public debt and moderate economic growth.	(+) Faster (+) Fairer (+) Cheaper
	Calcaterra et al. (2024)	Green Financial Risk Sharing	Financial risk sharing (integrated markets, SIBs, public loan guarantees) can reduce emissions and energy prices	Implement (international) policies that would speed up reduction and convergence in WACCs to promote faster, cheaper and fairer transition	(+) Faster (+) Fairer (+) Cheaper
	D'Orazio & Valente (2019)	Green Mandate for SIB	Green SIB mandates, particularly with strong consumer environmental preferences, help diffuse innovation from the green sector.	Implement a green SIB mandate to increase speed of transition and provide macroeconomic stimulus to growth.	(+) Faster (0) Fairer (+) Cheaper
	Dafermos, Nikolaidi & Galanis (2018)	Green Preferential Interest Rates and Green Credit Access	Green interest rates and expanded credit access increase investment and reduce emissions moderately. Penalty on brown firms reduces emissions further, but dampens aggregate demand	Implement green support and brown penalties to increases speed of transition at expense of growth.	(+) Faster (0) Fairer (-) Cheaper
	DiLuiso et al. (2021)	Carbon Tax, Green Micro prudential Policy and Green QE	Carbon taxes reduce emissions significantly, but disorderly implementation creates inflationary pressures. Green QE mitigates financial instability but does not further green sectors micro prudential policy helps banks decarbonize balance sheets.	Implement gradually increasing carbon taxes to further the transition with fewer disruptions. Use QE to counterbalance contagion from stranded assets.	(+) Faster (0) Fairer (+) Cheaper
Consumer Policies	Eppstein et al. (2011)	Carbon Tax	Higher fuel prices lead to faster transition.	Implement stronger long-term policy incentives, such as subsidies and taxes, when early adopters are spatially clustered.	(+) Faster (0) Fairer (-) Cheaper
	Edelenbosch et al. (2018) Knoblouch et al. (2019); Knobloch et al. (2021)	Carbon Tax and Subsidies	In early phases of transition, subsidies are only effective if they target early adopters.	Implement policy incentives, such as subsidies, that target early adopters in early phase.	(+) Faster (-) Fairer (+) Cheaper
	Brugger & Henry (2019)	Feed in Tariff and Leasing/Seeding	Feed-in tariffs are most effective if early adopters do not cluster. Leasing and seeding programs are most effective if early adopters do cluster.	Implement policies to reduce barriers to installation and seed installations among low propensity adopters when early adopters cluster spatially/socially.	(+) Faster (+) Fairer (-) Cheaper
	Rai & Robinson (2015); Charlier & Risch (2012)	Income Dependent Subsidies	Additional incentives for low-income households only modestly improve diffusion speed and incentives are ineffective as long as installation is unaffordable. Bonuses to low-income households are less cost efficient per ton of CO2 saved.	Implement (very) strong incentives for low-income households to achieve a meaningful increase in adoption.	(+) Faster (+) Fairer (-) Cheaper

Note: The table shows what policies (a subset of) the inspiration models in Table 4 have assessed and with what results. We have merged references that cover broadly similar policies for readability, even if the different papers differ in the details. In the final two columns we translated these results into what we believe are the normative policy implications and indicate how such intervention(s) would contribute to (+) or come at the cost (-) of a faster, fairer and cheaper transition, respectively.

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Largely within DSGE frameworks, the role of green Quantitative Easing (QE) through bond and other asset purchases has a much more moderate effect on reducing emissions (Diluiso et al., 2021).

Another important line of enquiry investigates the impact of climate change and transition risk on financial stability (e.g. Bovari et al., 2018; Dafermos et al., 2018), emphasizing that a smooth and timely transition may require flanking policies to prevent serious disruption in financial markets. Dunz et al. (2021) particularly highlight the macroeconomic importance of redistributive policies to households, not just from the direct implementation of a carbon tax, but also to mitigate the spread of transition risks to household balance sheets from banking instability. Calcaterra et al. (2024) discuss the importance of financial learning and derisking renewable energy installations, especially in developing country contexts.

In the final consumption models, the effectiveness of policies such as feed-in-tariffs and targeted subsidies have been compared and quantified, gaining new insights into various policy trade-offs in the presence of boundedly rational heterogeneous consumers. For example, Brugger and Henry (2019) show that in a fully developed agent-based model, the (relative) effectiveness of feed-in-tariffs and leasing and seeding programs depends on the structure of the social network (integrated versus segregated). The ability to model targeted subsidies is a key benefit of including meaningful heterogeneity in a technology diffusion model. Taking advantage of this, Rai and Robinson (2015) and Charlier and Risch (2012) show that promoting the uptake of green technology among low-income households requires much stronger financial incentives, increasing the government costs per unit of saved CO2. Moreover, these incentives are not likely to be effective if policy programs are only temporary, due to the information frictions inherent in segregated networks where high-propensity adopters tend to cluster (Eppstein et al., 2011). Because those high-propensity adopters are key in the early stages of diffusion, the models imply a trade-off between fairness and speed of the transition wherever household income and wealth are predictors of early adoption (Edelenbosch et al., 2018; Knobloch et al., 2021).

1.6 Conclusion

In this chapter we have systematically reviewed the literature that can help IAM modelers extend their models in three important directions. With the rationality and urgency of full decarbonization established in earlier cost-benefit IAMs and process IAMs currently working out the detailed environment-economy interactions along feasible decarbonization pathways, policy makers and stakeholders look to IAMs to answer new questions. These typically relate to what policy (packages) will ensure a faster, fairer and cheaper energy transition? We have shown that answering such questions implies looking more carefully at the representation of labour, financial and consumer markets in process IAMs. Across all three themes, we concluded that introducing heterogeneity and endogenizing the matching process will enrich IAMs' representation of highly policy-relevant aspects of reality. On the one hand, the matching frictions in heterogeneous labour, finance and consumer markets tend to slow down the transition to green jobs, green capital and green durables. But on the other, targeted policy interventions that reduce frictions and information costs can reduce the most binding constraints, lowering the overall costs of making the transition faster and ensuring that the burdens are shared equitably. In the next three chapters we briefly present and discuss three working papers that have been developed in the DIAMOND project (added in full in Annexes 2, 3 and 5). All three working papers are developed into publishable academic papers and will be submitted for review before the end of the DIAMOND project. In these working papers we first develop, from basic theory, how the most relevant mechanisms in labour, financial and consumer markets can be modelled, respectively. These models then provided the theoretical link from the basic assumptions on behaviour in these markets to the aggregate representation of such behaviours that can be introduced in IAMs. After that, the working papers briefly introduce specific DIAMOND IAMs, describe how the extension was implemented in them and present the simulation results for a baseline scenario with and without, to illustrate how the extensions affected the predictions of the models. We conclude this report with a chapter on the policy interventions that this allows us to simulate in these models. The results of those policy scenarios will be presented in WP5 (D5.2).

2 Labour Market Frictions

In this chapter we present a model of the labour market that will illustrate how search and matching frictions work as presented in O'Connell et al. (2026) (added in full as Annex 2 to this report). Building on that model, we develop a general approach to extend IAMs in general and specifically CGE-type IAMs in a tractable way, such that we can interpret a limited set of exogenous parameters in such models as a first approximation to the impact of directed search and matching frictions.

2.1 Introduction and Motivation

In O'Connell et al. (2026) we developed a novel labour market module designed to improve the representation of labour market frictions within integrated assessment models (IAMs) and computable general equilibrium (CGE) frameworks. The motivation stems from a clear mismatch between the stylised treatment of labour markets in standard IAM/CGE models and the empirical realities of structural transitions such as the energy transition. We have shown above that conventional models typically assume frictionless labour markets with full employment or rely on reduced-form representations such as constant elasticity of transformation (CET) functions to approximate intersectoral mobility. While computationally convenient, these approaches abstract from key mechanisms such as unemployment dynamics, vacancy creation, skill mismatch, and job search frictions.

As the energy transition is inevitably characterised by substantial gross job flows, sectoral reallocation, and transitional unemployment driven by matching inefficiencies and institutional constraints, in O'Connell et al. (2026) we proposed a framework that introduces micro-founded labour market frictions while remaining tractable for integration with large-scale CGE/IAM models. Our contribution lies in bridging structural search theory with applied energy-economy modelling.

2.2 Theoretical Framework

2.2.1 Limitations of CET-Based Labour Allocation

Our starting point is the CET formulation sometimes used in CGE models (Acar, 2003; Mu et al., 2018) to allocate labour across sectors. In such a framework, workers are distributed across sectors based on relative wages, with a transformation elasticity governing the responsiveness of labour supply. While this approach captures imperfect mobility in reduced form, it lacks explicit behavioural foundations. The elasticity parameter conflates multiple underlying frictions, including search costs, geographic immobility, and skill mismatch. Moreover, while it reflects labour reallocation costs, the corresponding levels of unemployment and sectoral labour shortages remain unaddressed, while the exogenously fixed elasticities are not directly linked to policy interventions.

