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Representation of financial markets in macro-economic transition models—a review and suggestions for extensions

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Abstract

As the energy transition accelerates and renewable energy technologies become cost-competitive with fossil fuels in many countries, the availability of finance could become a bottleneck. Integrated assessment models (IAMs) and other macro-economic transition (MET) models typically do not feature detailed financial markets and do not sufficiently consider financing barriers and opportunities for the transition to carbon neutrality. While progress has been made in the representation of financial markets in macro-models since the financial crisis of 2008 the focus has been on financial (in)stability of the financial sector, not its ability to finance investment projects in the energy transition. Hence, a crucial gap remains, preventing macro model-based analysis of financing barriers and policy interventions that may accelerate the energy transition. In this article we review how state-of-the-art macro-economic models consider the financial sector. From this review we identify what elements are still missing to adequately model the financial dynamics and challenges for the energy transition specifically. Based on a discussion of relevant parts of the finance literature, we then propose four steps to improve the representation of finance in global IAMs and MET models more generally.

1. Introduction

The energy transition is at the same time urgent and going too slow (Zappa *et al* 2019, IEA 2020). To mitigate dangerous climate change, the transition towards low and zero-carbon energy technologies needs to accelerate. Scenario studies show that there is still time to meet the Paris goals (Fragkos and Kouvaritakis 2018). But as time is passing by, there are many technically feasible and even economically attractive mitigation options that are not deployed to their full potential. Scholars have suggested that finance is one of the major bottlenecks for the transition (Peake and Ekins 2017, McCollum

et al 2018, Steffen and Schmidt 2021). However, there is no lack of financial resources in the global economy. Instead, it looks as if there is a serious qualitative mismatch between available sources of finance and the financial needs of the energy transition (Polzin and Sanders 2020). Moreover, investors face uncertainty in the early stages of the transition and for commercially immature technologies and may not be willing to commit their resources under these conditions.

Macro-economic transition (MET) models currently show us that the energy transition is technologically feasible and economically desirable. The models, however, typically abstract from financial

constraints[9]. The old neoclassical axioms that 'money is a veil' and 'money is neutral' (see Pollitt and Mercure 2018) have convinced modellers that the financial sector will mobilise and allocate the required funds at reasonable costs. The financial crisis of 2007–2008 was a wake-up call to the possibility that financial markets might become dysfunctional. But more importantly, even functional financial markets have their limitations. In fact, these limitations are well known from the finance literature, a body of knowledge that offers us relevant models and approaches from which to start building the most relevant frictions into the integrated assessment models (IAMs) and the MET models (Keppo *et al* 2021). Taking these frictions into account may qualify the conclusions we draw from IAMs and the MET models on the economic feasibility of the energy transition and may help formulate policy interventions to get us on track to meet Paris Agreement goals. As policy interventions with respect to the low-carbon transition are gaining momentum in many economies (Steffen 2021), it is urgent to build financial frictions into the models to ensure effective policy designs[10].

Of course, we are not the first to consider building more sophisticated financial markets into the IAMs and the MET models. Hardt and O'Neill (2017) assess recent modelling developments according to eight themes, one of which is the monetary system. The authors note that stock-flow consistent (SFC) models have come the closest to an explicit and complete representation of the banking sector[11]. These models also implement credit constraints and different kinds of assets. Second, Mercure *et al* (2019) discuss the role of money and finance in different modelling approaches (supply-led/equilibrium vs demand-led/non-equilibrium) with regard to the energy transition. They distinguish between models with finance as a commodity in limited supply with associated crowding-out mechanisms, and as an asset in unlimited supply with investment demand being limited by profitable opportunities. Third, Hafner *et al* (2020) echo earlier findings that SFC approaches integrate the most elaborate and complete representation of

the financial sector and call for 'a more detailed inclusion of key actors' expectations and decisions in the financial system into ecological macroeconomic energy transition models' (p. 12). Finally, Keppo *et al* (2021) review the landscape of IAMs and conclude that current state-of-the-art models miss the representation of financial market features (financial risks, debt accumulation, and repayment) and capital market imperfections (e.g. credit rationing, and asymmetric information).

In this paper we start from three empirical regularities that were shown to be relevant in the context of the energy transition: the qualitative mismatch between the supply and demand for finance, the financial lifecycle, and financial learning (Egli *et al* 2022). The *qualitative mismatch* refers to the fact that finance is not fully fungible (Polzin and Sanders 2020). That is, not all sources of funds are suitable and available for all types of investments. IAMs and MET models often implement a single cost of capital (CoC), assuming that all investments and technology types can be financed at that average cost. If finance is fully fungible, this assumption is a good first approximation. But we know from corporate finance that different types of funding come at different costs and with different risk-return profiles (Berger and Udell 1998). Moreover, technologies can differ with respect to which types of funding are appropriate and available (Steffen 2018). A qualitative mismatch may then put a restriction on the speed at which certain low-emission technologies will be introduced and diffused into the economy. The *financial lifecycle* refers to the fact that the funding mix that is demanded for given technologies will change over the lifecycle of the technology (Polzin 2017). Uncertainty is reduced as technologies mature and risk becomes more manageable. Therefore, new, cheaper funding sources can be tapped to finance the more mature projects (Polzin *et al* 2021a). Finally, *financial learning* then refers to the fact that the cost of financing projects also declines with experience. That is, as investors and financiers gain more experience in specific investments, the costs of mobilising the capital for similar projects can also drop due to financial learning (Egli *et al* 2018). IAMs and MET models currently include parameters for technological learning over the lifecycle but ignore the learning effects on financing costs (Keppo *et al* 2021). As a corollary, the IAMs and the MET models do not reveal that policy interventions that reduce the qualitative mismatch, accelerate the financial lifecycle, or support financial learning can be cost-effective interventions by which to accelerate the energy transition.

From the finance literature, we propose methods and concepts that can be used to improve the IAMs and the MET models in this respect. We need not go into sophisticated finance models to account for the above empirical regularities in IAMs and MET models. Basic textbook concepts already take us a

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[9] The family of MET models includes Integrated Assessment Models (IAMs) based on the neo-classical computable general equilibrium (CGE) approach, more specialized partial equilibrium and cost optimization models as well new approaches such as agent-based models (ABM) and stock-flow consistent models (SFC).

[10] It might, for example, make sense from a global perspective to compensate private investors for the risk on Greek solar and wind assets, when we know that they will generate more renewable energy for the same investment in Greece than in, for example, Germany.

[11] Stock-flow consistent models, in this definition, feature a full set of balance sheets for all agents in the model and track both the stocks on these balance sheets and the flows between them. These models are also known as balance sheet or accounting models. Models that keep track of only some (non-financial) stock variables such as CO_2 concentration or the physical capital stock, are not assigned to this category.

long way. For example, the term structure between short-term and long-term interest rates links the costs of capital over different maturities (Ellingsen and Soderstrom 2001); the pecking order to finance investment projects (Myers and Majluf 1984), starting with retained earnings up to issuing new equity and asset- or technology-specific capital structures, link the costs of capital over asset classes; and, finally, the capital asset pricing model (CAPM) (Courtois *et al* 2012) and the efficient market line describe the link between costs of capital and risks (Modigliani and Miller 1958). We also look at more macro-financial theories for elaborating on how the transmission of monetary policy and notably quantitative easing can play a role (for good or bad) in the clean energy transition (Schoenmaker 2021).