In O'Connell et al. (2026) we highlight that this limitation is particularly problematic for analysing transition dynamics, where the speed and efficiency of labour reallocation are central. We therefore first endogenise these elasticities using a structural model.

2.2.2 Standard Search-and-Matching (DMP) Model

We built on the standard Diamond–Mortensen–Pissarides (DMP) framework as a benchmark representation of frictional labour markets. In this setting, labour market outcomes are determined by a matching function that governs the formation of employment relationships between unemployed workers and vacancies. Key features include:

- **Endogenous unemployment** arising from matching frictions

- **Vacancy posting** decisions by firms under free entry
- **Wage determination** through Nash bargaining
- **Labour market tightness** as a central equilibrium variable

In O'Connell et al. (2026) in Annex 2 we have developed the model mathematically from first principles. The DMP model introduces dynamic adjustment processes through job creation and destruction, making it well suited for analysing transitional dynamics. However, the basic model still has a critical limitation: search is undirected. Workers do not choose where to search, and firms do not strategically post wages to attract specific workers. This limits the basic model's ability to capture *sectoral reallocation* mechanisms relevant to the energy transition.

2.2.3 Directed Search Model

The core theoretical innovation of O'Connell et al. (2026) is therefore the introduction of a directed search framework (as in e.g. Moen, 1997). In contrast to standard DMP models, directed search allows firms to post wages and vacancies in sector-specific submarkets, workers to choose where to search based on expected payoffs and endogenous sorting of workers across sectors. Again, the working paper in the Annex provides the full analytical derivation of the model in Annex 2. In our directed search model, the workers evaluate submarkets using a combination of expected wages and job-finding probabilities, adjusted for search costs. Their decision is then modelled using a logit formulation, allowing for probabilistic reallocation of labour across sectors. Firms, in turn, adjust wages and vacancy posting in response to their own labour demand and market labour supply conditions.

Our model now incorporates several key components:

- **Matching Technology**: Sector- and skill-specific matching functions determine job-finding and vacancy-filling rates.
- **Wage Determination**: Wages are set via Nash bargaining, incorporating both productivity and labour market tightness.
- **Job Creation Condition**: Firms post vacancies until expected profits are driven to zero.
- **Worker Sorting**: Workers direct their search based on expected utility across sectors.
- **Dynamic Adjustment**: Labour market transitions are captured through a Markov process governing employment and unemployment states.

The model can predict, when appropriately calibrated, both within-sector dynamics (matching frictions) and across-sector dynamics (reallocation decisions) and endogenously generates (relative) wages, (un)employment by skill level and sectoral vacancy rates and market tightness. The CET-elasticities used to represent labour market frictions in IAM and CGE models, are endogenous in the model as well.

2.2.4 Endogenising CET Elasticities

A central contribution of the working paper is demonstrating how the directed search model generates endogenous labour mobility elasticities. In equilibrium, relative wages and employment levels emerge from the interaction of matching frictions, bargaining, and worker sorting. By differentiating these relationships, the implied elasticity of labour supply across sectors can be derived. This provides a micro-founded interpretation of the CET-parameters, linking them to observable labour market mechanisms and policy-relevant variables such as training costs, mobility barriers, and information frictions.

2.3 Integration with the GEMINI-E3 Model

2.3.1 Baseline Model Description

The empirical application of the framework is conducted using the GEMINI-E3 EU model, a multi-region, multi-sector CGE model widely used for climate policy analysis. In its baseline form, GEMINI-E3 assumes:

- Perfectly competitive labour markets
- Full employment
- Flexible wages

To introduce labour market frictions, the model was extended with a CET-based labour allocation mechanism (Mu et al., 2018). This extension allows for imperfect intersectoral mobility but as was argued above, still relies on exogenous elasticity parameters.

2.3.2 Simulation Design

In the working paper (O'Connell et al. 2026) we presented the results of simulation runs under different values of the CET elasticity (0.3, 0.6, 0.9 and 1.5) to assess how labour market frictions would affect the outcomes of a carbon tax policy. The policy scenario involves a gradually increasing carbon tax applied in Germany, inducing structural shifts in production and employment.

Key findings from the simulations include:

- Emissions reductions are relatively insensitive to labour mobility assumptions
- The energy mix shifts strongly from fossil fuels to renewables
- Electricity prices increase, with smaller increases under higher mobility
- Labour reallocation is significantly affected by the elasticity parameter

Higher elasticities (lower frictions) lead to faster and larger shifts of labour into renewable sectors, while lower elasticities imply more constrained reallocation.

2.4 Directed Search Simulation Module

2.4.1 Module Design

To complement the CGE simulations we developed a standalone directed search simulation module that is described in detail in O'Connell et al. (2026). Our module replicates the labour market mechanisms described in the theoretical section and can be used to infer the additional labour market outcomes (notably unemployment and vacancy rates and durations) consistent with the CGE scenarios.

The module includes:

- Matching functions determining job flows
- Nash bargaining for wage determination
- Logit-based search decisions
- Markov dynamics for worker transitions

2.4.2 Partial-Equilibrium Inversion Approach

Rather than fully integrating the module into GEMINI-E3, we adopted a partial-equilibrium inversion strategy in which the employment levels from the GEMINI-E3 were treated as exogenous inputs, and parameters in the directed search model were calibrated to reproduce the assumed labour mobility elasticities (e.g. 0.3, 0.6, 0.9 and 1.5). This approach allowed us to compute the:

- Unemployment rates
- Vacancy rates
- Job-finding probabilities
- Unemployment durations

Where these important labour market outcomes were not captured in the GEMINI-E3 model due to its full-employment assumption. The partial equilibrium inversion approach has the advantage that it does not interfere with the inner workings of the complex and computationally challenging full CGE model. The weakness of our approach is related to the fact that our module simulations does not feed back into the model and rule out any general equilibrium feedback effects (e.g. higher unemployment reduces income which reduces demand, or higher relative wages stimulate investment in education causing skilled labour supply to rise). As the labour market frictions, however, tend to operate on a shorter timescale than the typical IAM, projecting developments into the distant future in relatively large intervals (e.g. GEMINI-E3 is calibrated on five-year intervals), such general equilibrium effects are less likely to play a very big role in the short-term labour market effects.

2.4.3 Calibration and Interpretation

The key parameter in the directed search model driving the value of the CET-elasticities turns out to be the dispersion parameter governing workers' responsiveness to wage differences. By adjusting this parameter, the model can easily replicate different CET-elasticities observed in the CGE simulations. Our calibration results indicate that higher mobility elasticities correspond to greater responsiveness of workers to wage differentials and result in lower mismatch between sectors, shorter unemployment durations and more dispersed vacancy creation across sectors. This calibration exercise provides a structural interpretation of the reduced-form CET parameter and also allows us to tie them to policy interventions.

2.5 Policy Insights and Implications

The framework we have developed in O'Connell et al. (2026) offered us several important insights for policy analysis and scenario formulation:

- **Labour Market Frictions Matter for Transition Dynamics**
  While aggregate outcomes such as emissions may be relatively insensitive, distributional and transitional effects depend strongly on labour market frictions.
- **CET-Elasticities Can Be Reduced Form Representations of Policy Interventions**
  By linking elasticities to underlying mechanisms, the model enables policymakers to assess how interventions would affect labour mobility.
- **Targeted Labour Policies Will Improve Labour Market Outcomes**
  Policies such as training subsidies, mobility support, and improved job matching reduce frictions and facilitate reallocation.
- **Unemployment and Vacancy Dynamics Are Critical**
  Ignoring these dynamics risks underestimating the social costs of transition policies.

2.6 Conclusion

In O'Connell et al. (2026) we provide a significant methodological contribution by integrating directed search theory into the CGE/IAM modelling landscape. Our approach advances the representation of labour markets from reduced-form approximations to micro-founded mechanisms that capture both matching frictions and sectoral sorting.

Although full integration into large-scale CGE models remains computationally challenging, the proposed module offers a practical pathway to account for labour market frictions in such models through calibration and partial-equilibrium analysis. Our framework enhances the ability of IAMs and CGEs to assess not only the aggregate rationale and impact of climate policy but also consider the labour market dynamics that result and will underpin a just transition.

Future work will focus on further integration, improved calibration, and the application of the module to simulate policy scenarios involving targeted labour market interventions.