To build on the literature that is already there, we therefore first survey 36 papers that represent the current state-of-the-art in how IAMs and MET models embody finance. We conclude that, especially since the financial crisis of 2007–2008, a lot of work has been done to represent financial markets more accurately in macro-models. However, this research is still fragmented (Hafner *et al* 2020, Keppo *et al* 2021). Moreover, only few papers and studies model finance to better understand the dynamics of the energy transition (e.g. Dafermos *et al* 2018, Bachner *et al* 2019, Paroussos *et al* 2019a, Battiston *et al* 2021). The contribution in this paper is that we link previous empirical work (e.g. Egli *et al* 2018, Polzin and Sanders 2020, Steffen 2020) to simple models of the term structure, pecking order theory, the CAPM-model, and macro-monetary transmission to develop approaches that capture financial constraints and dynamics and can be integrated into IAMs and MET models. To make this contribution as actionable as possible, we present four concrete steps on how finance theories could be applied in MET models, also highlighting the feasibility of implementation in different types of models. Finally, to further illustrate our proposed approach, we develop a blueprint for the GEM-E3 model, which is a well-established macro-model assessing the socio-economic implications of the energy transition (Pollitt and Mercure 2018, Paroussos *et al* 2019a). Introducing more realistic financial markets in MET models as proposed would allow for the analysis of policy options that facilitate the provision of low-cost finance for clean energy projects specifically and will establish links between large-scale transition finance, structural change and systemic risk.

The remainder of this paper is structured as follows. We first briefly present the method for collecting and reviewing the state of the art in modelling finance in MET models (section 2), after which we present a review of our findings (section 3). Having established that current state-of-the-art MET models do not account for qualitative mismatch, the financial lifecycle and financial learning, we turn to some basic finance theories that may inform the needed extensions (section 4). In section 5 we map out how these extensions are currently featured in the reviewed literature and comment on how they might be integrated into different types of MET models using the GEM-E3 model as an example.

2. Method

We deployed a semi-structured method, commonly used in the social sciences, to collect the relevant papers from the literature (Hansen and Rieper 2009, Reim *et al* 2015). This method provides a more transparent, reliable and replicable way of selecting papers than purely narrative reviews (Hart 1998), while being more flexible than rigid meta-analyses (Hunter and Schmidt 2004). This allows us to usefully consolidate the heterogeneous field of finance representation in IAMs and MET models.

We start with existing review papers to get an overview of the debate (Hardt and O'Neill 2017, Pollitt and Mercure 2018, Hafner *et al* 2020). Based on papers cited in these reviews, we summarise which modelling improvements have been made over the past years and complement the observations with keyword searches combining model type and financial terminology (e.g. invest*, finance*). We then analyse the resulting list of papers according to model type, key financial assumptions, financial actors and terms, parameters (such as interest rates) and a full financial sector description. From that information we build a broad overview of financial sector representations in different model classes (see table in supplementary materials).

To depict the landscape of MET models, we classified the different scientific papers and corresponding models according to the following typology: First, we distinguish agent-based models (ABM) from representative agent models (RAMs), which relates to models' ability to include different financial asset types. Second, we investigate the main market mechanisms upon which the models are based: price-adjusted (PA) or quantity-adjusted[12]. This modelling choice has consequences for how the financial sector can be integrated (e.g. endogenous interest rates based on relative demand in different sectors). Third, we distinguish between (G)eneral and (P)artial (dis)equilibrium models. This design feature determines whether financial constraints affect specific markets or affect the entire economy. Fourth,

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[12] A reviewer correctly pointed out that models are never exclusively price- or quantity adjusting. In the long run prices and quantities both adjust to changes in demand and supply in all models. The distinction is therefore not to be interpreted as a strict dichotomy, but rather as a continuum. Price-adjusted models are more neo-classical and allow for a rapid price adjustment, reestablishing equilibrium in the short run. More Keynesian models assume more sticky prices and therefore quantities (supplied) adjust to shocks in these models.

to differentiate the intertemporal dynamics of MET models, we distinguish between those that follow SFC accounting principles vs. those that do not (non-SFC)[13]. This feature would allow financial assets and liabilities to accumulate on agents' balance sheets (or not), affecting their choices but also allowing for (differentiated) rates of financial learning. Such an overview allows us to summarise state-of-the-art models and potential extensions to improve the representation of finance in MET models.

3. Findings

We first describe the main model types using exemplary papers and their key financial characteristics. These characteristics include the agents that are defined in the financial sector, the parameters according to which such agents operate, and any assumptions that underpin their behaviour and interactions, or the larger financial structure. The aim is to give a clear overview of the main 'ingredients' of the financial sectors in IAMs and MET models.

We drew our conclusions based on our full set of papers, as presented in table S1 in supplementary materials. For each model type we selected one or two papers based on the sophistication of their financial sector representation, the uniqueness of components (such as an endogenised Taylor-like rule in versions of the EIRIN model) or clear use of empirical data for model calibration (such as in Gerst *et al* 2013, Liu *et al* 2017, Bachner *et al* 2019). This representative sub-set of papers suffices to illustrate our main findings and is therefore presented in table 1.

3.1. Model characteristics, key financial assumptions, and actors

The approach of SFC models has been identified as the most innovative path for financial sector modelling in MET models by past reviews (Hardt and O'Neill 2017, Hafner *et al* 2020). Its principles appear in more than a third of the 36 articles reviewed for this paper. Based on the work of Godley and Lavoie (2006, 2007, 2012), post-Keynesian (demand-driven, boundedly-rational) assumptions emerge as a standard for SFC models. The defining principle is the use of a transaction-flow matrix to map financial balance sheets and transactions onto (representative) agents such as households, firms, banks, and the government (Godley and Lavoie 2007). The convention of double entry accounting is applied; money creation can be endogenized in the form of deposits that follow the loans given out by banks (Giraud and Grasselli 2017), which allows for the exploration of potential crowding-in and crowding-out effects (discussed also in Keppo *et al* 2021). However, SFC models can also focus on other assumptions, such as that demand by

households to buy firm equity is exactly equal to the amount of equity that firms are willing to sell (for example in Jackson and Victor 2016). A by-product of this approach can be implicit perfection in the capital market, an element challenged by, for example, Leimbach and Bauer (2021 see table 1 line 9) in the REMIND IAM. The authors impose region-specific debt constraints, demanding that each model region keep its accumulated current account deficits (and surpluses) below 20% of GDP and include risk premia differentiated by region.

One self-evident criterion on which to classify IAMs and METs is the actors and variables the authors include in their financial sectors. The most common financial agents that are included (often exclusively), are a (representative) commercial bank and a (representative) central bank (see for example Bovari *et al* 2020 in table 1 line 4). The commercial bank deals typically with loans and deposits to firms and households. The central bank (sometimes conceptualised as a State Investment Bank, when the focus is on green versus brown investments) is a lender of last resort and/or a monetary authority that sets reserve or capital requirements (see for example Monasterolo and Raberto 2018). Some models, such as that in Paroussos *et al* (2019a) in table 1 line 6, do not distinguish between commercial and state banking, and offer one aggregate financial agent, which they term the 'World Bank'.

A clear alternative is offered by ABM, which aims to explore the emergence of complex and adaptive systems on a foundation of heterogeneous, interacting agents (Caiani *et al* 2016). This forms another relatively innovative approach highlighted in recent reviews (Hafner *et al* 2020). However, ABM can also simplify the financial sector using representative financial agents, if, for example, their focus lies on the behavioural dynamics of heterogeneous firms, energy providers, differently skilled workers and/or households, rather than on the interactions between financial actors (Lamperti *et al* 2018 in table 1 line 3, D'Orazio and Valente 2019), or on modelling the credit worthiness of firms and the lending constraints of financial institutions, in conjunction with endogenous money creation (e.g. Lamperti *et al* 2018).

Very few model-based studies offer a framework for the interaction of heterogeneous financial agents or consider heterogeneous financial markets. A notable exception is Safarzynska and Van den Bergh (2017), who take an agent-based approach directly to the financial sector and look at a network of 50 heterogeneous commercial banks. This approach allows them to explore a financial 'topology of risk', with simulation results that include cascades of bank insolvencies, while no new banks are allowed to enter. Stolbova *et al* (2018) use networks to develop a methodology, which allows for the analysis of the transmission of (positive or negative) shocks throughout

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[13] See also footnote 2.