3 Financial Extensions for Integrated Assessment Models

3.1 Introduction and Motivation

In Serebriakova et al. (2026) (see Annex 3) we develop a novel financial extension for Integrated Assessment Models (IAMs), designed for integration into the CLEWs-EU energy systems framework and the NEMESIS macroeconometric model. With this working paper we addressed a central limitation in current IAM representations of energy investment: the reliance on uniform discount rates, frictionless capital markets, and representative agents with unconstrained access to finance.

As we show in the paper, standard IAMs such as MESSAGE, REMIND, and TIAM have historically abstracted away from the financial frictions — heterogeneous borrowing costs, credit constraints, and capital misallocation — that determine whether low-carbon investment pathways are actually feasible. The EU Commission estimates that annual green investments must reach an additional €477 billion by 2030, yet the ECB's Survey on the Access to Finance of Enterprises finds that 57% of firms cite financing constraints as a barrier to their green investments.

Our contribution in Serebriakova et al. (2026) is therefore threefold. First, we introduce a micro-founded theoretical framework of financial market equilibrium that explicitly incorporates investor heterogeneity, asset market clearing, and endogenous risk pricing. Second, we develop a finance module that maps technology life-cycle maturity to Weighted Average Costs of Capital (WACCs) and capital structure and embed it in both CLEWs-EU and NEMESIS. Third, we evaluate three targeted green financial policies: preferential interest rates, State Investment Bank expansion, and green Quantitative Easing, that our module can assess in ways not previously available within IAMs.

3.2 Theoretical Framework

3.2.1 Financial System as Resource Transfer

Our theoretical approach follows Boot and Thakor (1997) in conceptualising the financial system as a mechanism for transferring resources from surplus agents (financial investors) to those who need funds (investing firms). The model has three interlocking blocks. The first covers financial investors and their portfolio choices. The second covers investing firms and their sector-level production, capital accumulation, and capital structure decisions. The third covers asset market clearing, which pins down equilibrium returns endogenously.

3.2.2 Investor Portfolio Choice and Aggregate Demand

The starting point for the theoretical model is a standard portfolio optimisation problem, where a continuum of heterogeneous investors chooses portfolios of four asset classes — bank debt, bonds, public equity, and private equity — to maximise expected returns net of risk and transaction costs. Each investor type is characterised by a wealth level and a coefficient of absolute risk aversion. The key extension relative to a standard frictionless CAPM is the inclusion of a vector of per-unit transaction costs that investors face when acquiring each asset class. These costs reflect due diligence requirements, search frictions, and regulatory compliance burdens, and can be calibrated to reproduce the empirically observed Pecking Order of corporate financing in equilibrium (Myers & Majluf, 1984).

Aggregating across all investor types yields a market demand schedule: the total quantity demanded of each asset is proportional to its net excess return and the aggregate risk-absorption capacity of the investor base, and decreasing in its covariance with the rest of the market. This formulation retains the familiar CAPM structure (Sharpe, 1964) while introducing financial frictions that will — endogenously — drive firms' WACCs over their life cycle.

3.2.3 Firm Production, Valuation, and Endogenous Growth

Each sector in the model is then populated by a representative firm operating a capital stock with diminishing marginal returns to capital. The firm generates a stochastic operating profit, where both idiosyncratic volatility and market correlation evolve deterministically over the technology's life cycle. Early-stage technologies face high cash-flow volatility but low market correlation; as they mature, volatility falls but market correlation rises. This produces a hump-shaped asset beta over the life cycle, peaking at the growth stage, which is the central mechanism through which financial conditions evolve endogenously.

The firm's market value is determined as a growing perpetuity of mean operating profits, discounted at the WACC. Following Abel and Blanchard (1983), adjustment costs are assumed to be quadratic and exhibit constant returns to scale in investment and capital. Under these conditions, Hayashi (1982) showed that marginal q equals average q, so firms will invest following a simple rule: the investment-to-capital ratio is proportional to Tobin's q. This creates an important feedback loop: investment increases but a higher WACC reduces firm value. In turn, this affects investment and hence growth, which further drives firm value. This amplification mechanism is the model's central financial markets-real economy linkage.

3.2.4 Capital Structure and the Pecking Order

The firm finances itself by issuing four types of claims, ordered by contractual seniority from senior bank debt to residual private equity. Under CAPM pricing, the required return on each security is the risk-free rate plus the product of the asset beta and the market risk premium. The firm minimises its WACC by choosing the cheapest available source of funding at each point in time, under the constraint that its total capital structure adjusts only gradually as earlier debt matures and the value of its equity evolves. The result is a simple linear programme whose solution concentrates issuance entirely on the lowest-cost instrument available, generating discrete life-cycle transitions between financing modes as the costs of capital for different securities cross over the maturity path.

This framework can endogenously replicate the empirically relevant Pecking Order in corporate finance where early-stage firms rely on private equity and State Investment Bank loans because high idiosyncratic risk and information asymmetries make public markets inaccessible; as they mature and their risk profile becomes more legible to outside investors, they transition, first to private bank debt, then public equity then bonds. The transaction cost vector we have introduced in our module can be calibrated to reproduce this canonical ordering.

3.2.5 Asset Market Clearing and Equilibrium Returns

At every instant, each asset market clears: the quantity demanded by investors equals the outstanding stock supplied by firms. Substituting the aggregate demand schedule into this clearing condition yields a central pricing equation: the equilibrium return on each asset equals the sum of a risk compensation component that is proportional to the asset's variance and covariance with other assets, scaled by aggregate investor risk adjusted wealth and a friction component reflecting the average transaction cost that financial investors face. An increase in the supply of any asset then raises the required returns on that and correlated assets through a crowding-out effect. Finally, a valuation consistency condition ensures that the total market value of all outstanding claims equals the total portfolio value held by investors and is enforced through a fixed-point iteration at each period.

3.3 Finance Module for the Energy Sector

3.3.1 Technology Maturity and the Financing Mix

The finance module operationalises the theoretical framework for application within IAMs. Rather than assigning a single uniform discount rate to all technologies and countries, the module maps each technology's financial maturity — a normalised score between 0 (entry) and 1 (full maturity) — to a representative financing mix and a corresponding WACC.

Financial maturity, following Gumber et al. (2026), captures the trust and knowledge that financial intermediaries have accumulated about a technology, and encompasses financial depth, access, and efficiency. It does not evolve in exact parallel with technological maturity: the transition from one financial life-cycle stage to the next depends on demonstrated performance, accumulated banking relationships, and the gradual reduction of perceived novelty risk. To capture these transitions in the financing mix, logistic S-curve functions are used for each instrument — a formulation consistent with empirical models of innovation diffusion. As a technology matures, it gains access to progressively cheaper and more diversified sources of capital: venture capital and State Investment Bank loans for early-stage technologies such as battery storage and hydrogen; private bank debt and public equity for maturing ones; and the full range of debt and equity instruments, including corporate bonds, for mature technologies such as onshore wind and solar PV.

3.3.2 WACC Dynamics and Calibration

A notable feature of the module is that WACCs do not decline monotonically with maturity, even though the costs of individual instruments do. This is because leverage ratios — the share of debt in the total financing mix — change non-monotonically as technologies mature. Empirical data show that leverage ratios can rise to 0.95 for newly maturing technologies before settling at the 0.65–0.70 range typical of mature renewables. During this transition, elevated leverage increases default risk and pushes up required returns on debt, creating a potential bottleneck even as market access broadens.

The module is calibrated using empirical data from IRENA (2024), Hatton et al. (2025) and Steffen et al. (2025). The descriptive statistics from the calibration show a mean WACC of 6.5%, with a minimum of 2.75% for the most mature technologies and a maximum of 19.15% for the least mature — a range with significant implications for investment decisions and technology competition within IAMs.

3.3.3 Integration with CLEWs-EU and NEMESIS

CLEWs-EU is a bottom-up cost-optimising energy systems model built on the OSeMOSYS framework, covering EU member states through 2050. Its baseline discount rate of 7.5% is applied uniformly across all countries, sectors, and technologies. The module replaces this with empirically calibrated, country- and technology-specific WACCs from Hatton et al. (2025). For intertemporal dynamics, a financial learning function is applied so that WACCs decline as installed capacity grows, mirroring Calcaterra et al. (2024). Initial extension results indicate that introducing financing heterogeneity materially affects the technology mix in high-WACC countries, with restructuring towards gas and bio-energy, underlining how capital cost differentials shape technology competition.

NEMESIS is a sectoral demand-driven macroeconometric model for the EU with a neo-Keynesian structure, including adjustment lags, adaptive expectations, and endogenous technical change. It recently expanded its macro-financial representation, including a non-linear Taylor rule for the central bank policy rate, endogenous government bond yields, and commercial spreads. This makes NEMESIS particularly well-suited for exploring how monetary conditions and the module's financial friction mechanisms interact. The module enters NEMESIS through a feedback loop in which installed capacity determines technology maturity, which determines the financing mix and WACC, which feeds into Levelised Costs of Electricity and shapes investment demand for the next period.

3.4 Policy Scenarios

The finance module enables a richer space for policy evaluation than was previously available in these IAMs, by making explicit the channels through which financial conditions shape the energy transition. There is an urgent call for a better understanding of the interplay between monetary and financial policies and the energy transition. In Serebriakova et al. (2026 in Annex 4), we have already explored empirically how monetary policy operates on the installed capacity of green and fossil energy technologies. In that work, we have shown that more capital intensive and external finance dependent (early stage) green energy technologies, respond much stronger to overall monetary conditions than mature, less capital intensive and external finance dependent fossil energy technologies. Our work in the DIAMOND project provides a deeper theoretical understanding of these dynamics, opening a broader set of policy interventions to speed up the energy transition without prejudice to the ECB’s primary mandate for price stability and the need to maintain financial stability under external stress. Three policy scenarios are examined, each operating through a distinct channel.

3.4.1 Green Preferential Interest Rates

This scenario places a ceiling on the interest rates that private banks may charge on loans for renewable energy projects. It simulates micro- and macro-prudential regulatory interventions such as favourable reserve requirements for green loans, adjusted risk weights in credit assessment, and public guarantees for green projects in the absence of collateral. The result is a direct reduction in the cost of debt for qualifying technologies, an increase in the debt share of the financing mix, and a corresponding reduction in the WACC. Calibrated against the minimum viable WACC values observed across EU member states — ranging from 4.5% for hydro and onshore wind to 7% for geothermal — this instrument would particularly benefit renewable technologies in countries with unfavourable financing conditions.

3.4.2 Green Policies for State Investment Banks

This scenario increases the volume of financing channelled through State Investment Banks, targeting financially immature technologies that are evaluated as high-risk by private banks and face barriers to bond and equity markets. State Investment Banks (SIB) have historically provided approximately 15% of cumulative energy finance in Europe (Mazzucato & Semieniuk, 2018). Beyond directly easing credit constraints, expanded SIB lending can initiate a virtuous cycle: by enabling earlier deployment of immature technologies, the module's financial maturation dynamics imply faster progression along the financing mix, reducing WACCs and unlocking access to private capital sooner. SIBs also play a crucial signalling role for potential co-investors on large projects and help establish sustainability standards for financial instruments. Prior modelling efforts with simpler energy sector representations have shown positive results from this policy approach.

3.4.3 Green Quantitative Easing

This scenario increases the volume of bond market financing available to energy technologies, primarily benefiting mature technologies such as solar PV and onshore and offshore wind that can issue corporate bonds for long-term investment. Through central bank asset purchases, bond prices rise and yields fall, reducing the long-run cost of debt and expanding the available volume. The introduction of the European Green Bond Standard in 2024 represents a real-world step in this direction. DSGE modelling has associated green QE with increased financial stability and business cycle smoothing, but those models lack the sectoral resolution to assess technology-level impacts. Our module enables explicit simulation of how green QE operates through bond market expansion within a detailed energy-economy model, with direct relevance to ongoing central bank debates about the role of explicit decarbonisation goals in monetary policy mandates.

3.5 Conclusion

In Serebriakova et al. (2026) we provide a substantial methodological advance in modelling energy investment within IAMs. By combining a micro-founded financial market equilibrium with a technology life-cycle framework and embedding these within CLEWs-EU and NEMESIS, our working paper offers a powerful tool for analysing the financial and distributional dimensions of the European energy transition.

The central insight is that as energy technologies mature, they gain access to progressively cheaper and more diversified financing sources, and that this evolution can be captured through logistic diffusion functions governing the financing mix. The resulting WACC paths are non-monotonic, reflecting the interplay between declining instrument costs and shifting leverage ratios over the technology life cycle.

The three policy scenarios examined — green preferential interest rates, expanded State Investment Bank funding, and green Quantitative Easing — illustrate how the module opens a richer space for policy evaluation. Each instrument targets a different channel: cost of debt, quantity of early-stage finance, and volume of late-stage bond market financing respectively. Together they offer a systematic basis for assessing how targeted financial interventions can accelerate the mobilisation of public and private capital toward decarbonisation goals.

Some important limitations remain. The module employs a representative investing firm for each technology type, abstracting from the heterogeneity of actual project developers. Calibration is constrained by available data, given the proprietary nature of much financial information in energy markets. The behaviour of financial intermediaries is not yet fully endogenised. Future extensions to our work could include the incorporation of physical climate risk premia, links to financial stability and stranded assets, thermostatic policy rules responsive to macroeconomic conditions, and explicit Stock-Flow Consistent and Agent-Based Model structures.

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4 Green Tech Adoption by Consumers

4.1 Introduction and Motivation

In Morley et al. (2026) (see Annex 5) we develop a substantially expanded consumer choice and technology diffusion module for residential heating, which can be easily integrated into any recursive dynamic modelling framework (e.g. GCAM-Europe, OPEN-PROM, etc.). This working paper builds on earlier work (Morley, 2026; Morley et al., 2026) in Annexes 6 and 7, respectively), in which we explored the role of social networks in adoption decisions (Morley, 2026) and simulated a model where information and liquidity constraints interact (Morley et al., 2026) addresses a broader and more fundamental limitation in current IAM representations of end-use technology substitution: standard approaches rely heavily on representative-agent cost minimisation and static logit choice, while neglecting the combined roles of intertemporal budget constraints, income heterogeneity, liquidity constraints, social-network-mediated information diffusion, and endogenous evolutionary adoption dynamics.

As shown in chapter 1, most conventional IAMs (such as GCAM) model household heating technology adoption largely through levelized cost comparisons embedded in multinomial logit functions. While computationally tractable, these structures struggle to explain empirically observed patterns such as differentiated adoption across income groups, path dependence, and endogenous S-shaped diffusion curves.

Our contribution in Morley et al. (2026) is therefore threefold. First, we provide a more rigorous micro-founded household model that explicitly links technology adoption to intertemporal utility, up-front investment constraints, and heterogeneous income and credit conditions. Second, we situate household technology substitution more explicitly within the broader innovation diffusion and social network literature, emphasizing the interaction between affordability and locally biased information. Third, we construct an evolutionary diffusion module that embeds these mechanisms and shows how such a module can be integrated into a model like GCAM-Europe through iterative calibration. Thus, our module allows IAM simulations to better represent technology adoption frictions and related policy impacts.

4.2 Theoretical Framework

4.2.1 Household Technology Choice under Budget Constraints

Our starting point is an intertemporal household utility maximisation framework. Households choose heating technologies to maximise discounted lifetime utility subject to income and expenditure constraints, where heating is treated as a necessary good. This implies that households generally optimise over the means of delivering a relatively fixed heating service rather than over the heating quantity itself.

Under idealised conditions without liquidity frictions, this problem would simplify to minimising the levelized cost of heating (LCOH), incorporating up-front capital, as well as discounted lifetime operation & maintenance and fuel expenditures. The baseline model reproduces the basic logic used in the logit models of most standard IAMs and serves as a benchmark against which more realistic constraints are introduced.

4.2.2 Efficiency–Investment Trade-Off and Affordability

A core addition in our model is the more explicit analytical treatment of the efficiency–investment trade-off. Sustainable technologies such as heat pumps often combine high up-front capital requirements with lower operating costs. Adoption therefore depends not only on lifetime cost efficiency but on the timing of costs, climate-specific utilisation rates, and household discounting.

The revised framework demonstrates that adoption is more likely when:

- Variable cost reductions are large relative to capital cost increases
- Discount rates are lower
- Technology utilisation is higher (e.g. colder climates)

Our model then explicitly models time-varying budget constraints. Since capital costs occur immediately while savings accrue gradually, low-income households may rationally reject lifecycle-efficient technologies due to liquidity constraints. This creates affordability thresholds below which households do not adopt certain technologies regardless of long-run efficiency. Thus, income heterogeneity becomes central to aggregate diffusion outcomes.

The model also allows for a richer treatment of assets and consumer credit. While access to savings or borrowing can in principle relax liquidity constraints, these mechanisms are unequally available to households. Because low-income households face more limited access to credit and have smaller stocks of assets, they remain disproportionately constrained in adopting capital-intensive technologies. This strengthens our model's structural explanation for observed inequalities in green technology uptake and highlights that diffusion barriers are financial as well as technological.

With the above extensions, however, we still cannot endogenously reproduce empirically observed diffusion patterns. Therefore, in a final step, we integrate innovation diffusion theory. In Morley et al. (2026) we situate our household technology substitution module within the literature on Rogers-style diffusion models. We introduce this richer social diffusion perspective by modelling information as flowing through clustered social networks characterised by homophily and local bias. Households then rely disproportionately on similar households for information, implying that low-income groups may not only face affordability constraints but also reduced exposure to successful adopters, creating reinforcing feedback loops: low adoption reduces information availability, which further slows adoption. This interaction between income inequality and social-network bias is a major conceptual innovation in the representation of diffusion in IAMs.