Table 1. Representative overview of model types including financial characteristics.

#	Model type	Example paper	Characteristics	Key financial assumptions	Financial actors and terms	Parameters and rates	Financial sector mechanisms
1	APGF	Gerst *et al* (2013)	ENGAGE adopts an agent-based approach. Domestic actors include firms and households who function as agents within an evolutionary representation of economic growth, energy technology, and climate change.	Assumption that learning-by-doing and learning-by-searching effects are present.	No banks, but firms acquire loans.	Interest and discount rates set exogenously, based on US empirics.	No banks are modelled. Yet the consumer-goods firms first attempt to finance their production from their stock of liquid assets (NW). If liquid assets inadequately cover production costs, then firms may borrow up to a maximum debt/sales ratio (L). Firms then use residual liquid assets and additional debt to finance machine purchases. There is a cost of capital over time (annual interest on debt r_B and expected machine lifetime h_M).
2	AQGS	Ponta *et al* (2018)	EURACE is an ABM enriched with energy sector representation, based on Leontief production function. Agents have myopic behaviour and are boundedly rational, as they have backward-looking adaptive expectations.	Standard post-Keynesian and SFC underpinnings. Bounded rationality, demand-driven.	Commercial bank (CB), central bank. Deposits, mortgages, loans, firm stocks and government bonds exist.	Investment is planned according to NPV calculations and follows pecking order theory. See appendix C for rates in simulations (CB policy rate around 3%, bond yield around 6%).	There is a financial market for firms'/banks' stocks and government bonds. Banks provide short-term loans to firms and mortgages to households. Interest rates are determined by the CB rate plus a mark-up. Bank lending is not limited by available liquidity, but by a capital requirement rule. Banks assess creditworthiness of borrower by considering its leverage.

(Continued.)

Table 1. (Continued.)

#	Model type	Example paper	Characteristics	Key financial assumptions	Financial actors and terms	Parameters and rates	Financial sector mechanisms
3	AQGF	Lamperti *et al* (2018)	Dystopian Schumpeter meeting Keynes (DSK) model with endogenous growth, business cycles and crises. Heterogeneous firms (capital goods sector and consumption goods sector). Climate change impacts workers' productivity, capital stock, inventories and energy efficiency.	Imperfect credit markets, with potential for credit rationing. Endogenous growth, business cycles and crises. Boundedly rational agents.	Banking sector composed of a unique commercial bank (or multiple identical ones) that gathers deposits and provides credit to firms. Heterogenous firms can use loans (or retained earnings from prior sales) to finance R&D to improve efficiency (if they are in the capital good sector), or to invest in capital goods (if they are in the consumer goods sector).	'Central bank to grant credit above the funds obtained through deposits from firms in the two industries (and equal to firms' past stock of liquid assets) according to a multiplier $k > 0$.' (p. 331). Interest rates on deposits and loans are set as a mark-down and a mark-up on Central Bank rates, respectively.	Firms employ their cash stock, and if the latter does not fully cover total production and investment costs, they borrow external funds from a bank. 'Total credit demand can be higher than the maximum supply of credit, in which case credit rationing arises' (p. 318). The profits of the bank are equal to interest rate receipts from redeemable loans and from interest on reserves held at the central bank minus interest paid on deposits.
4	RQGS	Bovari *et al* (2020)	BGM-SFC is a model that is developed based on the myopic behaviour of imperfectly competitive firms, which is stock-flow consistent, allows for multiple long-run equilibria, and exhibits sticky prices, endogenously determined private debt, and underemployment.	Money is endogenously created by the banking sector. Usual SFC accounting principles must hold. Follows Minsky's intrinsic instability hypothesis, models it mathematically to assess private debts.	Central bank, commercial banks, which deal in loans, equities, and deposits.	Dividend function, short-term interest rate r, relaxation parameter of inflation η, price mark-up μ.	Firms can borrow money to finance dividends (follows Modigliani-Miller). Since dividends of both financial and non-financial entities are redistributed to households, the latter own both types of equities. Notice that, since the banks' financial balance is always zero, their equity, can 'safely' be assumed constant. An endogenous interest rate set by a central bank in response to inflation is set aside for future research.

(Continued.)

Table 1. (Continued.)

#	Model type	Example paper	Characteristics	Key financial assumptions	Financial actors and terms	Parameters and rates	Financial sector mechanisms
5	RQGS	Jackson *et al* (2016)	Falstaff is a system dynamic post-Keynesian stock-flow consistent model. Focus is on one state and one industry sector but includes an elaborate financial economy. Firms' green investment is exogenously determined.	SFC accounting principles: following the 'transaction flows' matrix, sum of all assets and liabilities across all sectors equalling zero. Demand -driven. Money creation parallel to interest-bearing debt (fractional reserves). Balance of trade. Demand for bonds/equity equals supply of bonds/equity.	Commercial bank, central bank. Loans, deposits, mortgages, equity, and government bonds exist. In an extension, also pension funds are added. Retained earnings and dividends also feature (p. 36).	Reserve ratio is 1%, capital adequacy is 8%. Central Bank can affect base interest rate in response to unemployment in the model.	Accounts for the performance of the economy in terms of financial balances, net lending positions, money supply, distributional equity and financial stability. Banks provide loans and receive deposits. Exogenous reserve ratio policy, and capital adequacy policy, can be imposed for stability. Central bank sets interest rates and provide liquidity on demand. 'Waterloo' version of FALSTAFF also includes mortgages and pension funds, plus an econometrically derived portfolio allocation function.
6	RPGF	Paroussos *et al* (2019a)	GEM-E3 is a hybrid recursive dynamic CGE model extended to account for finance and semi-endogenous technical progress. The model features perfect competition market regimes, discrete representation of power-producing technologies, semi-endogenous learning effects, equilibrium unemployment and option to introduce energy efficiency standards and emission permits for greenhouse gasses (GHGs).	Fixed money supply in each period, usually no crowding out effects.	World Bank.	Single global interest rate set at 2% (authors claim this can be endogenized in later research). Scenarios also set interest rates to be 1.5, 2.1, 3.8%.	World bank collects savings from agents in surplus and provides financing to agents in deficit. In standard closure of model, uniform global average interest rate independent of debt profile. In this study, interest rate varies with financing requirements and debt levels. In contrast, in 'normal' CGE models, agents finance energy-saving expenditures by reducing other expenditures. In this study, the money supply is fixed in a period.

(Continued.)

Table 1. (Continued.)

#	Model type	Example paper	Characteristics	Key financial assumptions	Financial actors and terms	Parameters and rates	Financial sector mechanisms
7	RPGF	Garaffa *et al* (2018)	COFFEE-TEA includes disaggregate capital flows from the current account balances in the GTAP database. The impacts of different greenhouse-gas (GHG) emission scenarios on green capital allocation are analysed.	Due to the Social Accounting Matrix (SAM): 'macroeconomic equilibrium implies an equality between the current account balance and the inflow and outflow of a country's foreign currency' (p. 2). In the rest of the economy: market clearance and perfect competition.	No explicit financial actors are defined.	All capital stocks and flows taken from GTAP9 database.	Further developing of the Social Accounting matrix approach on the Global Trade Analysis database: capital inflows and outflows between regions, but no explicit financial sector. However, climate flows that are private are difficult to deduce from these efforts (public finance on climate is better tracked by UN and OECD).
8	RQGF	Ameli *et al* (2021)	TIAM_UCL is an IAM with a focus on the energy sector: a technology-rich and bottom-up cost optimisation model.	Weighted average cost of capital (WACCs) differ by region, reflecting national risks.	No explicit financial actors are defined.	Country-specific WACCs reflecting the country risks. Calculation described in the Methods section (ratios of debt and equity, and costs of debt and equity, with a tax rate that amends the cost of debt). Data is taken from: the Damodaran dataset; EU and US yield statistics; KPMG tax rate approximations.	No explicit financial sector mechanisms, only implicit assumption on WACCs used in the energy sector.