4.3 Residential Heating Technology Diffusion Module

4.3.1 Model Structure

The Morley et al. (2026) module represents the population as a set of heterogeneous continuous sub-populations differentiated by income. Each group independently evolves its technology shares over time while gathering imperfect information through social networks. Technology choice is based on a generalised cost concept that extends LCOH by including empirically calibrated intangible costs. Following Klobloch et al. (2021) a key refinement we adopted is the formalisation of pairwise technology competition through binary logit fitness comparisons. Households compare technologies not simply through absolute costs but through probabilistic pairwise preferences under uncertainty.

The model now directly incorporates affordability constraints by preventing adoption of technologies with prohibitively high up-front costs below income-specific thresholds. These affordability barriers are then embedded into an evolutionary dynamic shares equation similar to a replicator equation, where technology shares evolve according to replacement decisions, relative fitness, and socially mediated information availability. This heterogeneous evolutionary framework is particularly important because it does not require exogenous assumptions about diffusion but allows the model to generate endogenous S-shaped diffusion, path dependence, and unequal diffusion speeds across socioeconomic groups.

4.4 Integration with GCAM-Europe

In Morley et al. (2026) we first describe how GCAM uses multinomial logit functions with calibrated share weights and we show that these cannot endogenously reproduce realistic diffusion patterns or social frictions. Rather than replacing GCAM-Europe's structure entirely, however, the Morley et al. (2026) module operates externally and iteratively. It projects technology shares by income group, converts these outcomes into implied share weights that will allow GCAM-Europe to replicate the projected market shares, and iterates until technology adoption patterns and endogenous energy prices converge. This approach preserves computational feasibility while significantly improving behavioural realism.

Although the full iterative empirical simulations remain under development at the time of drafting this deliverable, early simulations and calibration exercises with the new module already implies several important policy insights:

- Stronger path dependence and technological lock-in
- Persistent income-based adoption inequality
- Endogenous diffusion lags driven by both affordability and information constraints
- Differential policy effectiveness across income groups
- Greater importance of targeted subsidies, credit access, and information campaigns

These results will be further developed in the summer of 2026 and reported in an updated version of the working pare as well as the DIAMOND deliverable D5.2 in the fall of 2026. Relative to the traditional IAM simulation results, the new module especially strengthens the case that carbon pricing alone will disproportionately influence higher-income households, while low-income adoption requires direct intervention on liquidity and information barriers.

4.5 Conclusion

Morley et al. (2026) moves beyond a technology diffusion extension to provide a much broader behavioural and institutional framework for modelling green consumer technology adoption in IAMs. By integrating microeconomic household decision theory, liquidity and credit constraints, innovation diffusion theory, social networks, and evolutionary market dynamics into GCAM-Europe, our working paper offers a comprehensive framework for analysing how financial inequality and information structures shape the pace and distribution of the energy transition. Future work will need to focus on full empirical calibration, comparative baseline simulations, and policy experiments that evaluate how targeted interventions can accelerate equitable diffusion of low-carbon household technologies.

5 Synthesis and Outlook

5.1 Introduction

Chapter 1 of this deliverable argued that the next generation of Integrated Assessment Models (IAMs) must move beyond representative-agent, frictionless representations of labour, capital and consumer markets if they are to address the policy questions that stakeholders are now asking. The three subsequent chapters (summarized the working papers we have prepared to) operationalise that argument. Chapter 2 introduced labour-market frictions through a directed search-and-matching module, Chapter 3 embedded a micro-founded financial market equilibrium with endogenous technology life-cycle dynamics in finance, and Chapter 4 developed a heterogeneous consumer technology adoption module that integrates affordability constraints with social-network mediated information diffusion. Each contribution stands on its own as an academic exercise, but their value to the DIAMOND project lies in what they jointly enable: a coherent extension of process IAMs along the same two structural dimensions: heterogeneity on the supply and demand sides of relevant markets, and endogenization of the matching processes that connect them. The purpose of this concluding chapter is to draw out the implications of those extensions for climate policy analysis, to acknowledge their limitations, and to set the agenda for the policy-oriented work that will follow in the rest of the project.

5.2 What the Extensions Enable

Considered separately, each of the three modules sharpens IAM outputs along a familiar margin. The labour-market module of O'Connell et al. (2026) reinterprets the reduced-form CET elasticity as the equilibrium outcome of search frictions, wage bargaining and worker sorting, and recovers unemployment and vacancy rates and duration that conventional CGE-IAMs cannot produce. The finance module of Serebriakova et al. (2026a) replaces uniform discount rates with country- and technology-specific Weighted Average Costs of Capital that evolve endogenously with firm, sector and technology financial maturity, exposing a non-monotonic WACC profile that uniform-rate models systematically miss. The consumer module of Morley et al. (2026) replaces simple cost minimization or exogenously imposed diffusion with an evolutionary diffusion process in which heterogeneous, liquidity-constrained households learn from socially proximate neighbours, generating endogenous S-shaped diffusion and persistent income-related adoption gaps.

Considered jointly, the modules do something more. They shift the IAM toolkit from describing the equilibrium destination of decarbonization toward characterising the transition path itself. Each module relaxes an assumption that, in standard models, suppresses the very frictions that determine the speed and the level and distribution of the costs and benefits of the transition. The labour module makes transitional unemployment and skill mismatch visible, quantifying costs across employees and bottlenecks in the transition. The finance module focuses on the qualitative mismatch in finance and makes risk premia and pecking-order dynamics visible. The consumer module makes affordability thresholds and information bottlenecks visible. Where conventional process IAMs tend to find that aggregate emissions trajectories are robust to the precise specification of these markets, the extended models clarify that this aggregate robustness conceals substantial heterogeneity in who bears the burden of adjustment, when adjustment occurs, and through which channel. In all three cases, the inclusion of frictions slows down the transition relative to the frictionless benchmark. That is bad news, but the frictionless benchmark is not an adequate description of the friction-fraught reality that policy makers need to navigate. By explicitly and endogenously considering these frictions, our model extensions also open up the possibility to assess policy interventions that target these frictions specifically to accelerate the transition in the empirically more relevant real world.

5.3 A Broader Policy Space

The most consequential by-product of our extensions is the enlargement of the policy space that DIAMOND IAMs can credibly evaluate. In a frictionless world, the policy menu collapses essentially to the price of carbon and the choice of revenue recycling rule. This observation may well explain the call for “market-based instruments” such as carbon pricing, taxation and subsidies for renewables, that early IAMs have emphasized. Without diminishing the need for such policies, we have shown that, once heterogeneity and matching are made explicit, a much richer set of instruments becomes analytically tractable.

On the labour side, the directed search framework allows the modeller to distinguish, in welfare terms, between a uniform carbon tax and a carbon tax combined with training subsidies, mobility support, or place-based labour-market programmes. The endogenous CET elasticity provides a direct mapping from these interventions to the speed of sectoral reallocation, and in our extension to wage dispersion, unemployment and vacancy rates and durations and their regional and sectoral incidence. Policies that have hitherto been justified on qualitative "just transition" grounds can now be assigned quantitative impacts within a consistent model environment.

On the finance side, the module supports a structured comparison of three families of green financial policy: preferential lending conditions implemented through micro- and macro-prudential rules, expanded State Investment Bank financing aimed at the early life-cycle stage, and green Quantitative Easing operating through bond markets at the mature stage. Because the module makes the financing mix evolve endogenously with technology maturity, the evaluation can disentangle interventions that lower the marginal cost of capital from those that relax binding quantity constraints and can identify the technologies and member states for which each instrument is most binding. This is a level of granularity that is currently unavailable in IAMs that assume a single or perhaps exogenously differentiated discount rates.

On the consumer side, the diffusion module distinguishes between price-based instruments (carbon prices, energy taxes), liquidity-based instruments (targeted upfront subsidies, low-interest green credit, on-bill financing) and information-based instruments (trusted intermediaries, demonstration programmes, social-norm interventions). Because adoption is jointly determined by affordability and locally biased information, the model can articulate why carbon pricing alone benefits higher-income early adopters disproportionately, and why combined instruments tend to dominate single instruments on “just transition” grounds.

Read across the three chapters, a consistent message emerges. The classical "speed–fairness–cost" trade-off that has framed climate policy debate is not a fixed frontier. It is partly a consequence of the modelling assumptions used to derive it. Once frictions and heterogeneity are made explicit, well-targeted instruments can reduce the binding constraints in each market and shift the frontier outward, delivering combinations of speed, fairness and cost that are unattainable for instruments operating on the price of carbon alone. This is the central policy-analytic payoff of the deliverable.

5.4 Limitations and Agenda for Future Research

The contributions in this report should be understood as deliberate first steps on a clear trajectory rather than a complete(d) agenda. Several limitations carry over from the individual chapters and should be flagged here. First, all three modules are integrated through partial-equilibrium inversion or external-iteration strategies rather than full simultaneous coupling with the host IAMs. This is a pragmatic response to the computational cost of large-scale CGE and energy-system models, but it rules out some of the second-round general-equilibrium feedbacks that may matter on longer horizons. For example, the effect of higher unemployment on aggregate demand, or the effect of credit rationing on investment cycles have hitherto been ignored. Second, calibration relies, as always, on the data sources currently available, which are uneven across countries and technologies; financial and household micro-data are often proprietary or thinly populated for the early life-cycle stages where the new dynamics matter most. Therefore, the presented modules and results should not be taken literally. The models provide a structure and make explicit what variables and parameters are most important in driving the results. That should inform a quest for better calibration and empirical work, before policy conclusions are drawn. Third, each module focuses on a single market in isolation. Cross-market interactions, such as the effect of credit constraints on labour market mobility, or the joint determination of household balance sheets and technology adoption, are conceptually present in the complete framework, but not yet operationalized. Fourth, while the directed search labour module, the financial maturity module and the heterogeneous diffusion module each draw on well-developed literatures, they remain stylised relative to the complexity of the underlying institutions, and several behavioural parameters are still calibrated rather than estimated from primary data.

5.5 From Modules to Policy Scenarios: The Bridge to D5.2

The natural continuation of the work presented above, is the systematic policy evaluation that will be reported in DIAMOND deliverable D5.2 in late 2026. The modules described in Chapters 2 to 4 are intentionally designed to be policy-ready: each is parameterised so that its key frictions can be linked to specific policy levers. The scenarios that will be simulated and presented in D5.2 have been co-designed with project stakeholders and combine instruments from across the three markets. For example, we will simulate a carbon price recycled into training and mobility support, a green preferential interest rate and targeted heat-pump subsidies for low-income households. The capacity to simulate such policies in a coherent IAM environment, even if our simulations remains partial equilibrium, are principal methodological contributions that this deliverable hands forward.

5.6 Concluding Remarks

DIAMOND set out to deliver the next generation of open IAMs, and Work Package 4 set out to push those models beyond their structural limits. This deliverable demonstrates that the structural limits in the representation of labour, finance and consumer markets are not fundamental properties of IAMs but a remediable consequence of historical modelling choices. The three working papers summarised here, together with the working papers in the annexes, show that micro-founded heterogeneity and endogenous matching of supply and demand can be introduced into established IAMs in ways that remain computationally feasible, retain comparability with the existing literature, and that meaningfully expand the set of policy questions that IAMs can answer. The result is a richer toolkit for assessing how the European green transition can be made faster, fairer and more cost-effective. The remaining task — using that toolkit to evaluate concrete, stakeholder-informed policy packages — will be carried forward in D5.2 of the DIAMOND project.

ANNEXES

1. Sanders, M., Morley, P., O'Connell, E., Serebriakova, A., Botzen, W., Polzin, F. & Treibich, T. (2026) What Next for Integrated Assessment Models? Modelling Heterogeneity in Labour, Capital and Consumer Markets, under review at Reviews of Environmental Economics and Policy. Latest version is found here.

What Next for Integrated Assessment Models? Modelling Heterogeneity in Labor, Capital and Consumer Markets.

Mark Sanders[1*], Prescott Morley[1], Eoghan O'Connell[1], Alexandra Serebriakova[1], Wouter Botzen[2], Friedemann Polzin[3] and Tania Treibich[1]

Abstract: Integrated assessment models (IAMs) have helped policy makers conclude that rapid decarbonization is rational and urgent. To better guide policy makers on how to achieve rapid, inclusive and cost-efficient decarbonization, we argue that IAMs must now incorporate heterogeneity among workers, investors and consumers, and endogenize adjustment processes in labor, capital and consumer technology markets. This review synthesizes insights from labor economics, finance and technology adoption that can guide extensions to IAMs, so they better represent matching frictions, information asymmetries, diffusion dynamics and distributional impacts. Based on our review, we identify practical modelling avenues and policy levers, outlining a research agenda to enhance IAMs' relevance for designing effective transition strategies.

Keywords: Integrated Assessment Models; Climate policy; Energy transition; Agent heterogeneity; Labor and capital market frictions; Technology adoption; Distributional impacts; Decarbonization pathways.

JEL-codes: Q54, Q58, C63, O33, J64, G11

1. Introduction

Integrated Assessment Models (IAMs) have been central to formulating climate policy. IAMs help policymakers project climate, energy, and technology interactions, and continue to shape debates on decarbonization (Metcalf and Stock, 2017). The broad and expanding variety of IAMs that link climate change and economic processes can be broadly divided into aggregated cost-benefit analysis IAMs and more detailed process IAMs (Weyant, 2017). These model types differ in their general structure and the level of detail in natural and economic analyses, which means they give insights into distinct climate policy questions.

The first class of cost-benefit analysis IAMs usually provides an aggregate representation of climate change mitigation costs and the economic impacts of climate change. For example, the seminal work by Nordhaus using the DICE model produced global aggregated model outcomes (Nordhaus, 1992) and has been further developed into the most recent version DICE-2023 (Barrage and Nordhaus, 2024). Its regional alternative, RICE, divides the world into several regions (Nordhaus and Yang, 1996). Other influential IAMs in this category are the PAGE model, which estimates economic impacts for different aggregated categories (Hope, 2006), and FUND, which also includes some general sectors, such as agriculture (Anthoff and Tol, 2014). Cost-benefit analysis IAMs have focused on climate policy questions centered around optimal greenhouse gas abatement trajectories and estimating the social cost of carbon for setting the optimal carbon tax (van den Bergh and Botzen, 2015). Moreover, they have been used to study the economic effects of second-best policies such as climate targets (Weyant, 2017).

A rich literature has developed which, for example, adjusted these cost-benefit analysis IAMs to reflect new scientific insights, while also examining their sensitivity to included climate impact categories, risks and assumptions about discount rates, and social welfare functions (for reviews see Botzen and van den Bergh, 2014; Tol, 2018; van den Bergh and Botzen, 2015). Early IAMs were highly sensitive to assumptions about economic damage and discounting, sparking controversy around the optimal speed and timing of emission abatement (e.g. Pindyck, 2017). While open questions remain on the correct representation of social preferences in these models (e.g. Rebonato, 2023), growing evidence

1

2. O'Connell, E., Borghans, L., Perdana, S. P., Sanders, M., & Veille, M. (2026). *A frictional transition: Labor markets in IAMs* [Mimeo]. School of Business and Economics, Maastricht University; École Polytechnique Fédérale de Lausanne. Latest version is found here.

A Frictional Transition: Labor Markets in IAMs[1]

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Abstract

This paper introduces a novel directed search model that enhances the representation of labor market frictions within integrated assessment models (IAMs) and computable general equilibrium (CGE) frameworks. Conventional IAMs and CGEs typically assume frictionless labor markets or represent inter sectoral rigidities using a reduced-form constant elasticity of transformation (CET) parameters, which represent search costs, geographic immobility, skill mismatches, and queuing frictions without providing micro foundations. The proposed directed search module allows workers to endogenously select sectoral sub-markets based on posted wages and job-finding probabilities, while firms post vacancies under free entry conditions. This framework incorporates Diamond-Mortensen-Pissarides matching frictions, Nash wage bargaining, and a logit-based search direction mechanism, resulting in endogenous unemployment, vacancy creation, and wage dispersion across sectors and skill levels. The module provides an explicit interpretation for the CET substitution elasticities and allows us to link them to policy interventions. When linked to the GEMINI-E3 CGE model, our module offers a tractable and empirically grounded micro foundation for inter sectoral mobility elasticity, explicitly representing labor market frictions in energy transition modeling.

Keywords: IAMs, CGE, Energy Transition, Search and Matching, Directed Search

JEL Classification: C68, C78, J62, J64, Q52

[1] Parts of the LaTeX-code underlying this manuscript were generated with help of ChatGPT and Claude. The authors have carefully double checked and take full responsibility for the complete text.

3. Serebriakova, S., Boitier, B., Sanders, M., & Taliotis, C. (2026a). Financial extensions for IAMs [Mimeo]. Maastricht University School of Business and Economics; SEURECO; The Cyprus Institute, Science and Technology Driven Policy and Innovation Research Centre. Latest version is found here.