(Continued.)

Table 1. (Continued.)

#	Model type	Example paper	Characteristics	Key financial assumptions	Financial actors and terms	Parameters and rates	Financial sector mechanisms
9	RPGF	Leimbach and Bauer (2021)	REMIND- MAgPIE is an IAM with macroeconomic, energy, and agricultural components, and this paper adds current account imbalances and imperfect capital markets.	Imperfect capital markets: debt constraints on the current accounts of regions, and trade 'wedges' are imposed, in order to approach historical data.	Additional financial actors (other than the regions in the IAM), are not explicitly defined.	Debt constraint: current account deficit cannot exceed 20% of GDP. Discount rates, intertemporal elasticity, and pure rate of time preferences also feature (see p.7)	Imperfect capital market mechanisms are modelled into this IAM. The authors use the wedge analysis to identify and adjust different model parameters that affect capital flow, until selected model output (e.g. current accounts) match observed data. The trade wedge results in a mark-up in capital imports.
10	RPGF	Bachner *et al* (2019)	WEGDYN is a global multi-region, multi-sector, recursive-dynamic CGE model.	Behavioural assumptions include: lack of perfect foresight and use of second-best, rather than optimal policies. The authors assume a fixed savings rate, meaning that a fixed part of regional income is spent for investment, which accumulates over time to build up the generic capital stock.	Debt and equity are differentiated. No financial agents act in the model. Capital is constrained (as is 'common in CGE models').	WACCs differentiated by country and technology are applied, set exogenously through IMF, World Bank, and ECB data.	No explicit financial sector is defined, only implicit assumption on WACCs used in the energy sector.

Notes: Model type: (A)gent Based Model or (R)epresentative Agent Model, (P)rice-adjusted or (Q)uantity-adjusted (immediate vs. delayed price adjustment, flexible vs. sticky), (G)eneral vs. (P)artial (dis)equilibrium, (S)tock-flow consistent vs. Non-SFC(F)models.

the economy, induced by the introduction of specific climate policies. Thus, an agent-based approach to modelling financial markets appears reserved for questions of stability and solvency of the banking sector, not for the purposes of simulating, for example, the (qualitative and quantitative) mismatch between sources of finance and renewable (or other low-carbon) investment projects.

As a result of defining representative financial agents, the most common financial assets that are accounted for in the models are deposits, loans, and government bonds. These can variously be issued and held by agents such as households, firms, bank(s), and the government. Multiple papers add firm equity to the mix, particularly if they distinguish between firms based on energy-efficiency and propensity for green innovation (Ponta *et al* 2018 in table 1 line 2). Jackson *et al* (2016 table 1 line 5) offer an extended version of the FALSTAFF model, which can also include mortgages and pension funds, although this does not appear to affect their simulations or analysis greatly. Models focused on analysing a single country (Liu *et al* 2017) add components for foreign investment flows.

Although some papers (e.g. D'Orazio and Valente 2019) mention the relevance of R&D and innovation for the energy transition, few models consider the crucial difference between equity and debt and more specific financing instruments such as venture capital, asset finance and crowd funding that are relevant in the area of innovation finance. Similarly, the reviewed papers rarely consider the distinction between project and balance sheet finance (i.e. financing investments via the balance sheet of an established entity vs. creating a new special purpose vehicle for the investment project).

3.2. Financial terms, parameters and rates, financial sector mechanisms

Another distinguishing aspect between the models is how they set key finance-related parameters and determine key variables (such as interest rates and costs of capital). This follows three general approaches. The first involves deriving parameter values directly from disaggregated empirics and historical data (Liu *et al* 2017, Garaffa *et al* 2018 in table 1 line 7). The second involves setting a parameter exogenously, sometimes considering a handful of scenarios with diverging assumptions, based on a likely spectrum of values derived from previous works. This is the most common approach, and is applied to interest rates, capital requirements, and dividend yields, such as in the collection of SFC models (e.g. SIGMA, ECOGRO, FALSTAFF) developed by Jackson *et al* (2016 table 1 line 5). In another example, lower interest rates are offered by banks on loans to energy producing companies, as compared to final goods producers, to reflect the expected risk profiles of these different firms (Safarzyńska and van

den Bergh 2017). Finally, variables can be determined endogenously, through the interaction of goals, constraints and actions of a model's agents. In the model of Monasterolo and Raberto (2018), for example, a central bank sets inflation and unemployment targets, which are applied through an approximation of the Taylor Rule to endogenously determine interest rates.

Due to country risk profiles, climate factors, life cycle stages of different technologies, and the presence or absence of financial learning-by-doing effects, particularly from institutional investors, the weighted average costs of capital (WACC) vary between regions and technologies relevant to the green transition (Steffen 2020, Polzin *et al* 2021b). While a uniform CoC assumption has been applied in most past modelling work, recent attempts have been made to differentiate WACC values in energy transition scenarios (Polzin *et al* 2021b). Based on the assumption of a fixed savings rate, capital accumulation over time, and capital constraints, Bachner *et al* (2019 see table 1 line 10) differentiate WACCs by country and technology and these WACCs differ depending on specific scenario assumptions. In a GEM-E3-based study, Polzin *et al* (2021b) show that country- and technology-specific WACC assumptions influence the decisions to invest. Financing experience that influences (reduces) equity costs and debt-margins over time leads to falling WACCs for innovative technologies over time. Moreover, a study using TIAM-UCL shows that this leads to an unequal distribution of capital for low-carbon technologies between the North and the global South, whereas converging WACCs towards industrialised country values would accelerate the energy transition (Ameli *et al* 2021 in table 2 line 8).

More recently, modelers have also started to zoom in on the risk transmission channels from credit markets to the economy via loan contracts (Dunz *et al* 2021). Dealing explicitly with the accumulation of debt, firms' leverage ratios, and the potential for entry-bankruptcy-exit dynamics for both firms and banks enables models to incorporate systemic risk and financial instability. For example, parts of investors' portfolios can be subject to physical climate or transition risks, which could be mitigated through risk management strategies. By requiring such strategies, financial supervisors affect investors' behaviour (Battiston *et al* 2019). The CLIMAFIN model, for example, embeds climate scenarios adjusted for financial pricing (for equity holdings and for sovereign and corporate bonds) to model transition risk associated with energy technologies (Battiston *et al* 2021).

3.3. Conclusion

Several studies advance the implementation of financial markets and risk into MET models and IAMs. Through the addition of frictions and imperfections,

Table 2. Overview integration of financial markets in macro- energy models.