Financial Extensions for IAMs

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1 Introduction

Financing conditions play a central role in the pace and scale of real investment, innovation, and structural economic transitions. The availability of internal and external funding, its cost, and the terms on which it is extended shape which projects are undertaken (Frank and Shen, 2016). These dynamics are particularly important for the European green transition, where the deployment of utility-scale low-carbon infrastructure must proceed under increasing time pressure from climate targets (Nerlich et al., 2025). While European Commission (2023) estimates that annual investments should reach an *additional* €477 billion by 2030 to meet decarbonization targets, mobilizing these funds from public and private sources remains difficult. The ECB's *Survey on the Access to Finance of Enterprises* shows that an average 57% of firms name financing constraints as a barrier to their green investments, such as high interest rates, limited access to bank-lending and capital markets (European Central Bank, 2026).

Despite their relevance, the financial conditions facing energy projects have been historically overlooked in Integrated Assessment Models (IAMs) (Pollitt and Mercure, 2018). MESSAGE, REMIND and TIAM are among the models which have previously relied on uniform discount rates (Hatton et al., 2025), frictionless capital market adjustments, and representative agents with unconstrained access to finance (Keppo et al., 2021). These assumptions abstract away from precisely the frictions (heterogeneous borrowing costs, financing constraints and misallocation) that determine whether low-carbon investment pathways are feasible.

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4. Serebriakova, A., Polzin, F., & Sanders, M. (2026b). Monetary policy and energy installation: Implications for the European green transition. Energy Economics, 109159. Published version is found here.

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Monetary policy and energy installation: Implications for the European green transition

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ABSTRACT

Policymakers have raised concerns that the required transition to renewable energy sources in the European Union could be stalled by a period of higher ECB policy rates meant to combat inflation. Prior research shows heterogeneous effects of policy rates on sectors with varying industrial characteristics, meaning that renewable technologies may be hit disproportionately by monetary contractions due to their investment requirements, life-cycle stage, and/or dependence on external finance. This paper uses fixed effects panel analysis of 28 European countries to look at the interactions between installed capacity of 10 utility-scale energy technologies, their characteristics, and monetary policy. Over the period of 2001–2024, fossil fuel, hydropower and nuclear technologies remained unaffected by monetary contractions, while a 25 basis point rise in policy rates was associated with a 3.2% decrease in total installed capacity for onshore wind, and a 5.3% decrease for solar PV. Significant interaction effects, using measures of investment intensity and external finance dependence for energy technologies, yield evidence in favour of the interest rate and balance sheet channels of monetary policy transmission. To address endogeneity concerns, we use a two-stage least squares (2SLS) approach in an LCOE specification for the interest rate channel in the energy sector, which confirms these findings. Our results suggest the existence of an unintended bias in contractionary monetary operations; central banks should consider flanking policies (such as preferred interest rates) to offset the disadvantage for renewables.

1. Introduction

As the world grapples with the dual challenges of climate change and energy security (European Council, 2019; Lee et al., 2023), transitioning to sustainable energy sources has never been more urgent. Utility-scale renewable energy technologies, particularly solar photovoltaics (PV) and onshore wind, have matured significantly (Panetta, 2022), converging in terms of Levelised Cost of Electricity (LCOE) towards historically cheap fossil fuel plants (IRENA, 2022). However, cost-competitive renewables are not sufficient for achieving EU Net-Zero goals: they need to *replace* (not only complement) existing fossil fuel installations (Sutherland, 2019). A critical driver of the LCOE for renewable projects is the cost of capital (CoC), which is heavily influenced by (expected) market interest rates (Schmidt et al., 2019). It is the cost of (refinancing) the capital that in part drives their *relative* profitability.

From 2008 to 2020, the ECB pushed interest rates close to the lower bound, which encouraged investment in capital-intensive industries such as renewables. Now, the decade will likely be defined by contractionary monetary responses to inflation (De Guindos, 2023). Schmidt et al. (2019) predicted that a rise in policy rates to 4% (which they deemed an “extreme scenario”) could cause the LCOE of German renewables to rise by 25%. At its peak in September 2023, the ECB raised the main refinancing rate to 4.50% (ECB, 2025). This may well have unintended consequences for the relative competitiveness of renewables and the energy transition.

This paper therefore seeks to examine the effect of monetary policy rates on the adoption of utility-scale renewables in electricity production in Europe. Monetary transmission mechanisms, including the interest rate, asset price, and credit channels (Mishkin, 1995), could result in policy rates heterogeneously impacting the growth of sectors based on their industrial characteristics (Dedola and Lippi, 2005). Building on the seminal work of Rajan and Zingales (1998), previous research has shown that financial development affects energy technologies differently (Kim and Park, 2016) and that monetary policy shocks indeed affect manufacturing sectors differently (Choi et al., 2024), based on their

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Consumer Choice GCAM Implementation

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Abstract

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1

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Keeping Up or Catching Up?

Income Inequality, Social Comparisons, and the Shape of Expenditure Cascades

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May 7, 2026

Abstract

The shape of expenditure cascades has important implications for, as it helps to understand the transmission process from policies affecting inequality to changes in total consumption volumes. The hypothesis, that income gains at the top of the income distribution lead to greater expenditures throughout the distribution, is typically built on *strictly upward-looking* social comparisons, the idea that individuals only compare themselves to those with higher income (consumption) than themselves. However, this assumption is unnecessary and insufficiently justified. I propose an agent-based model of consumption decisions, which employs a novel method of integrating the consumption reference into the utility function. Using this model, I demonstrate that expenditure cascades can occur in the microeconomic sense without the *strictly upward-looking* assumption, but that dropping the assumption can reverse the direction of the effect of inequality on the aggregate savings rate. The model offers a new theoretical perspective on the ambiguous empirical evidence.

JEL-Classification: E21, D31, B55, C63
Keywords: Agent-Based Modeling, Consumption, Inequality, Relative Income Hypothesis, Positional Goods

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Declarations of Interest: none

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Sustainable Technology Uptake Under Local Information & Liquidity Constraints

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May 7, 2026

Abstract

TBD

JEL-Classification: B55, C63, E21, Q55

Keywords: Technology diffusion; Renewable heating; Policy simulation; Decarbonisation pathways; Liquidity constraints; Energy modelling; Behavioural modelling; Agent-based modeling

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Declarations of Interest: none

Landscape-Oriented Tables

Here we reprinted the landscape-oriented tables in the deliverable.

Table 3: State of the Art in (Process) IAMs

Model	Reference	Labor				Finance				Consumers			
		Dimension	Heterogeneity	Endogeneity	Stylised facts *not* addressed	Dimension	Heterogeneity	Endogeneity	Stylised facts *not* addressed	Dimension	Heterogeneity	Endogeneity	Stylised facts *not* addressed
E3ME	Cambridge Econometrics, 2022	Search & Matching Frictions	1	1	L3, L1	Financiers	2	1	F1, F4	Geography	1	1	C2, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	4	1	
		Wage Differentials	3	3		Investors/Projects	2	2		Technology	1	5	
		Human Capital Accumulation	1	1		Macro-Monetary	3	4		Income/Wealth	1	1	
GCAM	PNNL, 2020	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	2	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	1	1		Income/Wealth	4	2	
GEM-E3	ICCS, 2017	Search & Matching Frictions	1	1	L3, L1	Financiers	3	1	F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	2	2		Assets	4	3		Preferences	1	2	
		Wage Differentials	2	2		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	3	3		Income/Wealth	1	4	
GEMINI-E3	EPFL, 2025	Search & Matching Frictions	1	1	L3, L1	Financiers	1	1	F1, F2, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	1	
		Wage Differentials	2	2		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	2	1		Macro-Monetary	2	2		Income/Wealth	1	1	
IMAGE	PBL, 2022	Search & Matching Frictions	1	1	L1, L2, L3	Financiers	1	1	F1, F3, F4	Geography	2	1	C1, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	3	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	2	1		Income/Wealth	3	2	
MESSAGEix	IIASA, 2020	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	2	1		Income/Wealth	1	2	
NEMESIS	ERASME, 2025	Search & Matching Frictions	1	1	L3	Financiers	2	2	F3	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	2	1		Preferences	1	1	
		Wage Differentials	2	1		Investors/Projects	2	2		Technology	1	1	
		Human Capital Accumulation	2	2		Macro-Monetary	3	2		Income/Wealth	1	5	
PROMETHEUS	E3M, 2018	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	2	1		Income/Wealth	1	2	
REMIND-MAgPIE	PIK, 2020	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F4	Geography	1	1	C1, C2, C4
		Labour Mobility Constraints	1	1		Assets	2	1		Preferences	1	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	5	
		Human Capital Accumulation	1	1		Macro-Monetary	2	1		Income/Wealth	1	1	
TIAM-UCL	IER, 2020	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	2	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	2	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	1	1		Income/Wealth	1	2	
WITCH	EIEE, 2019	Search & Matching Frictions	1	1	L1, L2, L3, L4	Financiers	1	1	F1, F3, F4	Geography	1	1	C1, C2, C3, C4
		Labour Mobility Constraints	1	1		Assets	1	1		Preferences	1	1	
		Wage Differentials	1	1		Investors/Projects	2	1		Technology	1	1	
		Human Capital Accumulation	1	1		Macro-Monetary	1	1		Income/Wealth	1	2	

Note: To have a rough first impression we (generously) scored the models on heterogeneity 1-homogenous, 2=two representative agents, 3= three or more representative agents, 4-one dimension of heterogeneity continuous, 5=all relevant dimensions continuously distributed. And on endogeneity 1=exogenous static, 2=exogenous dynamic, 3-iterative consistent static, 4-iterative consistent dynamic and 5-recursive dynamic. We report a "0" for absent or insufficient information or not applicable. It is hard (impossible) to score these very different models very precisely on these categories and the reader is referred to the references in the table for precise details.

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Table 5: Policies and Policy Implications

Theme	Reference(s)	Policies Assessed	Policy Results	Policy Prescriptions to make the Transition…	…Faster, Cheaper and/or Fairer
Labor Policies	Hafstead & Williams III (2018)	Carbon Tax and Carbon Regulation	Performance standards generate smaller sectoral employment shifts than emissions taxes while keeping aggregate unemployment effects small.	Implement apprenticeship support and hiring credits aligned with performance-standard changes	(+) Faster (+) Fairer (-) Cheaper
	Aubert & Chiroleu-Assouline (2019); Castellanos & Heutel (2024); Guivarch et al. (2011); Hafstead, Williams III & Chen (2022)	Carbon Tax and Revenue Recycling	Carbon pricing is fairer and more effective when revenues are recycled progressively rather than uniformly, as it offsets regressivity and can reduce low-skilled unemployment.	Implement carbon-tax funded progressive labor-tax recycling policies, such as payroll tax cuts for low-wage workers, EITC expansion, mobility and hiring support for displaced workers, work share credits,	(+) Faster (+) Fairer (-) Cheaper
	Zaussinger et al. (2025); Lankhuizen et al. (2023)	Decarbonization	Decarbonization headwinds can be mapped ex ante and mitigated through occupational and regional exposure to high-carbon job risk.	Implement training and education policies to address predictable shortages and support vulnerable sectors and regions	(+) Faster (+) Fairer (-) Cheaper
	Wasmer (2006)	Employment Protection	Stronger EPL supports specific-skill accumulation and job stability but raises hiring and separation costs.	Implement Retention-Conditional Training and Accreditation and a Layoff Tax	(-) Faster (+) Fairer (-) Cheaper
	Mu et al. (2018)	Feed in Tariff	Feed-in tariffs yield net job gains when financed via lump-sum taxation rather than electricity consumption surcharges, since electricity-fee financing raises power costs and induced job losses offset green-job creation.	Finance feed-in tariffs from general or carbon revenues, not electricity or other utility surcharges and use renewable auctions funded from broad revenues instead of fixed feed-in tariffs.	(+) Faster (+) Fairer (-) Cheaper
	Oikonomou (2023)	Migration Policy	Mitigate skill-draining outflows / promote skilled return to avoid a deeper, more protracted downturn via weaker investment and reduced supply capacity, and to limit inequality increases.	Implement skill retention-oriented migration policies, such as return programs and targeted tax relief	(-) Faster (+) Fairer (-) Cheaper
	Marten, Schreiber & Wolverton (2025)	Regulation	If compliance with regulation relies on high skill non-routine cognitive labor, demand and wages for those workers rise.	Implement task-modular compliance standards and stackable transition credential bridges	(+) Faster (+) Fairer (+) Cheaper
Financial Policies	Monasterolo & Raberto (2018)	Regulation, Green Fiscal Support and Green QE	Regulation against brown sector reduces emissions and resource imports. Green fiscal support reduces emissions but dampens growth and raises unemployment. Green QE reduces emissions but raises public debt.	Implement a mix of green policies to increase speed of transition, but with risk of lower employment, higher public debt and tax burdens on households.	(+) Faster (-) Fairer (+/-) Cheaper
	Ponta et al. (2018)	Feed-in-Tariff	Feed-in tariffs increase share of renewables in energy mix.	Implement higher feed-in tariffs for faster green transition; this also raises the public cost burden, which is distributed to households.	(+) Faster (-) Fairer (0) Cheaper
	Dunz, Naqvi & Monasterolo (2021)	Carbon Tax and Green Capital Requirements	Green capital requirements (supporting factor) increase green capital share moderately, and rate of non-performing loans (stranded assets). Carbon taxes increase green capital share sharply but dampen aggregate demand.	Implement green capital requirements and taxes to speed up transition, at the expense of financial instability. Effects on household budgets require additional redistributive policies.	(+) Faster (-) Fairer (-) Cheaper
	Lamperti et al. (2020)	Green Capital Requirements, Green Public Guarantees and Carbon Risk Ratings	Favorable capital requirements help green sector growth, reduce aggregate emissions, and act pro-cyclically. Green public guarantees reduce aggregate emissions and act counter-cyclically. Carbon risk ratings reduce emissions least.	Implement mix of all three policies to help green transition speed, while maintaining financial stability, manageable public debt and moderate economic growth.	(+) Faster (+) Fairer (+) Cheaper
	Calcaterra et al. (2024)	Green Financial Risk Sharing	Financial risk sharing (integrated markets, SIBs, public loan guarantees) can reduce emissions and energy prices	Implement (international) policies that would speed up reduction and convergence in WACCs to promote faster, cheaper and fairer transition	(+) Faster (+) Fairer (+) Cheaper
	D'Orazio & Valente (2019)	Green Mandate for SIB	Green SIB mandates, particularly with strong consumer environmental preferences, help diffuse innovation from the green sector.	Implement a green SIB mandate to increase speed of transition and provide macroeconomic stimulus to growth.	(+) Faster (0) Fairer (+) Cheaper
	Dafermos, Nikolaidi & Galanis (2018)	Green Preferential Interest Rates and Green Credit Access	Green interest rates and expanded credit access increase investment and reduce emissions moderately. Penalty on brown firms reduces emissions further, but dampens aggregate demand	Implement green support and brown penalties to increases speed of transition at expense of growth.	(+) Faster (0) Fairer (-) Cheaper
	DiLuiso et al. (2021)	Carbon Tax, Green Micro prudential Policy and Green QE	Carbon taxes reduce emissions significantly, but disorderly implementation creates inflationary pressures. Green QE mitigates financial instability but does not further green sectors micro prudential policy helps banks decarbonize balance sheets.	Implement gradually increasing carbon taxes to further the transition with fewer disruptions. Use QE to counterbalance contagion from stranded assets.	(+) Faster (0) Fairer (+) Cheaper

Table 5: Policies and Policy Implications (Cont'd)

Theme	Reference(s)	Policies Assessed	Policy Results	Policy Prescriptions to make the Transition…	…Faster, Cheaper and/or Fairer
Consumer Policies	Eppstein et al. (2011)	Carbon Tax	Higher fuel prices lead to faster transition.	Implement stronger long-term policy incentives, such as subsidies and taxes, when early adopters are spatially clustered.	(+) Faster (0) Fairer (-) Cheaper
	Edelenbosch et al. (2018) Knobloch et al. (2019); Knobloch et al. (2021)	Carbon Tax and Subsidies	In early phases of transition, subsidies are only effective if they target early adopters.	Implement policy incentives, such as subsidies, that target early adopters in early phase.	(+) Faster (-) Fairer (+) Cheaper
	Brugger & Henry (2019)	Feed in Tariff and Leasing/Seeding	Feed-in tariffs are most effective if early adopters do not cluster. Leasing and seeding programs are most effective if early adopters do cluster.	Implement policies to reduce barriers to installation and seed installations among low propensity adopters when early adopters cluster spatially/socially.	(+) Faster (+) Fairer (-) Cheaper
	Rai & Robinson (2015); Charlier & Risch (2012)	Income Dependent Subsidies	Additional incentives for low-income households only modestly improve diffusion speed and incentives are ineffective as long as installation is unaffordable. Bonuses to low-income households are less cost efficient per ton of CO2 saved.	Implement (very) strong incentives for low-income households to achieve a meaningful increase in adoption.	(+) Faster (+) Fairer (-) Cheaper

Note: The table shows what policies (a subset of) the inspiration models in Table 4 have assessed and with what results. We have merged references that cover broadly similar policies for readability, even if the different papers differ in the details. In the final two columns we translated these results into what we believe are the normative policy implications and indicate how such intervention(s) would contribute to (+) or come at the cost (-) of a faster, fairer and cheaper transition, respectively.

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