Theory	Pecking order	Term structure	Capital asset pricing model	Macro-monetary
Step 0: Sources of capital	Differentiate different sources of equity and debt capital	Introduce debt markets	Introduce public equity markets	Introduce central bank agency
Integration in GEM-E3	Incorporate a representation of the financial sector, with different financing sources, central banks, and debt markets. A prototype of this has been implemented in GEM-E3 in Paroussos *et al* (2019b).			
Step 1: Differentiate CoC	Differentiated cost of capital for debt and equity.	Differentiated cost of capital for long-term and short-term debt.	Differentiated cost of capital on assets by risk level.	Exogenous risk-free short-term interest rate/discount rate.
Integration in GEM-E3	Differentiated WACCs based on empirical data for different sources of capital (e.g. debt, equity, long- and short-term debt, etc) and exogenous risk-free interest rates. The link between different types of assets and energy technologies should be made.			
Step 2: Link CoC to finance demand	Pecking order calibrated on data equilibrates demand to total (exogenous) supply.	Term Structure calibrated on data equilibrates demand to total exogenous supply.	Capital Asset Pricing Market line calibrated on data equilibrates demand to total exogenous supply.	Risk-free short-term interest rate equilibrates investment demand to exogenous or semi-endogenous savings.
Integration in GEM-E3	The methodological integration in GEM-E3-FIT can be implemented through expanding the usual investment = savings equation of CGE models to account for differentiated asset prices while ensuring economic equilibrium.			
Step 3: CoC to equilibrate demand to supply	Asset type linked to life cycle stage on demand side and pecking order preferences on supply side.	Maturity linked to real asset lifetime on demand side and on supply side to preferences over time.	Risk premia linked to real asset risk on demand side and to risk preferences on the supply side.	Risk-free short-term interest rate equilibrates savings to total new investment demand.
Integration in GEM-E3	This requires methodological advancements to endogenize differentiated financial asset markets driven by demand–supply interactions through prices for different assets (e.g. traded equity, debt, long- and short-term interest rates, risk preferences) and consumers' savings decisions.			

assets can be stranded, and some capital may be idle during the transition. Some state-of-the-art models distinguish between green vs. brown innovations, investments, and bonds to explore more targeted transition policies (Liu *et al* 2017, Monasterolo and Raberto 2018). These models already include differentiated risks and rates. Creating such differentiated financial sectors 'from the bottom-up', primarily with an agent-based approach, allows for a spectrum of actors with different environmental and risk preferences to interact with (and learn from) each other, and to finance projects that are differentiated on an ecological dimension (discussed also in Hafner *et al* 2020).

Despite these improvements, several state-of-the-art models (e.g. REMIND or GEM-E3) still overestimate the crowding-out of finance that decarbonisation will entail in other productive sectors/projects when they assume that total investment is given and equals to total savings (without the possibility for issuing new loans that can be paid back in the future) according to the loanable funds theory. Others instead assume that firms have access to unlimited financial resources at a uniform and low CoC, by for example assuming a small open economy or full fungibility of finance and an endogenous

money supply. Both extremes are misleading and can give rise to seriously misguided policies and unrealistic transition scenarios (Keppo *et al* 2021). The lack of finance may seriously hinder the transition. But the transition may also seriously affect the financial sector.

Recent evidence suggests that financial stability can be affected by the transition, as financial risk is re-allocated between different types of activities and technologies (Battiston *et al* 2017, 2021, Mercure *et al* 2019). Models can only start capturing such dynamics if they differentiate among assets and model the asset valuation in these markets explicitly. The modelling of differentiated capital and financial markets is complicated by the lack of consensus on how capital markets operate and how finance is created. This is, for example, demonstrated by diverging assumptions used in neo-classical CGE models such as GEM-E3 or WorldScan, compared to assumptions in the post-Keynesian school of thought and macro-economic demand-led models such as the E3ME or NEMESIS models (Capros *et al* 2014). But extension of these models to better capture the interlinkages between energy transition and the finance sector is urgent, and fortunately there is a wealth of research in the field of finance that can guide this endeavour.

In sum, to the best of our knowledge, there have not been attempts to explicitly link finance through multiple asset classes (notably equity vs. debt and traded vs over-the-counter debt) to transition investments by technology. Also, most papers do not consider the endogenous evolution of the financing mix over sources of funding and types of assets (Polzin and Sanders 2020, Polzin *et al* 2021a) and do not capture financial learning (Egli *et al* 2018).

4. Conceptual extensions

We want to propose extensions that can accommodate these important linkages between finance and the energy transition. The goal of this is twofold. On the one hand, these incorporations of established financial market dynamics would make IAM and MET model results more reliable and relevant, especially as capital-intensive technologies are concerned. On the other hand, more sophisticated financial market representations also allow us to assess the scope and impact of 'green' monetary policy that an increasing number of academics (e.g. Schoenmaker 2021) and policy makers (e.g. Dafermos *et al* 2021) are advocating.

First, we want to incorporate multiple financial assets, notably debt and equity markets, to model the possible qualitative mismatch of available and demanded finance for energy transition projects. Second, we want to link the demanded finance mix and corresponding weighted COC to the technology life cycle of individual technologies and, finally, we want to be able to model differential rates of financial learning in different transition technologies (Steffen 2020). To do so, we need to introduce heterogeneous assets and markets in MET models and IAMs. But, of course, these markets do not move independently. Instead, different assets in different financial markets are linked. Risk and return are linked through the CAPM-model, suggesting that assets command a risk premium that is proportional to the asset's beta, which reflects the degree to which the asset moves with the entire market (beta = 1). The term-structure links the return on equally risky assets with different time horizons. Again, arbitrage ensures that in efficient markets the rate of return on a ten-year bond or loan is equal to the average expected return on two consecutive five-year bonds or loans. Finally, the pecking order links different asset types that are available to finance a project by CoC, notably explaining why and by how much equity is more costly than debt, implying that investors will prefer to finance their projects with debt over equity (Frank and Goyal 2003).

4.1. Capital asset pricing model (equity markets)
In traded equity markets, the CAPM quantifies the appropriate rate of return of an asset, by considering the asset's sensitivity to market risk (beta), market return, and risk-free rate (Courtois *et al* 2012). Originally presented by Sharpe (1964) and Lintner (1965), it is widely used by financial practitioners, including for low-carbon assets specifically (Steffen 2020). While the market return and risk-free rate are economy-wide parameters, the beta is asset-specific, and hence can differ between countries and technologies (such as renewables vs fossil fuel technologies), leading to differentiated costs of capital. Empirically, betas for different technologies can be estimated by choosing technology-specific comparison groups, as done by for example Partridge (2018) and Werner and Scholtens (2017).

To allow for costs of equity that differ between technologies and potentially between countries, IAMs and other MET models could introduce a financial market that differentiates the transition (and other) technologies on their market risk (beta) and equilibrates the financial market on the risk-free rate and the market risk premium, such that all technologies face a different CoC in equity markets. If the projects' and technologies' betas are taken from empirical data, then having a financial market that yields a risk-free rate and a market risk premium (two endogenous variables), calibrated on empirical values for the market rate of return on traded equity, would allow for much richer financial markets and computationally should still be manageable.

4.2. Term structure of interest rate (debt markets)
In debt markets, bonds with different maturities usually exhibit different yields with longer maturities increasing the yields. This difference, called the term structure of interest rates, stems from investor characteristics, such as risk aversion and preference for liquidity; the overall market environment, such as future expectations and investment alternatives; and, finally, structural differences, such as different holding and management costs (Culbertson 1957, Cox *et al* 2005). Therefore, 'normal' yield curves are concave with a positive and declining slope over the maturity horizon. However, yield curves can also 'invert' if investors anticipate a recession, leading to lower yields of long-term bonds compared to short-term bonds. Due to this link to (market) expectations, yield curves also depend on monetary policy. In general, if central bank rates go up, interest rates of all maturities tend to go up (Ellingsen and Soderstrom 2001). However, if central bank rates change because policy preferences have changed (e.g. a higher weight put on the inflation target), short-term yields move up in accordance, but long-term rates move in the opposite direction (Ellingsen and Söderstrom 2001) as investors read a higher central bank rate as a higher weight on inflation control and anticipate lower long-term inflation rates. Empirically, yield curves are usually established using government bonds because of the widespread trading at different maturities

(Gürkaynak *et al* 2007). The relationship between different maturities in the term structure should, however, also hold for corporate bonds.

In the case of project-finance technology assets, scholars have additionally observed a decrease in the CoC with increasing financing experience. As investors became more acquainted with a technology, its risks, and its regulatory environment, they offered better financing conditions (Egli *et al* 2018). This effect was observed on the debt margin that banks offer. Hence, for loans with equal term length, banks decreased the required yield as the technology-specific financing experience accumulated over time (ibid.).

In sum, models could consider representing three artefacts. First, models could implement yield curves for debt. This would entail a differentiation of the cost of debt for different technologies depending on the technology lifecycle. However, this differentiation is not trivial, as assets are routinely refinanced. The more common and commercially mature the technologies are, the more liquid the financial markets become, and the less important the yield curves become. Hence, there is a link to market size and potentially to technology maturity. Second, models could make the yield curve dynamic. Based on the mechanisms described above, the yield curve (of all technologies) could be linked to the general economic environment using various scenarios. Furthermore, yield curves could be linked endogenously to monetary policy. Third, models could also explicitly implement the effect of financing experience on the cost of debt. This would link the cost of debt across all maturities to technology maturity as done previously in Polzin *et al* (2021b).

4.3. Pecking order and asset classes (different sources of finance for energy investments)

A pecking order in sources of finance exists when corporate (or project for that matter) financiers exhibit myopic behaviour and information asymmetry between investor and project/firm exist (e.g. Jensen and Meckling 1976, Carpenter and Petersen 2002). This theory is one of the most widely used in corporate finance. Mainly by building on this mechanism, Myers and Majluf (1984) derived a standard pecking order theory, which states that firms prefer to finance new projects with internal cash flows first and then, if necessary, seek additional external debt capital and, lastly, seek external equity capital (Cosh *et al* 2009, p 1494). To avoid dilution of ownership, empirical evidence points towards reliance of new firms on debt (Robb and Robinson 2014).

Financiers are partly able to mitigate information asymmetries (e.g. lending technologies by banks and due diligence from equity investors) (Gompers 1995, Berger and Udell 1998, Harrison and Mason 2000). Hence, the investment decision is determined by the screening efforts of the financier and by the quality and credibility of the signals of potential investment projects/firms. Credit rationing occurs as the relationship between assessed risk and cost of the loan is not assed contingently, for example too risky projects will not be financed by debt (Stiglitz and Weiss 1981). Overall, the capital structure of firms and projects will thus be determined by the firms' characteristics (innovativeness, opaqueness, etc) as well as by the relationship between capital expenditure, profits and the external finance sought (Cosh *et al* 2009).

To introduce markets for equity and debt based on pecking order theory would require linking the relative return (equity premium) to the endogenous risk-free rate that clears financial markets. The equity premium is driven by taxes (on profits and dividends vs exemptions on interest payments), an average risk premium and the option value of the equity upside. Moreover, on the demand side, less mature technologies require a higher equity/debt ratio in finance. That equity/debt or inverse leverage ratio can be endogenized by linking it to the cumulative production or installed capacity (technology life cycle) or to the cumulative investment (financial learning) or to a combination of the two with different elasticities. We would then need to specify per technology what is meant by over the technology life cycle, the maximum leverage, and the beta. Then the market clearing risk-free rate plus the term structure slope, equity premium and market risk premium together determine the WACC that each technology faces (Polzin *et al* 2021a). Adding up over all technologies gives the total demand for finance, differentiated by maturity (for debt) and type. Confronting that with supply can create the mismatches in transition scenarios in which we are interested. These imbalances can also be used to adjust financial markets parameters in logical directions to re-establish equilibrium between demand and supply. Even in that equilibrium, however, targeted interventions can reduce the costs of transition. Some of the agent-based SFC models have already implement similar dynamics (Bovari *et al* 2020), suggesting impacts are significant.

4.4. Macro-finance and monetary policy

Monetary transmission describes how monetary policy changes are transmitted to real economic variables, such as output, income, and employment (Ireland 2010). As the monetary authorities control the monetary base and/or manipulate the short-term interest rates at which financial intermediaries can (re)finance their operations, they directly or indirectly change the CoC for the real economy. This CoC, evaluated against the internal rate of return of investment projects or consumption expenditures, then affects the demand for consumption and investment in the aggregate. The textbook models typically simplify the mechanism a great deal by

assuming there is only one interest-bearing asset (bonds) and modelling the money market as a market where 'the public' holds a stock of money and bonds. The demand for money then depends positively on income, as income determines the need for money to make transactions. It depends negatively on the interest rate on bonds as that represents the opportunity cost of holding wealth in the form of money. In real financial markets, however, there are many assets in which wealth can be stored and they all have their own unique risk, return and cash-flow profiles (e.g. corporate and government bonds, traded and untraded equity, deposits, loans, money market funds). The efficient market hypothesis postulates that all these asset classes, corrected for risk, convenience, and liquidity, should offer the same rate of return. If the central bank increases the monetary base and therefore the money in circulation, the tide will lift all boats. However, reality is more complex, and as (some) markets hit a zero lower bound (Schoenmaker 2021), unconventional monetary policies are introduced (Kempf 2020) and central banks start to implement policies to support the transition (Kempf 2020, Dafermos *et al* 2021).

At the zero lower bound, interest and inflation rates become so low that further decreases cannot be implemented through regular monetary tools, such as open market operations and the discount windows. In the two-tier banking system, the central bank relies on commercial banks to pass-through the favourable funding conditions in the form of lower lending rates and larger lending volumes. But if the private sector already has high debt and/or no demand for new loans because prospects are bleak, then lowering interest rates and increasing the monetary base has little to no effect on real economic variables. The transmission channel is blocked.

Since the financial crisis of 2007–2008, many central banks, importantly including all in the developed world, have resorted to unconventional policies and 'quantitative easing'. Central banks around the world have been buying up massive amounts of assets to push capital costs down. They try to do so in a neutral way by buying these assets in proportion to the total market index, such that their policies do not benefit some issuers of assets over others. But it has been shown that this market neutrality benefits carbon intensive sectors and projects over renewable energy technologies (Schoenmaker 2021). Moreover, considering the financing lifecycle, a central bank buying up tradable debt with newly printed money will bias the availability of cheap finance towards those sectors and activities that can be financed with debt.

If monetary transmission in IAMs and MET models is modelled as reducing the costs of capital across the board, the models miss the fact that monetary transmission, especially in heavily bank-based

financial systems, such as that in Europe, runs through commercial banks offering more favourable terms of finance to sectors and projects that are 'bankable' (Campiglio 2016, 2017, Campiglio *et al* 2018, Campiglio and der Ploeg 2021). In efficient financial markets, where the tide lifts all boats, this would also imply a reduction in the cost of other types of assets. Financial intermediaries would issue more debt to intermediate into other forms and the monetary expansion would reduce the CoC across the board. But if there are any types of frictions (such as imperfect competition, regulation, and asymmetric information) that prevent this pass-through, then monetary policy ceases to be neutral. To capture such non-neutrality in monetary transmission, it is essential that IAMs and MET models distinguish between different financial asset markets, including, importantly, traded equity, bank debt and traded debt. As that extension was already proposed to incorporate the qualitative mismatch between demand and supply in finance, what remains is to build in separate transmission mechanisms from monetary policy to these markets. The pecking order theory can link costs of capital across different asset classes, whereas the empirical and theoretical literature on monetary transmission channels can inform how these asset classes respond (differentially) to traditional and unconventional monetary policy instruments.

5. Integrating the conceptual extensions into MET models

The way finance is represented in macro-economic models is a key source of uncertainty in model projections of mitigation costs and impacts on economic activity and employment. Research efforts should be directed towards further improving the representation of the financial system in MET models and IAMs to better understand the interplay between energy transition and financial dynamics. We suggest practical ways to integrate a much-improved representation of the finance sector in large-scale MET models and IAMs, building on recent scientific evidence and methodological advances. Table 2 outlines four methodological steps that we can distinguish in bringing financial markets in energy- and macro models more in line with the state of the art in finance. We also depict to what degree the proposed steps exist in the reviewed literature. Table S1 in the supplementary materials offers an overview on the extent to which each paper currently applies our recommendations, while some significant trends are summarised, below. In addition, figure 1 depicts the stylised integration of differentiated financial markets using the GEM-E3 CGE model set-up. As many other METs, the GEM-E3 currently features a simple financial market module (FIT) consisting of representative banks that match deposits and loans from households

as well as government bonds with investment needs by firms on a single money market. All investment is financed with the same type of funds at a common interest rate and the capital stock is the perpetual inventory of capital investments with a set depreciation rate.

Based on differentiated assets (considered as step 0), we propose that modelers differentiate the CoC on different dimensions of financial assets (step 1). All theories mentioned herein suggest that MET modelers should first differentiate between different types of assets. We should distinguish equity from debt and that crude first split needs to be more sophisticated in different directions to accommodate insights from advanced financial theories. Pecking order theory argues that firms will try to finance their operations with a mix of financial assets available to them at the lowest cost, also considering the 'costs' of giving up control rights. Issuing new, publicly traded equity is then typically considered most expensive, as that waters down the value of the ownership shares of existing owners and reduces the voting rights. The 'cheapest' funds are therefore retained profits and earnings, then securitised (bank) loans, then traded debt and then traded equity. Similarly, in step 1, modelers can distinguish debt by maturity following the Term Structure and distinguish traded debt and equity by their respective 'betas' as their level of risk following the CAPM[14]. The first, essential step towards fully endogenizing differentiated costs of capital is to distinguish and introduce these different asset types in the energy and macro-models and create realistic scenarios for (relative) costs of capital between these types of assets (exogenously).

While several studies make inroads into our proposed step 1, this is done in an uneven and incomplete fashion. No study achieves a differentiation of costs of capital on all dimensions that we have identified as relevant from the financial literature (pecking order, term structure, risk assessment, and macro-monetary considerations).

Despite differentiating between debt and equity sources of finance, some models choose to explicitly define an interest rate on loans while leaving the cost of equity more implicit (such as in Fontana and Sawyer 2015); other models even assume equal costs to both debt and equity, to uphold a Modigliani-Miller assumption (see Bovari *et al* 2018). While the agent-based DSK model of Lamperti *et al* (2018, 2020) directly references pecking order theory, with the intention of reflecting this aspect of firm-level financing decisions, so far they only distinguish between retained earnings from sales and credit from banks, as finance sources.
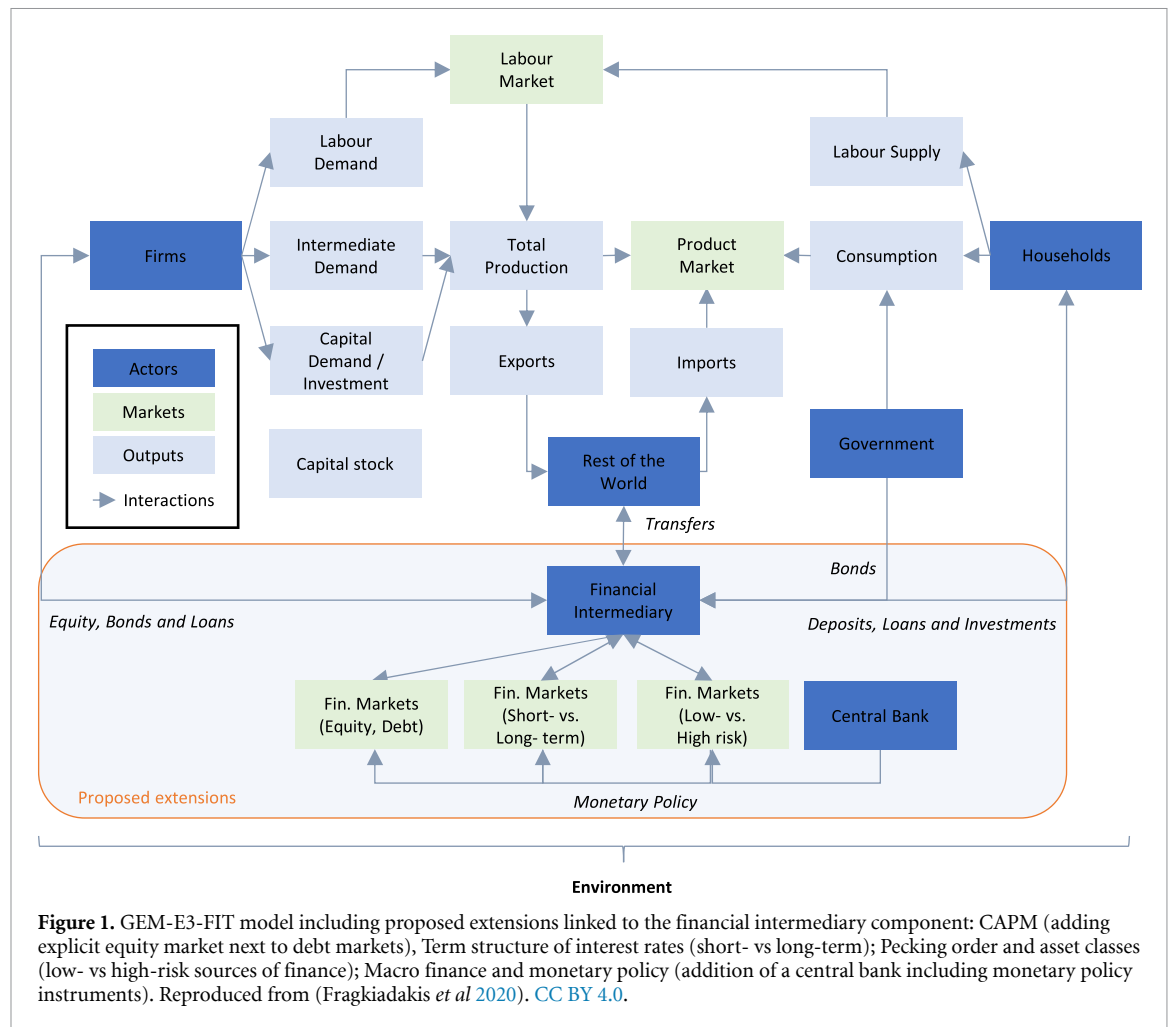
On the next dimension of interest, the introduction of asset classes with varying maturities has been rare in the surveyed models. Although combinations of short-term Treasury bills, mid-term loans, and long-term mortgages have been included (see Naqvi 2015, Ponta *et al* 2018), these asset classes are usually available to different agents in the model. As an example, Treasury bills may only be used by the government sector and sold to a central bank, while mortgages are available to households; this does not allow for the choice of a preferred term structure for green investments and projects.

In several macro-econometric models in our review (Dafermos *et al* 2017, Battiston *et al* 2021), representative 'green' and 'brown' investment opportunities are distinguished by risk, with renewable energy being seen as the riskier option. However, other models assume an equal CoC and/or bond price between low- and high-carbon technological categories (in order to explore fiscal green incentives in Monasterolo and Raberto 2018). It is in process-based IAMs, with their more extensive electricity sector modules and multi-region disaggregation, that risk premia have been added to countries and technologies based on available data (Ondraczek *et al* 2015, Bachner *et al* 2019). Battiston *et al* (2021) make inroads in their CFR model, which includes a climate financial risk assessment module, to allow capital costs in one period of simulation to affect available transition pathways in following iterations. To what extent this can be used to explicitly explore the life cycles of technologies, is a matter for future research.

This first step is easily implementable in most macro-transition models (and in GEM-E3), as it involves the numerical differentiation of CoC values for different types of assets, which is done exogenously based on empirically estimated data (see e.g. Polzin *et al* 2021b).

A step further up the endogenization ladder (step 2) is to link the demand for and supply of these different asset types to their respective costs of capital. To take this step, one needs to link differentiated asset prices to theory more carefully. In the pecking order theory, the degree of asymmetric information and opacity drives the gap between internal and external funds. The leverage and quality of the firm's balance sheet drives the gap between debt and equity. These patterns are well established at the firm level (Aysun and Hepp 2013) and can be relevant at the aggregated sector or technology level, as included in macro-transition models. On the demand side we can use the industry or technology life cycle to use a set of stylised facts on finance as a steppingstone between exogenous scenarios for costs of capital (step 1) and fully endogenized price formation in markets for differentiated financial assets (step 3). In the early stages of the product/technology/industry lifecycle a sector invests a lot in new technology, as it typically has high entry of new firms and high exit of existing ones, such that

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[14] Bank debt, over the counter debt and equity and non-traded equity are not traded in markets, but risk management and asset pricing models used by professional investors follow the CAPM-logic that more risky assets require a higher return.

Figure 1. GEM-E3-FIT model including proposed extensions linked to the financial intermediary component: CAPM (adding explicit equity market next to debt markets), Term structure of interest rates (short- vs long-term); Pecking order and asset classes (low- vs high-risk sources of finance); Macro finance and monetary policy (addition of a central bank including monetary policy instruments). Reproduced from (Fragkiadakis *et al* 2020). CC BY 4.0.

track records are short, firms are small, and financiers face significant asymmetric information problems while profitability is low and competition intense. In that stage of the cycle, the entire sector's financing mix shifts in the direction of the more expensive sources of external funding (see e.g. Polzin *et al* 2021a). If, after the industry shake-out, profitability is high in oligopolistic markets and risks are low in very mature technologies, the sector can fund its (replacement) investments much more cheaply. The same life cycle dynamics can also be linked to the maturity of debt, moving from short and low to longer and more debt financed over the cycle, and to risk, moving from high to low. By linking the life cycle of sectors and technologies to, for example, cumulative production, installed capacity or total accumulated investment of specific energy technologies (or sectors), the finance supply mix of sectors can move back and forth between these industry life cycle stages in a semi-endogenous way[15]. If the composition of

finance demand is known, we can compute the vector of asset prices that would equate the total supply of savings as a share of total income to the total demand for new investments across sectors, to establish also the macro-economic equilibrium.

The papers surveyed for this review have not yet linked differentiated costs of capital to demand for finance, as is recommended in step 2. Models such as EIRIN (Monasterolo and Raberto 2018) and EURACE (Ponta *et al* 2018) begin by linking the firm-level decision to request investment finance to a net present value calculation, thus making it dependent on defined costs of capital and discount rates. However, this is insufficient for an endogenization of capital costs with the demand and supply dynamics of various financial assets. As table 2 indicates, if data for different types of assets are available from empirical analyses, the methodological integration of this mechanism in GEM-E3-FIT can be implemented through expanding the usual investment = savings equation of CGE models to account for differentiated asset prices while ensuring economic equilibrium.

Step 3 would be the full endogenization of differentiated financial asset markets and consumers' savings decisions. Theory and empirics suggest that strong linkages exist between financial markets. And

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[15] Note that a product cannot, but a firm, technology or sector can 'rejuvenate' and restart the life cycle. Examples that come to mind are the rejuvenation of the telecom industry with mobile and then smart phones. And perhaps now the automotive industry with electrification.

Table 3. Feasibility of implementing more sophisticated financial market modules across model types.

Model types	A/R	P/Q	G/P	S/F
Step 0: Sources of capital	++/++	+/++	+/++	+/++
Step 1: Differentiate CoC	++/+	+/++	+/++	++/+
Step 2: Link CoC to demand	0/0	0/− −	0/− −	0/0
Step 3: CoC equilibrate demand and supply	–/–	–/–	–/–	–/–

of course, our models should replicate these patterns. For pecking order theory to hold, traded equity must always carry a premium over debt and debt over (the opportunity costs of) internal funds. The term structure suggests that, in most cases, long-term interest rates exceed short-term rates due to a liquidity preference of investors, but, in exceptional times, the term structure can be inversed (reflecting expectations of strong interest rate drops in the future) (Ellingsen and Soderstrom 2001). Finally, the CAPM asset market line is always upward sloping, reflecting that the market rewards risk. But within these bounds, there is room to calibrate or even solve for the parameters of the asset market line, the term structure, and the pecking order to equilibrate finance supply and demand in all markets simultaneously. To truly endogenize the supply in each of the identified asset markets, information on the substitutability between financial assets in investors' portfolios is required. That substitutability would be linked to their risk appetite, liquidity preferences and the degree of asymmetric information between issuer and investor. It would make sense to also fully endogenize the consumer's savings decision in this step, following for example the neoclassical Ramsey model, such that also the short-term risk-free interest rate can be pinned down endogenously.

Understandably, given the complexity of the task, and the need for significant new data sources, the endogenous financial equilibria recommended in step 3 are completely absent from current modelling efforts. The implementation of this step into the GEM-E3-FIT model requires significant methodological advancements and new source code developments. It involves the endogenization of differentiated financial asset markets driven by interactions between finance demand and supply through prices for different assets (e.g. traded equity, debt, long- and short-term interest rates, risk preferences), consumers' savings decisions and investors' portfolio management techniques in the model. These improvements, however, would then support the analysis of socioeconomic, financial and competitiveness impacts of policy measures to de-risk low-carbon investment and clean technologies.

In table 2, we have added a line with every proposed step, indicating what would be needed to implement the proposed extensions in the GEM-E3-FIT model. Of course, for every IAM or MET, the required adjustments are different, and some extensions cannot be implemented in some model types without significant effort. Modellers will need to make this trade-off between costs and benefits for their models specifically. Still, we will try to draw some general conclusions on the model categories we have identified in table 1. Table 3 summarizes per model aspect (agent-based versus representative agent, price versus quantity adjusting, general vs partial (dis)equilibrium, and SFC versus flow models), how easy (++) or difficult (—) we think the proposed extensions will be to implement.

We consider steps 0 and 1 feasible in most model types. The biggest challenge in implementing these steps will be to collect the data needed to set the differentiated costs of capital exogenously. It is probably easier to implement CoC differentiation across asset classes, maturities and risks in ABMs, as these models routinely handle heterogeneity. Similarly, it is easier to do so in partial equilibrium models, such that imbalances do not spill over through the entire model, and exogenous prices are easier to handle when quantities are endogenous. Finally, it is probably more complicated to account for both stocks and flows of different assets, explaining the two + for flow-models in the last column. In step 2, especially partial equilibrium models and quantity adjusting models will be hard to extend in the directions proposed. If markets are not connected through prices, linking a differentiated CoC to total demand for finance is not helpful, as total supply of finance is not driven by price changes. Especially, in step 3, in the more sophisticated SFC models, if they are agent-based, implementing the full endogenization of (interlinked) financial market prices will be complex, whereas with full endogenization, the problems of quantity adjusted models become less severe.

Implementing the proposed extensions would enable IAMs and MET models of all types to model the constraints in financial markets, especially if they turn out to be qualitative rather than quantitative in

nature. That can help us understand and prevent a situation where some types of finance are not (sufficiently) available at the time they are needed and at going market rates. Capturing the pecking order, the term structure, the CAPM and monetary transmission in a differentiated financial market module would allow for the identification of bottlenecks that slow down the transition and identify policy measures to speed up and make the transition more affordable. By tracking the differential impacts on various sources of capital income, a richer picture of the distributional effects of the energy transition will also arise and can help policy makers gear instruments towards a more inclusive and just energy transition. This sets an ambitious but also urgent challenge for future research.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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